The Effect of Plant Size on the Economics of Producing Energy from Biomass

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Abstract

This working paper details the methodology used for [Marrison and Larson, 1995a and 1995b], it also extends the theory of how to analytically derive the scale that will give the least cost. For the most the most recent data, use [Marrison and Larson, 1995a and 1995b].

Several technologies are under consideration for the production of electricity or liquid fuels from biomass. The primary candidates for electricity production are steam turbines and biomass integrated gasifier/gas turbines. For liquid fuels, methanol and ethanol production facilities are under consideration. A unique feature of biomass energy conversion technologies is that the feedstock must be gathered and transported from a wide area around the production facility. For a small-scale facility, the transport costs will be low, but the capital cost per unit of output will be high. For a large-scale facility, the transport costs will be high, but the capital cost will be low. At some medium scale, there is a balance that gives the minimum cost for energy production. This paper shows the size at which facilities should be built, e.g., is it cheaper to use one central 150 MW facility or ten 15 MW facilities distributed across the countryside? The purpose of this paper is to investigate the effects of scale on the economics, and determine the optimal size for biomass energy production facilities.

The supply curve for biomass feedstock is found using a geographic information system (GIS) to determine transport costs for an area in south-central Iowa. A simplified theory is also derived and is found to match the GIS results for Iowa. This simplified theory is also applied to a Brazilian plantation and predicts the feedstock supply curve. The capital cost curves for the conversion factors are derived from several sources of published data. Adding the feedstock and capital cost curves gives the electricity and fuel production costs for Iowa and Brazil and defines the best scales for production facilities.

1.1. Introduction

Biomass is attractive as a commercial fuel because it often has significant environmental and economic advantages over fossil fuels [Johansson, 93]. Biomass is becoming economically attractive in the US for two reasons: the recent development of efficient technologies for energy conversion, and the desire, in the United States, to find an environmentally benign cash-crop for land that is currently under the Conservation Reserve Program (CRP). The CRP pays farmers to keep fragile lands idle, and it currently costs the US taxpayer \$ 1.8 billion per year. An attractive alternative to the CRP is to use the land for an energy crop such as switchgrass, which does not require annual tilling of the soil and therefore can be grown sustainably on fragile lands[1].

Six technologies for biomass energy conversion are considered in this paper. For electricity production, the technologies are a traditional steam turbine and two types of biomass-integrated-gasifier / gas-turbines. For liquid-fuel production, methanol synthesis and ethanol fermentation are considered. A unique feature of biomass energy conversion technologies is that the feedstock must be gathered and transported from a wide area around the production facility.

[1] Switchgrass is harvested like straw and is typically replanted once every ten years [Walsh, 94].

For a small-scale facility, the transport costs will be low, but the capital cost per unit of output will be high. For a large-scale facility, the transport costs will be high, but the capital cost per unit of output will be low. At some medium scale, there is a balance that gives the minimum cost for energy production. The purpose of this paper is to investigate the effects of scale on the economics, and determine the optimal size[2] for biomass energy production facilities.

It is important to know the optimal size not only because it affects the future economics, but also because the scale affects policy decisions. Once the range of acceptable sizes has been determined, technological research can be focused on those sizes and the public policy framework can be established for the new technology. If we know that the scale should be large, then large central utilities will continue to be the norm, if the scale should be small then the supply industry should be geared towards decentralized, rural, production.

Biomass supply curves have been developed by other authors (e.g., [Graham, 93], [Noon, 94],[English, 94]). These studies took bounded geographic areas and focused on how the marginal cost would increase as more expensive land was brought into energy-crop production. These gave results showing how the cost would change as the regional demand for biomass increased, but the effects of transport costs were either neglected, or simplified (e.g., [English, 94] considered biomass to be produced in hauling regions of 0 to 30 miles, 30 to 60 miles, or 60 to 90 miles). Moreover, the previous analyses did not consider facility capital costs and did not attempt to determine the optimal size for a production facility. This paper concentrates on establishing the optimal capacity for an individual energy production facility in an unbounded area[3]. This requires detailed knowledge of the local transportation costs.

The required transport distances are established by using a geographic information system (GIS) to analyze an area of four adjacent counties in south-central Iowa. The four counties are Appanose, Lucas, Monroe, and Wayne. This area was chosen because Chariton Valley Resource Conservation and Development Inc. is actively promoting biomass energy in southern Iowa as an alternative to the Conservation Reserve Program. This paper defines detailed feedstock supply curves for the four-county area. A simplified analysis is also developed to allow the feedstock supply curve to be predicted for other areas. The results of the simplified analysis compare well with the results of the detailed GIS analysis and are used to predict the feedstock supply curve for a plantation in Brazil.

The feedstock supply curve is added to capital cost curves for each technology to estimate the total cost of energy, and determine the size of facility that minimizes the energy cost. Finally, the paper shows how the energy costs vary when economic assumptions are varied.

2 Establishing the Feedstock Supply Curve

2.1 Sources of Economic Data

The economic data used for the production of biomass in Iowa is based on reports from the Oak Ridge National Laboratory. The cost of growing and harvesting switchgrass are estimated in [Walsh, 95]. Switchgrass budgets are given for different soil types in four regions of the United States (Iowa is in the North-Central United States). The soils are grouped into five Land Capability Classes (LCC). Within each class, the soils are further broken down according to restrictions on the land management[4]. For each soil type, [Walsh, 95] gives the total area, expected switchgrass yield, and related budget. These are reproduced in Table 2.1-1.

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[2] The optimal size is defined as the size that minimizes the total cost of energy production.

[3] The case where there are 'competing' biomass facilities in one bounded area is discussed in Appendix D.

[4] These restrictions are c-climate, e-erosion, s-soil, and w-wet.

Table 2.1-1. Switchgrass Production Data from [Walsh, 95][5]

Soil Type	Area in North-Central USA (1000 acres)	Switchgrass Yield in 2000 (dry tons/acre)	Switchgrass Yield in 2020 (dry tons/acre)	2000 Establishment Cost ($/acre)	2000 Maintenance Cost ($/acre)	2020 Establishment Cost ($/acre)	2020 Maintenance Cost ($/acre)
LCC2c	8344	3.16	4.51	183.47	159.79	186.70	171.40
LCC2e	53427	4.14	5.91	215.77	202.97	219.75	223.49
LCC2s	6837	4.35	6.21	215.77	202.97	219.75	223.49
LCC2w	42629	4.50	6.43	215.77	202.97	219.75	223.49
LCC3c	6	3.71	5.30	150.70	124.03	159.97	152.59
LCC3e	37103	4.08	5.82	215.77	202.97	219.75	223.49
LCC3s	4965	3.20	4.57	183.47	159.79	186.70	171.40
LCC3w	11756	4.30	6.14	215.77	202.97	219.75	223.49
LCC4e	12769	4.02	5.74	215.77	202.97	219.75	223.49
LCC4s	3586	3.33	4.76	183.47	159.79	186.70	171.40
LCC4w	2306	3.04	4.35	183.47	159.79	186.70	171.40

No yield is expected in the establishment year, in the next year the yield is expected to be two thirds of the normal yield, thereafter the yield is assumed to be steady at the level shown in Table 2.1-1. Switchgrass is expected to produce well for at least ten years before the crop needs to be reestablished. The yields are expected to rise between the years 2000 and 2020 due to improvements in the varieties used, improved understanding of farm management, and improved technology for harvesting and storage. The costs for the year 2020 are slightly higher than 2000 costs due to the increased costs of fertilizer and harvesting. The establishment cost only occurs in the first year. The maintenance cost applies to each year after establishment. The opportunity cost of not planting other crops is captured by the cost of land rental and is included in maintenance and establishment costs.

In our analysis of the four-county area, three soil types were available. The cost and yield data were taken to be the weighted average for Land Capability Classes 2, 3, and 4. For example, the average yield for LCC2 was taken to be

$$Y_{LCC2} = \frac{a_{LCC2c}Y_{LCC2c} + a_{LCC2c}Y_{LCC2c} + a_{LCC2s}Y_{LCC2}s + a_{LCC2w}Y_{LCC2w}}{a_{LCC2c} + a_{LCC2c} + a_{LCC2s} + a_{LCC2w}} \qquad (2.1\text{-}1$$

Where a_{LCC2x} is the area and Y_{LCC2x} is the yield from Table 2.1-1. Similarly, the average budget for LCC2 was taken to be

$$c_{LCC2} = \frac{a_{LCC2c}c_{LCC2c} + a_{LCC2e}c_{LCC2e} + a_{LCC2s}c_{LCC2s} + a_{LCC2w}c_{LCC2w}}{a_{LCC2c} + a_{LCC2e} + a_{LCC2s} + a_{LCC2w}} \qquad (2.1\text{-}2$$

where c_{LCC2x} is a cost from Table 2.1-1. The same method of weighting was used to obtain average yield and cost data for LCC3 and LCC4. The results are shown in Table 2.2.

[5] In 1993 US$.

Table 2.1-2. Averaged Yield and Cost Data.

Soil	Year 2000 Yield (tonnes/ha-yr)	Year 2020 Yield (tonnes/ha-yr)	Year 2000 Establishment Cost ($/ha)	Year 2000 Maintenance Cost ($/ha-yr)	Year 2020 Establishment Cost ($/ha)	Year 2020 Maintenance Cost ($/ha-yr)
LCC2	10.4	14.8	527	494	537	543
LCC3	10.0	14.2	526	492	535	540
LCC4	9.2	13.1	508	468	517	512

2.3 Levelized Production Costs

The economic theory deriving the levelized costs of biomass production is given in Appendix A. Starting from the assumptions that the present value of costs are

$$\text{Present Production Cost per Area} = \sum_{y=0}^{N} \frac{\text{Cost per Area}_y}{(1+i)^y} \qquad (2.2\text{-}1$$

$$\text{Present Transport Cost per Area} = \sum_{y=0}^{N} \frac{\text{TC} \bullet \text{TD} \bullet \text{Y}_y}{(1+i)^y} \qquad (2.2\text{-}2$$

where y denotes the year, i is the interest rate, N is the rotation period, TC is the transport cost per tonne-km, TD is the transport distance, and Y_y is the yield in year y. The present value of revenues is

$$\text{Present Revenue per Area} = \sum_{y=0}^{N} \left(\frac{\text{Price}}{\text{Ton}}\right)\left(\frac{Y_y}{(1+i)^y}\right) \qquad (2.2\text{-}3$$

In general the price per tonne (or levelized cost) is then

$$\text{LevelizedCost} = \frac{\sum_{y=0}^{N} \frac{\text{CostperArea}_y}{(1+i)^y}}{\sum_{y=0}^{N} \left(\frac{Y_y}{(1+i)^y}\right)} + \text{TD} \bullet \text{TC} \qquad (2.2\text{-}4$$

and for the specific case of switchgrass the cost is

$$\text{LevelizedCost} = \frac{E + M \sum_{y=1}^{9} \left(\frac{1}{(1+i)^y}\right)}{Y_{\text{steady}}\left[\frac{\frac{2}{3}}{(1+i)} + \sum_{y=2}^{9}\left(\frac{1}{(1+i)^y}\right)\right]} + \text{TD} \bullet \text{TC} \qquad (2.2\text{-}5$$

where E is the establishment cost, M is the annual maintenance cost, and Y_{steady} is the steady yield. Equateion 2.2-5 gives the cost, but to know the area required for plantations we must know the average physical production yield. The average annual production in a region will be less than the steady production because there is no yield for farms in their establishment year, and low yield the next year. The yield, averaged over the first 10 years is:

$$\text{TimeAverageYield} = \frac{(0 + \frac{2}{3} + 8) \bullet Y_{steady}}{10} \qquad (2.2\text{-}6$$
$$= 0.87 \bullet Y_{steady}$$

Assuming a discount rate of 4.9%[6], the costs and yields for Iowa are given in Table 2.2-1[7]. The costs in Table 2.2-1 include storage losses. Storage losses for switchgrass are typically 10% [Michigan report].

Table 2.2-1. Levelized Costs and Average Yields for Iowa

Soil Type	LCC2	LCC3	LCC4
Year 2000 Levelized Production Cost ($/dry tonne)	64.74	67.23	68.87
Year 2020 Levelized Production Cost ($/dry tonne)	49.36	51.28	52.25
Levelized Transport Cost ($/dry tonne-km)	0.18	0.18	0.18
Year 2000 Time Averaged Yield (dry tonnes/ha-yr)	8.1	7.8	7.2
Year 2020 Time Averaged Yield (dry tonnes/ha-yr)	11.6	11.1	10.4

Economic data for Eucalyptus production in Brazil are given in Appendix B and the economic theory is in Appendix A. Assuming a discount rate of 10% gives the production costs shown in Table 2.2-2.

Table 2.2-2. Levelized Costs and Average Yields for the Brazilian Site[8].

Levelized Production Cost ($/tonne)	$ 25.10 / tonne
Levelized Transport Cost ($/tonne-km)	$ 0.19 / tonne-km
Time Averaged Yield (tonnes/ha-yr)	8.63 tonnes / ha-yr

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[6] This discount rate was chosen because it coincides with the discount rate used for utilities in the EPRI TAG [EPRI, 93b]

[7] These costs are similar to those calculated in [Brown, 94] where switchgrass in Chariton Valley is expected to cost $ 206.37per acre (including $19.46 of transport costs) and yield 4.69 dry tons/acre, giving a levelized cost of $ 48.70/dry tonne (excluding transport costs, but adding 10% storage losses).

[8] Costs are in 1994 dollars, converted from 1992 dollars using the GDP deflator.

2.3 Transport Costs

There are many conflicting estimates for transport costs. Here we review the problems inherent in stating transport costs and review several references to derive an estimate of the cost. The standard model for transport costs has the form

$$\text{Cost}\left(\frac{\$}{\text{tonne}}\right) = a + TC \bullet TD \qquad (2.3\text{-}1$$

where a is a constant that represents costs that are independent of transport distance, TC is the transport cost per tonne-km, and TD is the transport distance in km. Both a and TC affect the cost, but only TC is important in determining the optimal size (as shown later in equation 4.3-9).

There are several factors that must be carefully considered when quoting transport costs for biocrops:

- It is necessary to define whether the distance is the single or round-trip distance. In this work, all distances are for the single trip: TD is therefore the distance between the field and the faciliy, not the round-trip distance. Unless otherwise stated, all prices are in 1994$.
- It is necessary to quote costs in dollars per dry tonne, if a cost is quoted for tonnes of raw biomass, the moisture content must be stated. Typically woodchips have 50% moisture content and switchgrass is field-dried to 10 to 20% moisture content [Miles, 80].
- It is necessary to recognise that loads of biomass may be limited by either mass or by bulk. Miles states that the bulk density of wet woodchips is 18-22 lb/cubic foot (0.29-0.35 tonnes/m3) and the density of a standard bale of moist straw is approximately 0.16 tonnes/m3. With a slightly reinforced baler, the bale density can be increased to 0.24 tonnes/m3. More expensive balers have been able to produces bales at 0.43 tonnes/m3. Straw can also be formed into pellets, typically with a density of 0.25-0.64 tonnes/m3. These material densities can be compared with truck capacities and weight limits to determine whether the maximum load will be bulk or weight limited. In [Vranzian, 87] the weight capacities and volumes are given for several types of truck that are candidates for transporting woodchips. This data is reproduced in the first 3 columns of Table 2.3-1. The fourth column of Table 2.3-1 shows the load density for the truck to be both weight and bulk limited. Materials with densities less than this limit will be bulk limited. For each vehicle, woodchips and switchgrass would be bulk limited. The density of moist switchgrass bales (0.24 tonnes/m3) is 0.75 times the bulk density of wet woodchips, therefore the cost of transporting one tonne of moist switchgrass will be 1.33 times the cost of transporting one tonne of wet woodchips.

Table 2.3-1. Physical Parameters for Transport Vehicles [Vranzian, 87]

Vehicle Type	Weight Limit (tonnes)	Volume (m3)	Density Needed to Reach Weight Limit. (tonnes/m3)
Truck with Log Trailer	24.6	54.2	0.45
Truck with Chip Van	24.6	76.4	0.32
Truck with 30 yd Rock Trailer	23.6	26.7	0.88
12 yd dump truck	11.8	12.5	0.94
12 yd dump truck with 10 yd dump trailer	24.6	21.4	1.15
Dump truck with 30 yd box	11.8	22.9	0.52
Truck with solid waste container	12.80	16.8	0.76

Costs of Transportation: Source One [Vranzian, 87].

The costs of vehicle operations from [Vranzian, 87] are shown in Table 2.3-2. These costs are derived from hourly rental costs and from average speeds of 27 miles per hour for tractor trailers, and 28 miles per hour for dump trucks.

Table 2.3-2. Costs of Transportation [Vranzian, 87]

Vehicle Type	Operation Cost (1994$/km)	Cost per Tonne-km for Wet Woodchips	Cost per Tonne-km for Moist Straw Bales
Truck with Log Trailer	37.3	0.16	0.21
Truck with Chip Van	37.3	0.11	0.15
Truck with 30 yd Rock Trailer	37.3	0.32	0.43
12 yd dump truck	29.8	0.52	0.70
12 yd dump truck with 10 yd dump trailer	37.3	0.38	0.51
Dump truck with 30 yd box	29.8	0.29	0.38
Truck with solid waste container	33.6	0.44	0.59

This assumes the following bulk densities: wet woodchips 0.32tonnes/m3, wet switchgrass 0.24 tonnes/m3. These costs include the time taken for the return (unladen) journey. Assuming a moisture content of 15%, Table 2.2-2 suggests costs of 18 to 82 cents per dry tonne km for switchgrass. Clearly, a large-volume vehicle similar to the Chip Van would be used for any large scale movement of switchgrass, giving a cost of 18¢/dry tonne-km.

Costs of Transportation: Source Two [Bludau, 90]

[Bludau, 90] gives the cost of transport based on the quoted cost of freight for short distances. For woodchips the cost is

$$\mathrm{Cost}\left(\frac{1994\$}{\mathrm{tonne}}\right) = 2.57 + 0.10 \bullet \mathrm{TD(km)} \qquad (2.3\text{-}2$$

For switchgrass the cost is

$$\mathrm{Cost}\left(\frac{1994\$}{\mathrm{tonne}}\right) = 2.57 + 0.15 \bullet \mathrm{TD(km)} \qquad (2.3\text{-}3$$

Assuming a 15% moisture content, the cost per dry tonne is

$$\mathrm{Cost}\left(\frac{1994\$}{\mathrm{dry\ tonne}}\right) = 3.03 + 0.18 \bullet \mathrm{TD(km)} \qquad (2.3\text{-}4$$

This agrees with the cost derived from [Veranzian, 87].

Costs of Transportation: Source Three [Young, 88]

[Young, 88] gives the mean cost for transporting woodchips to be 14¢ per wet ton-mile (9.6¢ per wet tonne-km) for transport distances of 1 to 20 miles[9]. This was based on a survey of 80 companies who haul woodchips in Tennessee. Assuming that the moist switchgrass load is 0.75 of the wet woodchip load, and there is 15% moisture content, the cost is 13.3¢ per dry tonne-km. However, the standard deviation on this estimate is per 8.6¢ per dry tonne-km. This standard deviation is high because the cost includes the fixed costs[10]. Also, it is not clear whether the quoted costs are for single, or round trip distances. This data is therefore not useful.

Costs of Transportation: Source Four [Bhat, 92]

In [Bhat, 92], transport costs for woody crops are given as

$$\text{Cost}\left(\frac{\$}{\text{load}}\right) = 3.65 + 0.62 \bullet d \qquad (2.3\text{-}5$$

and for herbaceous crops as

$$\text{Cost}\left(\frac{\$}{\text{load}}\right) = 34.08 + 0.62 \bullet d \qquad (2.3\text{-}6$$

for herbaceous crops where *d* is the round-trip distance in km. One load of switchgrass is said to be 17 tons of field-dry crops. Assuming a moisture content of 15%, the cost per dry tonne-km is 9¢ (where the distance is the single-trip distance). Baht's analysis correlated the cost of transporting many different types of crops including produce such as mixed vegetables. As there was only one data point for herbaceous crops, the results of the analysis should be treated with some caution, however this figure has been used in several recent analyses [U of Minnesota Report], [Brown, 94].

Costs of Transportation: Source Five.

In Brazil, Prof. Carlos C. Machado with the Department of Forestry at the University of Viçosa in Minas Gerais has built up a block of 10 reports which are collectively called the "Transroad" reports. These have not been published. He has developed software which gives the transport cost for different distances over 27 different types of road. For a medium sized (12 tonne) truck, the cost of transport per tonne of wet biomass on good forest roads is given by

$$\text{Transport Cost}\left(\frac{\$}{\text{tonne}}\right) = 1.04 + 0.118 \bullet \text{TD(km)} \qquad (2.3\text{-}7$$

For fair forest roads the cost is

$$\text{Transport Cost}\left(\frac{\$}{\text{tonne}}\right) = 1.05 + 0.167 \bullet \text{TD(km)} \qquad (2.3\text{-}8$$

On poor forest roads the cost is

$$\text{Transport Cost}\left(\frac{\$}{\text{tonne}}\right) = 1.05 + 0.230 \bullet \text{TD(km)} \qquad (2.3\text{-}9$$

These are in 1994$, Appendix B gives further details. Assuming a moisture content of 50% for Eucalyptus, the cost is 33¢ per dry tonne-km for fair roads.

The Brazilian data can also be used to predict the cost of transportation in the US. Prof. Machado's analysis assumes a fuel cost of 0.25¢/liter and a labor cost of $3/hour. If these assumptions are replaced with a cost of $1.30/gallon and $5/hour then the transport cost for a good forest road will be

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[9] This study is also quoted in [EPRI, 93a].

[10] Quoted Cost=(a+TC•TD)/TD.

$$\text{Transport Cost}\left(\frac{\$}{\text{tonne}}\right) = 1.04 + 0.136 \bullet \text{TD(km)} \qquad (2.3\text{-}10$$

Assuming a moisture content of 15% for switchgrass, and a load of 9 tonnes (12 tonnes × 0.75), the cost per dry-tonne km is 21.3¢. This is higher than the 18¢ predicted from the [Biomass Handbook] data, which is reasonable considering that 21.3¢ is for a forest road rather than a fully paved road.

For this study, the transport cost for switchgrass in Iowa is taken to be 18¢ per dry tonne-km as in equation 2.3-4.

2.4 Topographic Data

The topographic information for the four-country area in Iowa was obtained from two sets of maps. The soil system was obtained from [IGS, 1973] which shows three soil types: Loess is described as being generally very good agricultural land, Complex-Alluvial-Deposits are intermediate for agriculture, and Till-and-Outcropping-Paleosols are difficult for farm management. The layout of the road system was obtained from US Geological Survey maps [USGS, 86 a-d]. These maps also showed the areas where biomass cannot be grown. These no-grow areas are typically urban areas or bodies of water. The most significant body of water is Rathbun Lake, in the center of the four-county area. No-grow areas cover 6% of the four counties.

From this data, four digital maps were created: a map of soil types, a map of the road system, a map of no-grow areas, and a map with a single dot to show the position of the energy conversion facility. The facility was chosen to be in the center of the four county area, near the north shore of the lake. (details of the digitization process are in Appendix C). These maps were passed to a geographic information system for the calculation of transportation distances.

2.5 Calculation of Production Costs using a Geographic Information System

The geographic information system (GIS) used for the analysis is a software package, MapBox, produced by Decision Images Inc. of Princeton [Tomlin, 90] (details of the GIS calculations are in Appendix C). The transport distance for each acre is found by locating the nearest point on the road system, and counting the distance along the road to the site of the energy production facility. The result is a map on which every acre has an assigned road transport distance. The transport cost can then be calculated from eq. 2.3-4. The production cost for each area is established by using the soil map to assign yields and levelized production costs, from Table 2.2-1. Adding the production and transport costs gives Fig. 2.5-1, a graphical view of the cost per ton for each acre. The black areas are no-grow areas. The dark blue areas around the facility in the center of the map show where the biomass can be grown most cheaply. The colors move towards red as the transportation cost increases. This procedure is useful to give graphical illustrations of the problem, but for numerical results, the GIS is used to prepare data for a spreadsheet[11].

To extract the geographic data for the spreadsheet calculations, the map of transport distance is simplified into a set of rings. The first ring is made up of all the acres that have transport distances between zero and one mile, the second ring is of acres with distances between one and two miles, etc. For the four-county area, the largest ring was for 24 to 25 miles. The

[11] It is possible to carry out the full analysis using the GIS, but it is slow and computationally expensive, therefore it is better to use a spreadsheet where possible. The 'spreadsheet' is programmed in Matlab and is printed in Appendix J.

analysis was limited to transport distances of less than 26 miles because at 26 miles the ring touched the edge of the digitized map and was unable to expand into the next county. The next step overlays the map of distance rings onto the map of soil types. The GIS then counts the area of each soil type within each ring. For each of the 25 rings there are four results: the number of acres of Loess, the number of acres of Alluvial-Deposits, the number of acres of Till, and the number of acres of no-grow land. For example, for transport distance between 24 and 25 miles there are 7,272 acres of Loess, 40,254 acres of Alluvial-Deposits, 14,923 acres of Till, and 2,091 acres of no-grow land.

The spreadsheet uses the 100 data points for the four land types at 25 distances. Each data point is assigned a levelized production cost according to the soil type, plus a levelized transport cost equal to the transport distance times the cost per tonne-km[12]. The 100 growing areas are then rearranged to be in order of the total cost per tonne such that

$$\text{Cost}_{k+1}\left(\frac{\$}{\text{tonne}}\right) \geq \text{Cost}_k\left(\frac{\$}{\text{tonne}}\right) \quad (2.5\text{-}1$$

where k is the index for the area. This gives a series of increasing marginal costs.

The annual production from each area is

$$\text{Production}_k\left(\frac{\text{tonnes}}{\text{year}}\right) = \text{Area}_k \bullet \text{Yield}_k \quad (2.5\text{-}2$$

At a set biomass price, all the fields with a cost less than that price will come into production. The total number of fields in production will be n, such that

$$\text{Cost}_{n+1} \geq \text{Price} \geq \text{Cost}_n \quad (2.5\text{-}3$$

The corresponding supply of biomass will be

$$\text{Supply}_n\left(\frac{\text{tonnes}}{\text{year}}\right) = \sum_{k=1}^{n}\text{Production}_k \quad (2.5\text{-}4$$

If the utility pays the same price for every tonne delivered to the utility gate, then it must pay an excess profit to the farmers nearby, and the average price will be equal to the marginal price. A more realistic scenario is that the utility will pay a price that covers the expenses of each farmer, in this case the average cost will be

$$\text{AverageCost}_n\left(\frac{\$}{\text{tonne}}\right) = \frac{\sum_{k=1}^{n}\text{Cost}_k \bullet \text{Production}_k}{\sum_{k=1}^{n}\text{Production}_k} \quad (2.5\text{-}5$$

2.6 Results of the Feedstock Analysis

Figure 2.6-1 shows the supply curve for switchgrass in Iowa in 2000 and 2020. For year 2000, the average and marginal costs start at $72/dry-tonne. The maximum production within a

[12] The GIS work was conducted in English units because of the original maps, all units were converted to metric for the spreadsheet.

transport distance of 25 miles is 1.7 million dry tonnes/year, with a marginal cost of \$79, and average cost of \$77. For year 2020, the average and marginal costs start at \$55/dry-tonne. The maximum production is 2.4 million dry tonnes/year at a marginal cost of \$63, and average cost of \$61.

2.7 A Simplified Analysis of Transport Costs

The methods described above give detailed results for the specific region in Iowa. However, the complexity of the GIS and the effort involved in producing the above results make it arduous to reproduce them for other areas. Also, the complexity masks the major underlying factors that affect the supply curve. To overcome these problems, a simplified method is developed here. The topography is simplified by assuming that biomass is produced, with a uniform yield and production cost, in a circle around the facility (Figure 2.7-1) (one segment, of angle θ, is taken out to represent the no-grow areas.)

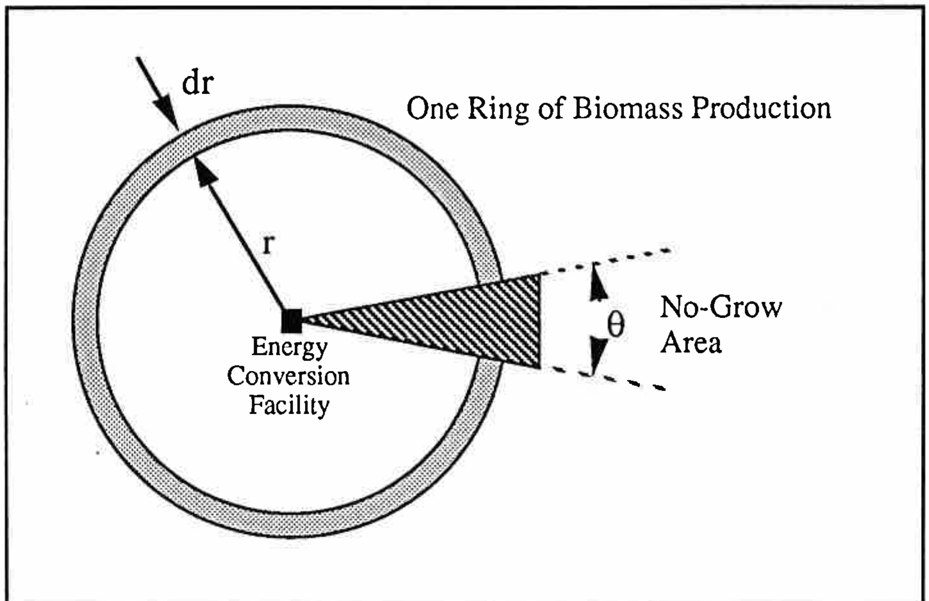

Figure 2.7-1. Simplified Model of Biomass Production Areas.

The average cost of producing biomass in this region is

$$c = \frac{c_{Loess}a_{Loess} + c_{Alluvial}a_{Alluvial} + c_{Till}a_{Till}}{a_{Loess} + a_{Alluvial} + a_{Till}}$$
$$= \$67.3/\text{dry tonne} \quad \text{(2000 Levelized)} \qquad (2.7\text{-}1$$
$$= \$51.0/\text{dry tonne} \quad \text{(2020 Levelized)}$$

Similarly, the time-average yield, including storage losses is

$$Y = \frac{Y_{Loess}a_{Loess} + Y_{Alluvial}a_{Alluvial} + Y_{Till}a_{Till}}{a_{Loess} + a_{Alluvial} + a_{Till}}$$
$$= 7.71/\text{ha.yr} \quad \text{(2000 Averaged over 10 years)} \qquad (2.7\text{-}2$$
$$= 11.00/\text{ha.yr} \quad \text{(2020 Averaged over 10 years)}$$

Production from a single incremental ring is

$$\text{Incremental Production} = Y\rho 2\pi r dr \qquad (2.7\text{-}3$$

where ρ is the density of biomass plantations:

$$\rho = \frac{\text{Area Available for Energy Crops}}{\text{Total Area}} = 1 - \frac{\text{No Grow Area}}{\text{Total Area}} = 1 - \frac{\Theta}{2\pi} \qquad (2.7\text{-}4$$

For the four county area in Iowa, within a transport distance of 25 miles, there are a total of 258,770 ha of which 14,278 ha are no-grow areas, ρ is therefore 0.94.

Integrating eq. 2.7-3 over the disc of radius R gives a total supply of

$$\text{Total Production} = Y\rho\pi R^2 \qquad (2.7\text{-}5$$

The transport distance for the incremental ring is

$$\text{Transport Distance} = F \bullet r \qquad (2.7\text{-}6$$

where F is a constant which accounts for the layout of the road system. If the roads spread out radially from the plant then the feedstock can be transported in a straight line from the fields to the plant, and F equals one. If the road system is a simple grid then F equals 1.25 (see Appendix D). For the road system in Iowa, a value of F can be derived from the GIS data. Define the effective radius, $\hat{r}$, to be

$$\hat{r} = \sqrt{\frac{\text{Area}}{\pi}} \qquad (2.7\text{-}7$$

where the Area is the number of hectares within a chosen transport distance. F can then be calculated as

$$F = \frac{\text{Transport Distance}}{\hat{r}} \qquad (2.7\text{-}8$$

For a transport distance of 25 miles (40.2 km), the enclosed area is 258,770 ha, $\hat{r}$, is 28.7 km, and F is equal to 1.4 (see Appendix E for a further discussion of the value for F).

The maximum transport distance is $F \bullet R$. The average transport distance is obtained by dividing the total tonne-km by the total tonnes:

$$\begin{aligned}\text{Average Distance} &= \frac{\int_{r=0}^{R} FrY\rho 2\pi r\,dr}{\int_{r=0}^{R} Y\rho 2\pi r\,dr} \\ &= \frac{F\frac{2}{3}\pi R^3 Y\rho}{\pi R^2 Y\rho} \qquad (2.7\text{-}9 \\ &= F \bullet \frac{2}{3} R\end{aligned}$$

The average levelized cost of the feedstock is

$$\begin{aligned}\text{FeedstockCost} &= \text{ProductionCost} + \text{TransportCost} \\ &= \text{ProductionCost} + F \bullet \tfrac{2}{3}R \bullet \text{CostperTonnekm}\end{aligned} \quad (2.7\text{-}10$$

From eq. 2.7-1, the feedstock cost in Iowa in 2020 is[13]

$$\text{FeedstockCost} = 51.00 + 1.4 \bullet \tfrac{2}{3}R \bullet 0.20 \quad (2.7\text{-}11$$

And from eq. 2.7-5 the total production is

$$\text{Total Production} = 11.00 \bullet 0.94 \bullet \pi R^2 \cdot 100 \quad (2.7\text{-}12$$

(The factor of 100 is needed because R is in units of km and yield is in tonnes/ha.) Plotting eq. 2.7-11 against eq. 2.7-12 gives the feedstock supply curve in Fig. 2.7-2. Figure 2.7-2 also shows the curve from the GIS analysis (reproduced from Fig 2.6-1). The GIS results and the results from the simplified theory do not match exactly for low tonnages. This is because local anomalies, such as the lake, increase the true transport distance. For large tonnages the match is very good because anomalies are averaged over a large area[14].

Having shown that the simplified theory gives a good approximation to the detailed analysis, we can make predictions for feedstock costs in areas other than Iowa. In Appendix B, data is given for the Floryl Plantation in North Eastern Brazil. This plantation has a maximum planting density of 0.8 ($\rho = 0.8$) and a regular grid road network. For such a network, the F factor is 1.25 (as derived in Appendix E). From Table 2.3-2 the predicted costs and yields for the Floryl site are

$$\text{FeedstockCost}\left(\frac{\$}{\text{tonne}}\right) = 25.1 + 0.20 \bullet 1.25 \bullet \tfrac{2}{3}R(\text{km}) \quad (2.7\text{-}13$$

$$\text{TotalSupply}\left(\frac{\text{tonnes}}{\text{year}}\right) = 8.63 \bullet 0.8 \bullet \pi \bullet R^2 \cdot 100 \quad (2.7\text{-}14$$

The predicted feedstock supply curve for Brazil is shown in Figure 2.7-3.

3 Capital Costs for Energy Conversion Facilities

3.1 Assumed Form of the Capital Cost Curve

We assume that the capital cost of an energy conversion facility can be described by an equation of the form

$$\text{UnitCost} = \text{Offset} + D(\text{Capacity})^E \quad (3.1\text{-}1$$

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[13] The variable transport cost is 20¢/dry tonne-km because it includes 10% storage losses.

[14] This theoretical analysis can be expanded to include cases where the different soil types cause significantly different feedstock costs, this approach is detailed in Appendix G.

For electricity generation the unit cost is in terms of \$/kilowatt (\$/kW) and the capacity is in Megawatts (MW). For methanol and ethanol production, the unit cost is in dollars per gigajoule per hour (\$/GJ/hr) and the capacity is in gigajoules per hour (GJ/hr). The Offset is equal to the cost of a very large facility[15]. Once the Offset is established, the values for D and E can be obtained using two data points relating cost to capacity:

$$E = \frac{\log\left(\frac{\mathrm{Cost}_1 - \mathrm{Offset}}{\mathrm{Cost}_2 - \mathrm{Offset}}\right)}{\log\left(\frac{\mathrm{Capacity}_1}{\mathrm{Capacity}_2}\right)} \qquad (3.1\text{-}2$$

$$D = \frac{\mathrm{Cost}_1 - \mathrm{Offset}}{\mathrm{Capacity}_1^E} \qquad (3.1\text{-}3$$

Table 3.1-1 gives the capital cost data for a steam-turbine, two biomass-integrated-gasifier / gas-turbines, a methanol plant, and two types of ethanol plant. Conversion efficiencies are based on higher heating values. Conversion efficiencies for the liquid fuels are in GJ of fuel produced per GJ of feedstock.

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[15] E is negative, therefore as the capacity becomes large, the cost becomes equal to the Offset.

Table 3.1. Data for Capital Costs*

Technology	Capacity	Cost	Conversion Efficiency	Operation and Maintenance[16]
Steam Turbine	10	$ 3510/kWe	0.199	0.0125/kWh
	50	$ 1647/kWe	0.199	0.0125/kWh
	large	$ 1200/kWe	0.199	0.0125/kWh
Unpressurized Biomass-Integrated-Gasifier / Gas-Turbine	10 MW	$ 2577/kWe	0.340	0.008/kWh
	60 MW	$ 1288/kWe	0.340	0.008/kWh
	large	$ 1200/kWe	0.340	0.008/kWh
Pressurized Biomass-Integrated-Gasifier / Gas-Turbine	30 MW	$ 1800/kWe	0.365	0.008/kWh
	60 MW	$ 1425/kWe	0.365	0.008/kWh
	large	$ 1100/kWe	0.365	0.008/kWh
Indirect Gasifier Low Pressure Methanol Plant	1049 GJ/hr	$ 162/MJ/h	-	-
	5245 GJ/hr	$ 112/MJ/h	-	-
	large	$ 85/MJ/h	-	-
BCL Methanol Plant	811 GJ/hr	$ 273/MJ/h	0.60	$ 2.43/GJ
Ethanol Plant	590 GJ/hr	$ 341/MJ/h	0.40	$ 2.29/GJ
	2956 GJ/hr	$ 230/MJ/h	0.40	$ 2.29/GJ
	large	$ 180/MJ/h	0.40	$ 2.29/GJ
Advanced Ethanol Plant	1355 GJ/hr	$151/MJ/h	0.50	$ 2.03/GJ

* Data are from the following sources: Steam Turbine [EPRI, 92], unpressurized BIG/GT [Lundberg, 94], pressurized BIG/GT [Consonni, 94], Ethanol [Williams, 94], Indirect Gasifier Methanol [Johansson, 93], Batelle Columbus Laboratory (BCL) Methanol [Williams, 94].

[16] We assume that the O&M cost is fixed with respect to capacity. Any variations with respect to capacity could be treated in the same way as the capital cost with a model of the form of eq. 3.1-1.

The results for Offset, D, and E are shown in Table 3.1-2. The corresponding capital costs curves are shown in Figs 3.1-1 and 3.1-2. For the steam-turbine, BIG/GT, and conventional ethanol plants, the values for Offset, D, and E were obtained directly by substituting the data in Table 3.1-1 into eqs. 3.1-2 and 3.1-3. For conventional ethanol plants two data points are available, but for Advanced Ethanol, only one data point is available, at 1355 GJ/hr. The ratio of the cost of conventional and advanced ethanol plants can be defined as

$$\begin{aligned}\text{Ratio} &= \frac{\text{Cost of Advanced at } 1355\text{GJ/hr}}{\text{Cost of Conventional at } 1355\text{GJ/hr}} \\ &= \frac{151000}{180000 + 16103000(1355)^{-0.72}} \\ &= 0.56 \end{aligned} \qquad (3.1\text{-}4$$

The values of Offset and D for the Advanced Ethanol design were obtained by multiplying Offset and D for the conventional design by the ratio in eq. 3.1-4 (E is the same for both designs). The values for the Methanol plant were calculated similarly: values for Offset, D, and E were obtained from the two Indirect-Gasifier-Low-Pressure designs [Johansson, 93], and then rescaled according to the cost of the Batelle Columbus Laboratory (BCL) design (which is considered to be more representative of likely methanol operations).

Table 3.1-2. Parameters Describing Capital Cost Curves

Technology	Offset	D	E
Steam Turbine	\$ 1200/kW	\$ 22195/kW	-0.93
Unpressurized BIG/GT	\$ 1200/kW	\$ 47198/kW	-1.53
Pressurized BIG/GT	\$ 1100/kW	\$ 110420/kW	-1.42
BCL Methanol Plant	\$ 131460/GJ/h	\$ 11717000/GJ/h	-0.66
Ethanol Plant	\$ 180000/GJ/h	\$ 16103000/GJ/h	-0.72
Advanced Ethanol Plant	\$ 101500/GJ/h	\$ 9080200/GJ/h	-0.72

The capital cost data given above is the total plant cost. This can be converted into an annual charge according to the accounting procedure in the EPRI TAG [EPRI, 93b] (see Appendix H). This assumes that the real cost of money for a utility is 4.9%. With this assumption the levelized carrying charge fraction (LCCF) is 0.101, i.e., the annual cost of the capital investment is 10.1% of the total plant cost. For Brazilian operations, the cost of money is approximately 10%, using the TAG procedure, the LCCF is then 0.110. For Methanol and Ethanol plants the LCCF is equal to 15.1%, based on standard corporate cost of investment [Williams, 94].

4.1 Total Cost of Energy

4.1-1 Conversion Factors for Feedstock and Capital Costs

The total cost of energy is obtained by adding the feedstock cost, the capital cost, and the Operations and Maintenance cost (O&M). These costs must all be in the same units. For electricity generation, the cost is in terms of \$/kWh and the facility size is described in MW. For liquid-fuel production, the cost is in dollars per gigajoule ($/GJ) and the facility size is described in GJ/hour. The annual feedstock tonnage is related to the facility's capacity by making the following assumptions:

- switchgrass has a higher heating value (HHV) of 18.44 GJ/tonne.
- on average, the electricity plants operate at 75% of maximum output (Capacity Factor = 0.75).
- on average, the liquid fuel plants operate at 90% of maximum output (Capacity Factor = 0.9).
- the conversion efficiency is as in Table 3.1-1.

The relation between the annual supply and the size of an electric power plant is then

$$\text{Capacity}_n(\text{MW}) = \frac{\text{Supply}_n\left(\frac{\text{Tonnes}}{\text{year}}\right) \bullet \text{HHV}\left(\frac{\text{GJ}}{\text{Tonne}}\right) \bullet 10^3 \bullet \eta_{th}}{3600 \bullet 365 \bullet 24 \bullet \text{CF}} \tag{4.1-1}$$

where η_{th} is the thermal efficiency. For a liquid fuel plant the relationship is

$$\text{Capacity}_n\left(\frac{\text{GJ}}{\text{hour}}\right) = \frac{\text{Supply}_n\left(\frac{\text{Tonnes}}{\text{year}}\right) \bullet \text{HHV}\left(\frac{\text{GJ}}{\text{Tonne}}\right) \bullet \eta_c}{365 \bullet 24 \bullet \text{CF}} \tag{4.1-2}$$

where η_c is the number of GJ of fuel that can be produced from one GJ of biomass. Similarly the cost per tonne is converted into cost per kWh or cost per GJ of liquid fuel:

$$\text{Cost}\left(\frac{\$}{\text{kWh}}\right) = \frac{3600 \bullet \text{FeedstockCost}\left(\frac{\$}{\text{Tonne}}\right)}{\text{HHV}\left(\frac{\text{GJ}}{\text{Tonne}}\right) \bullet 10^6 \bullet \eta_{th}} \tag{4.1-3}$$

$$\text{Cost}\left(\frac{\$}{\text{GJ}}\right) = \frac{\text{FeedstockCost}\left(\frac{\$}{\text{Tonne}}\right)}{\text{HHV}\left(\frac{\text{GJ}}{\text{Tonne}}\right) \bullet \eta_c} \tag{4.1-4}$$

The annual capital costs are spread over the year's energy production:

$$\text{CapitalCost}\left(\frac{\$}{\text{kWh}}\right) = \frac{\text{LCCF} \bullet \text{CapitalCost}\left(\frac{\$}{\text{kW}}\right)}{365 \bullet 24 \bullet \text{CF}} \tag{4.1-5}$$

$$\text{CapitalCost}\left(\frac{\$}{\text{GJ}}\right) = \frac{\text{LCCF} \bullet \text{CapitalCost}\left(\frac{\$}{\text{GJ/hr}}\right)}{365 \bullet 24 \bullet \text{CF}} \tag{4.1-6}$$

4.2 Results of Energy Costs

We are now able to add the costs of feedstock, capital, and O&M to obtain the total energy cost for a reange of possible capacities. The results for Iowa with year 2000 and 2020 data are shown in Figures 4.2-1 to 4.2-4. Figures 4.2-1 and 4.2-2 show a sharp reduction in electricity costs as the capacity increases and the unit capital costs reduce. At one point the rate of decrease of the capital cost equals the rate of increase of the transport cost, this is the optimal capacity of minimum total cost. At large capacity, there is a very gradual rise as the transport costs become important. In all scales, the lower efficiency of the steam turbine make it significantly more expensive then the gas turbines. There is a significant difference between the 2000 and 2020 resultsdue to differences in yields. This alters the cost and it also alters the optimal size because increased yields make transport costs less important. In 2000, the optimal size for the unpressurized BIG/GT is 116MW with an electricity cost of 7.0¢. In Fig 4.2-2, for 2020, the unpressurized BIG/GT is within 1% of its minimum cost at 51 MW, and reaches its minimum cost at 96 MW (6.0 ¢/kWh). The pressurized technology is within 1% of its minimum at 127 MW and has a minimum at 265 MW (5.7¢/kWh). The cost of electricity from the pressurized and unpressurized technologies crossover at 53 MW. The general conclusions are that if power requirements are less than 53 MW, unpressurized BIG/GT technology is cheapest. For scales greater than 53MW, pressurized BIG/GT is cheaper. The absolute minimum cost of electricity is obtained by using pressurized BIG/GT technology with a capacity of 265 MW, but costs within 1% of this minimum can be obtained by building capacities as small as 127 MW (smaller scales may be preferable to reduce the lumpiness of investments and maintenance).

Figures 4.2-3 and 4.2-4, show the fuel costs for methanol and ethanol. At all the capacities analyzed, the capital costs of the fuel production facilities are dominant. For scales larger than this, the analysis exceeds the 25 mile transport distance. At the maximum transport distance, the capital costs still fall slightly faster than the fall in the transport cost, and although the curves are almost flat, the absolute minimum has not been reached. This suggests that if large volumes of fuel are required, the cost is minimized by building single plants of capacity larger than 3000 GJ/hr, rather than multiple small plants.

The optimal capacities and associated total energy costs are summarized in Table 4.2-1.

Table 4.2-1. Optimal Sizes and Associated Energy Costs for Iowa.

Technology	Year	Optimal Size	Minimum Cost
Steam Turbine	2000	215 MW	10.8 ¢/kWh
	2020	249 MW	9.1 ¢/kWh
Unpressurized BIG/GT	2000	116 MW	7.0 ¢/kWh
	2020	96 MW	6.0 ¢/kWh
Pressurized BIG/GT	2000	246 MW	6.6 ¢/kWh
	2020	265 MW	5.7 ¢/kWh
Methanol Plant	2000	>2500 GJ/hr	$12.72/GJ
	2020	>2500 GJ/hr	$12.09/GJ
Ethanol Plant	2000	>2000 GJ/hr	$16.79/GJ
	2020	>2000 GJ/hr	$14.46/GJ
Advanced Ethanol Plant	2000	>1500 GJ/hr	$11.01/GJ
	2020	>1500 GJ/hr	$9.53/GJ

The total energy costs for Brazil are shown in Figures 4.2-5 and 4.2-6 and summarized in Table 4.2-2.

Table 4.2-2. Optimal Sizes and Associated Energy Costs for Brazil

Technology	Optimal Size	Minimum Cost
Steam Turbine	190 MW	5.6¢/kWh
Unpressurized BIG/GT	105 MW	4.2¢/kWh
Pressurized BIG/GT	180 MW	3.9¢/kWh
Methanol Plant	8300 GJ/hr	$8.4/GJ
Ethanol Plant	4400 GJ/hr	$10.6/GJ
Advanced Ethanol Plant	4500 GJ/hr	$7.0/GJ

4.3 Theoretical Derivation of the Optimal Size

In the above section, the optimal size was found numerically from Figures (4.2-1 to 4.2-6). By combining eqs. 2.7-11 and 3.1-1, the optimal size can be derived theoretically. This avoids the necessity of plotting the cost curves, and more importantly, it clearly shows the parameters that affect the choice of facility size. From eq 2.7-11, the cost of feedstock is

$$\begin{aligned}\text{FeedstockCost}\left(\frac{\$}{\text{Tonne}}\right) &= \text{ProductionCost}\left(\frac{\$}{\text{Tonne}}\right) + F \bullet R(\text{km}) \bullet \text{TransportCost}\left(\frac{\$}{\text{Tonne km}}\right) \\ &= A_{ton} + B_{ton} \bullet R\end{aligned} \qquad (4.3\text{-}1$$

Equation 2.7-5 allows R to be expressed in terms of the annual biomass supply:

$$R(\text{km}) = \sqrt{\frac{\text{Supply}\left(\frac{\text{Tonnes}}{\text{year}}\right)}{\rho \bullet \pi \bullet Y\left(\frac{\text{Tonnes}}{\text{km}^2\text{year}}\right)}} \qquad (4.3\text{-}2$$

Equation 4.1-1 allows the annual production to be expressed in terms of the capacity

$$\text{Supply}\left(\frac{\text{Tonnes}}{\text{year}}\right) = \frac{\text{Capacity(MW)} \bullet 3600 \bullet 365 \bullet 24 \bullet \text{CF}}{\text{HHV}\left(\frac{\text{GJ}}{\text{Tonne}}\right) \bullet 10^3 \bullet \eta_{th}} \qquad (4.3\text{-}3$$

Combining eqs. 4.3-1, 4.3-2, and 4.3-3 allows the feedstock cost to be expressed as a function of the capacity

$$\mathrm{FeedstockCost}\left(\frac{\$}{\mathrm{Tonne}}\right) = A_{ton} + B_{ton} \bullet \sqrt{\frac{\mathrm{Capacity} \bullet 3600 \bullet 365 \bullet 24 \bullet CF}{Y\rho\pi \bullet HHV \bullet 10^3 \bullet \eta_{th}}}$$

$$= A_{ton} + B_{ton} \bullet \sqrt{\frac{3600 \bullet 365 \bullet 24 \bullet CF}{Y\rho\pi \bullet HHV \bullet 10^3 \bullet \eta_{th}}} \sqrt{\mathrm{Capacity}} \qquad (4.3\text{-}4$$

$$= A_{ton} + B'_{ton} \bullet \sqrt{\mathrm{Capacity}}$$

$$\mathrm{FeedstockCost}\left(\frac{\$}{\mathrm{kWh}}\right) = \frac{3600}{HHV \bullet 10^6 \bullet \eta_{th}}\left(A_{ton} + B'_{ton}\sqrt{\mathrm{Capacity}}\right) \qquad (4.3\text{-}5$$

$$= A_{kWh} + B_{kWh}\sqrt{\mathrm{Capacity}}$$

Equation 3.1-1 gives the capital cost per kW, this can be converted to a cost per kWh:

$$\mathrm{CapitalCost}\left(\frac{\$}{\mathrm{kWh}}\right) = \frac{LCCF}{365 \bullet 24 \bullet CF}\left[\mathrm{Offset} + D(\mathrm{Capacity})^E\right] \qquad (4.3\text{-}6$$

$$= C_{kWh} + D_{kWh}(\mathrm{Capacity})^E$$

Adding eqs. 4.3-5, 4.3-6, and the O&M cost gives the total electricity cost:

$$\mathrm{ElectricityCost} = A_{kWh} + B_{kWh}\sqrt{\mathrm{Capacity}} + C_{kWh} + D_{kWh}(\mathrm{Capacity})^E + O\,\&\,M \qquad (4.3\text{-}7$$

(the subscript kWh will now be dropped for clarity). If A, B, C, D, E, and O&M are assumed to be fixed with respect to capacity, then the optimal (least cost) capacity can be found by differentiating eq. 4.3-7 and setting the result equal to zero:

$$\frac{d\mathrm{ElectricityCost}}{d\mathrm{Capacity}} = B0.5(\mathrm{Capacity})^{-0.5} + ED(\mathrm{Capacity})^{E-1} \qquad (4.3\text{-}8$$

$$\mathrm{Capacity} = \left(-\frac{B}{2D}\frac{1}{E}\right)^{\frac{1}{E-0.5}} \qquad (4.3\text{-}9$$

The optimal capacity is therefore influenced by only two variables: the value of E, and the ratio of B to D. E is the exponent from the capital cost curve and is negative, D is the multiplication of the variable part of the capital cost, B is the multiplication on the variable part of the transportation cost (and includes F, η_{th}, and the cost per tonne-km). The O&M cost, the fixed biomass production cost, and the capital-cost Offset have no influence on the optimal size. The same analysis can be carried out for liquid fuel plants by using the appropriate conversion factors.

4.4 Effect of Changing Assumed Values for Parameters

Figure 4.4-1 shows the effect on the price of electricity if the cost of transport cost changes. This is for an unpressurized BIG/GT in 2020. The graph shows curves for costs of 9, 18, 27, and 36 ¢/dry-tonne-km. Increases in the transport cost shift the cost up and move the optimal capacity to the left. For example, with transport costing 9¢, the optimal capacity is 200 MW and the minimum cost of electricity is 5.6¢/kWh, with transport costing 36¢, the optimal capacity is 80 MW, and the minimum cost of electricity is 5.9¢/kWh.

For all of the above analyses, we assumed that all agricultural areas, were available to supply biomass. It is possible that only certain areas may be made available for biomass production, for example there may be a policy that only allows CRP land to be used. Reducing the density of farms increases transport distances. The effect of using 100%, 50%, and 25% of the agricultural land is shown in Fig 4.4-2. Again, the increasing importance of transport costs shifts the curves up and moves the optimal capacity to the left. At 100% the minimum cost is 5.7¢/kWh, at a capacity of 120 MW; at 25 the cost is 5.8¢/kWh at a capacity of 90 MW.

Costs which uniformly effect the cost of producing biomass simply shift the curves up and down without changing the shape. Figure 4.4-3 shows the effect of changing the land rentals by plus and minus $50 per hectare (for example, this could be due to a change in corn prices). A reduction of $50 lowers the cost of electricity by 0.7¢/kWh, an increase of $50/ha raises the price by 0.7¢.

Summary

We reviewed the costs of producing and transporting biomass and developed a GIS model of a four-county area in Iowa. We produced feedstock supply curves for 2000 and 2020 and developed a simplified theory, which allowed us to predict the supply curves for Brazil. Capital cost curves were derived and combined with the feedstock curves to get the electricity and fuel costs for a range of capacities. We derived a theoretical relationship to describe the optimal size without using GIS, and we carried out a sensitivity analysis.

Conclusions

This work confirmed that the electricity costs are on the order of 5.5¢/kWh, and that BIG/GT is cheaper than traditional steam technology. Biomass yields have a strong influence on the the costs of electricity, there being a 1¢/kWh difference between electricity in 2000 and 2020. Transport costs were found to be less important than expected, leading to optimal sizes on the order of 100MW.

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Appendix A.
Economic Theory.

General

This appendix develops the equations used to find the levelized cost of biomass feedstock. Assume the cost of production in year y is 'Cost per Area$_y$'. For a rotation period of N years, the present value of the costs is

$$\text{Present Cost per Area} = \sum_{y=0}^{N} \frac{\text{Cost per Area}_y}{(1+i)^y} \qquad \text{(A-1}$$

Where i is the interest rate. The transportation costs occur whenever biomass is harvested. The present value is

$$\text{Present Transport Cost per Area} = \sum_{y=0}^{N} \frac{TC \bullet TD \bullet Y_y}{(1+i)^y} \qquad \text{(A-2}$$

where TC is the transport cost (\$/tonne-km), TD is the transport distance (km), and Y_y is the yield in year y (tonnes/ha). The distance and real value of the cost per ton-mile are constant over time and can be extracted from the summation to give

$$\text{Present Transport Cost per Area} = TC \bullet TD \bullet \sum_{y=0}^{N} \left(\frac{Y_y}{(1+i)^y} \right) \qquad \text{(A-3}$$

The farmer is assumed to be paid a fixed amount for each ton of biomass, and the payment is made in the year that the biomass is harvested. The present value of this revenue is therefore

$$\text{Present Revenue per Area} = \sum_{y=0}^{N} \left(\frac{\text{Price}}{\text{Ton}} \right) \left(\frac{Y_y}{(1+i)^y} \right) \qquad \text{(A-4}$$

The revenue must be equal to or greater than the cost of production. Equating eq. A-4 to the sum of eq. A-2 and eq. A-3, we can extract the price per tonne, which is the levelized cost:

$$\text{LevelizedCost} = \frac{\text{Present Cost per Area} + \text{Present Transport Cost per Area}}{\sum_{y=0}^{N} \left(\frac{Y_y}{(1+i)^y} \right)} \qquad \text{(A-5}$$

$$\text{LevelizedCost} = \frac{\sum_{y=0}^{N} \frac{\text{CostperArea}_y}{(1+i)^y}}{\sum_{y=0}^{N} \left(\frac{Y_y}{(1+i)^y} \right)} + TD \bullet TC \qquad \text{(A-6}$$

This is the levelized cost for biomass delivered from a given area at distance TD from the facility. The levelized costs are now derived for the specific cases of switchgrass and eucalyptus production.

Switchgrass

For switchgrass, there is the initial establishment cost and an annual maintenance cost for each year thereafter. This maintenance cost includes fertilizer and weedkiller application, land rentals, and harvest costs. For switchgrass, we assume that the real cost of the maintenance is the same each year. For a ten year rotation, the present cost is

$$\text{Present Cost per Area} = \text{Establishment Cost} + \text{Maintenance Cost} \sum_{y=1}^{9} \frac{1}{(1+i)^y} \qquad \text{(A-7}$$

For switchgrass there is no yield in the establishment year, and the yield in the next year is only 2/3 of the steady yield. The total present cost of transportation is then

$$\text{Present Transport Cost per Area} = TC \bullet TD \bullet Y_{steady} \bullet \left[\frac{\frac{2}{3}}{(1+i)} + \sum_{y=2}^{9} \left(\frac{1}{(1+i)^y} \right) \right] \qquad \text{(A-8}$$

The farmer receives no income in the establishment year, receives 2/3 of the regular amount in the next year, and receives the full amount for each year thereafter:

$$\text{Present Revenue per Area} = \left(\frac{\text{Price}}{\text{Ton}} \right) \bullet Y_{steady} \bullet \left[\frac{\frac{2}{3}}{(1+i)} + \sum_{y=2}^{10} \left(\frac{1}{(1+i)^y} \right) \right] \qquad \text{(A-9}$$

From eq. A-6

$$\text{LevelizedCost} = \frac{\text{EstablishmentCost} + \text{MaintenanceCost} \sum_{y=1}^{9} \left(\frac{1}{(1+i)^y} \right)}{Y_{steady} \bullet \left[\frac{\frac{2}{3}}{(1+i)} + \sum_{y=2}^{9} \left(\frac{1}{(1+i)^y} \right) \right]} + TC \bullet TD \qquad \text{(A-10}$$

Eucalyptus

For Eucalyptus, there is an establishment cost and an annual maintenance cost. The maintenance cost is not the same each year. For an 18 year rotation the present value of the total cost is

$$\text{Present Total Cost per Area} = \text{Establishment Cost} + \sum_{y=1}^{18} \frac{\text{Maintenance Cost}_y}{(1+i)^y} \qquad \text{(A-11}$$

There is only yield in the 6th, 12th, and 18th years. The yield in the 12th year is 0.9 times the first harvest and in the 18th year is 0.72 times the first harvest. If Y_{max} is defined to be the total harvest in the 6th year, then the present value of the transport cost is

$$\text{Present Transport Cost per Area} = TC \bullet TD \bullet Y_{max} \bullet \left[\frac{1}{(1+i)^6} + \frac{0.9}{(1+i)^{12}} + \frac{0.72}{(1+i)^{18}} \right] \text{(A-12}$$

Similarly, the farmer only receives revenue in the 6th, 12th, and 18th years.

$$\text{Present Total Revenue per Area} = \left(\frac{\text{Price}}{\text{Ton}}\right) \bullet Y_{max} \bullet \left[\frac{1}{(1+i)^6} + \frac{0.9}{(1+i)^{12}} + \frac{0.72}{(1+i)^{18}}\right] \quad \text{(A-13}$$

This gives a levelized cost of

$$\text{LevelizedCost} = \frac{\text{EstablishmentCost} + \sum_{y=1}^{18} \frac{\text{MaintenanceCost}_y}{(1+i)^y}}{Y_{max} \bullet \left[\frac{1}{(1+i)^6} + \frac{0.9}{(1+i)^{12}} + \frac{0.72}{(1+i)^{18}}\right]} + TC \bullet TD \qquad \text{(A-14}$$

Appendix B. Eucalyptus Production Costs in Brazil

Tables B-1 and B-2 show the production costs for Eucalyptus in Brazil that were derived from the site visits detailed at the end of this Appendix.

Table B-1. Production Costs in Brazil (1992 US$)

Establishment	
Ground Clearance	\$ 55.0/ha
First Plowing	\$ 49.0/ha
Second Plowing (only practiced by Shell)	\$ 9.5/ha
Cost of Killing Ants before planting	\$ 36.5/ha
Production of Seedlings	\$ 67.0/ha
Planting Seedlings	\$ 10.0/ha
Replanting where originals died	\$ 5.6/ha
Marking and Surveying the Site	\$ 9.1/ha
Fertilizer	\$ 42.0/ha
Total for Establishment	*\$ 283.7/ha*
Annual Maintenance (incl. \$42/yr of fertilizer)	
Years 1, 7, and 13	*\$ 107.0/ha*
Years 2, 8, and 14	*\$ 72.0/ha*
Other Years	*\$ 48.0/ha*
Costs Fixed by Yield	
Cutting	\$ 1.04/tonne (\$2.08/m^3sol)
Baldeio	\$ 1.18/tonne (\$2.36/m^3sol)
Loading	\$ 0.28/tonne (\$0.56/m^3sol)
Fixed Transport Costs	\$ 1.00/tonne
Total per Tonne	*\$ 3.50/tonne*
Costs Fixed by Yield and Distance	
Variable Transport Cost	*\$0.16/tonne-km*
Administration	
Overhead, Research	*20% added to all other costs*

Table B-2. Layout of Annual Costs For Brazilian Plantation

Year	Establishment	Maintenance	Harvest and Transport	Physical Yield (dry tonnes/ha)
0	$ 283.7/ha			
1		$ 107.0/ha		
2		$ 72.0/ha		
3		$ 48.0/ha		
4		$ 48.0/ha		
5		$ 48.0/ha		
6		$ 48.0/ha	$ 355.8/ha	59.3 tonnes/ha
7		$ 107.0/ha		
8		$ 72.0/ha		
9		$ 48.0/ha		
10		$ 48.0/ha		
11		$ 48.0/ha		
12		$ 48.0/ha	$ 320.2/ha	53.4 tonnes/ha
13		$ 107.0/ha		
14		$ 72.0/ha		
15		$ 48.0/ha		
16		$ 48.0/ha		
17		$ 48.0/ha		
18		$ 48.0/ha	$ 256.1/ha	42.7 tonnes/ha

The establishment, maintenance, harvest, and fixed transport costs are added to give the fixed production cost for each year. All these costs must be multiplied by 1.2 to account for administrative costs. Assuming a discount rate of 10%, and adjusting to 1994 dollars, the levelized cost is

$$\text{LevelizedCost}\left(\frac{\$}{\text{tonne}}\right) = 25.1 + 0.20 \bullet \text{TD(km)} \quad \text{(B-1}$$

The average annual yield for an area over the lifetime of the plantation is 8.63 tonnes/ha. In Brazil there are laws requiring 20% of land in plantation areas to be left untouched. If the untouched areas are evenly distributed, the maximum density of planting is 80%, i.e., $\rho = 0.8$. The data given above was gathered from two visits to foresters in Brazil, as summarized in the following pages.

Report of Visit to Shell's Director of Forestry Operations

Site	Shell, Rio de Janeiro	
Date	2 Sep. 92	
Participants	Jose Rivelli	Shell (Gerente de Operacoes Florestais)
	Chris Marrison	Princeton University

Style of Plantation Layout

The Floryl site is in an arid area of North-East Brazil. The site is 80 km by 40 km and is divided into 500m by 500m plots with a 10m wide road around each plot. There are two main 40m wide roads which run the length of the site. Within the site there are areas where the natural vegetation is not disturbed. This is to prevent the effects of hybridization which would attack the monocultures of the Eucalyptus plantation. On the Floryl site there are 250m wide strips of natural vegetation alternately spaced 1.5 and 2 km apart. There is one large area of natural preserve on the site to act as a fauna reserve. In general in Brazil there is a law which requires that 20 to 50% of a plantation site must be left untouched. 20% applies in areas of thin vegetation, 50% applies in regions with thick forests.

Fertility of Soil

The major effect on yield is due to differences in the ability of the soils to retain moisture. The soil is generally sandy and it is necessary to apply fertilizer repeatedly because it quickly drains away. Fertilization is one of the highest cost activities at Floryl, approximately 5 applications are required over 6 years.

Some of the best areas on the Floryl site are cerrado. Cerrado areas are those on which the vegetation is woody brush, with trees around 6 feet high. Without fertilizer, a typical yield for Eucalyptus would be 42 m^3sol/ha in 68 months. With the best known fertilizer combination the yield is up to 223m^3sol/ha. In open grassland, the best yield with fertilizer was 112m^3sol/ha. The best yield of course requires high expenditure on fertilizer and is not necessarily the most economic. Although these yields may not be large compared with other sites, there are many cost savings for the Floryl site compared with others. The savings include low costs for ground clearance and preparation, low infrastructure costs (road building is easy, they simply run a grader once across the ground), and low harvesting costs because the ground is very flat and accessible. The overall result is that the low cost compensates for the low yields and makes the levelized cost comparable with production in other areas.

Costs

The following costs include immediate supervision and materials and are in 1992 US$.

Establishment

Ground Clearance	$ 0-85/ha
(For grassland no clearing is carried out and there is no cost)	
(Cerrado of medium density takes $55/ha to clear)	
(Heavy cerrado requires $ 85/ha)	
First Plowing	$ 49.0/ha
Second Plowing (only practiced by Shell)	$ 9.5/ha
Cost of Killing Ants before planting	$ 36.5/ha
Production of Seedlings	$ 67.0/ha
Planting Seedlings	$ 10.0/ha
Replanting where originals died	$ 5.6/ha
Marking and Surveying the Site	$ 9.1/ha
Fertilizer (over 6 years)	$ 200-300/ha

Maintenance

1st year Weeding

	Killing Ants	
	Maintaining Fire Brakes	\$ 65.0/ha
2nd year	(there are less weeds)	\$ 25-30/ha
3rd to 6th year		\$ 6.0/ha

For comparison with Floryl, Sr. Rivelli quoted the costs for some sites in northern Brazil where the natural vegetation is thicker. There it costs \$375/ha to clear the ground plus \$159/ha to remove the debris. Thereafter such costs as plowing are similar to Floryl's. In that area 30 ha plots are used and it costs and average of \$88.93/ha to construct roads.

Harvesting Costs

Cutting	\$2.08/m^3sol
Baldeio	\$2.36/m^3sol
(baldeio is the operation of moving the logs from the cutting site to the edge of the road)	
Loading	\$0.56/m^3sol
(the cost of the loader and the operator without any truck costs)	

Transport Costs

Mechanical forwarders can only be used for distances of less than 1 km. For longer distances trucks must be used. Large trucks will tend to be cheaper per km than small trucks but they are less able to get close to the logging site so the baldeio cost will be higher. On the Floryl site small trucks of 12-15 tons will be able to drive within each plot so there will be no baldeio cost. It is probably more efficient to use small trucks for distances of less than 30-60 km. Scania, Volvo, and Mercedes have software that will work out the cost of a given trucking operation and recommend the most suitable truck.

Administration Costs

Administration includes safety, health, environmental monitoring, accounting, research, and general administration. These account for an extra 20% on top of the sum of all other costs.

Report of Visit to Florestas Rio Doce S.A.

Site	Florestas Rio Doce S.A., Belo Horizonte	
Date	3&4 Sep. 92	
Participants	Darcio Calais	Forester
	Chris Marrison	Princeton University

General

Florestas Rio Doce S.A. is the forestry subdivision of the mining company CVRD. Florestas Rio Doce operates around the town of Grao Mogol in the state of Minas Gerais (16°30'S 42°50'W). The plantations are on hill tops and are therefore somewhat scattered. Up to 80% of the ground is hilly and requires a lot of manual labor to operate. Mechanized operations are generally feasible on slopes of less than 20%. The wood is generally used for charcoal. The charcoal industry operates with short transport distances unlike the pulp industry, therefore charcoal costs will more accurately reflect the costs of a dedicated energy farm.

Site Layouts

In hilly terrain, the baldeio costs are significant and to insure adequate access to the site the roads are spaced no more than 500m apart, so that the longest distance from a road to a point on the site is 250m. Not all the land can be used for plantations. The natural reserve areas are dictated by law and by erosion considerations. The law states that around every river there must be a natural strip on each side which is at least half as wide as the river. The strip must be at least 5m wide but need not be more than 100m wide. In Minas Gerais there are plantations on hill top plateaus. The sides of the hill can be very steep. To prevent erosion, strips of natural vegetation are left around the edge of the plateau. Firebreaks are used to divide the area into plots no greater than 50 ha. The fire breaks must be 10m wide between plantation plots and 20m between the plot and land outside the plantation.

Yields

Generally similar yields will be achieved on all the soils in the Grao Mogol area. However the different soil types will affect the type and amount of fertilizer required. As a general rule of thumb Mr. Calais suggests that on good soil the fertilizer cost would be $50/ha and for poor soil this cost may rise to $150 (this is the cost of just the fertilizer, not including the labor cost of distribution). Yields will be effected by bioclimatic region because water availability has a large influence on yield.

Baldeio Operations

The following forms of baldeio are used in Minas Gerais:

- Tombo (Manual movement): if the site is on a steep hill, men will simply throw the logs downhill until they reach the road.
- Mule: the logs are hand-loaded onto mules and then the mules are driven to the road.
- Winch: bundles of logs are winched to the road.
- Big Ring: the logs are loaded inside steel hoops of 1m diameter and the full loads are rolled down the hill.
- Forwarder: a mechanical all-terrain vehicle with its own grab and a truck body.

The following Baldeio costs were available from Acesita Energetica S.A.

• Tombo	$ 1.11/stere
• Mule	$ 0.92/stere
• Big Ring	$ 0.97/stere

Transport Costs

To obtain transport costs, Mr. Calise contacted Prof. Carlos C. Machado at the Department of Forestry at the University of Viçosa in Minas Gerais. Prof. Machado has built up a block of 10 reports which are collectively called the "Transroad" reports. These reports have not been published. He has developed software which will give the transport cost for different distances over 27 different types of road. The road differences are in terms of:

VG - Vertical Geometry, derived from the number of hills per km.
HG - Horizontal Geometry, derived from the number of turns per km.
% - Percentage of Irregularity, derived from the surface roughness.

Prof. Machado printed out the costs for a medium sized (12t) truck traveling over unsurfaced roads. The costs include waiting during loading and unloading, stoppages, the loaded journey, and the unloaded journey. The results can be closely represented by linear formulas with respect to distance. The cost of transport per ton is given by

Cost (\$US/t) = 0.998 + 0.113 K	Good Road
Cost (\$US/t) = 1.002 + 0.160 K	Fair Road
Cost (\$US/t) = 1.008 + 0.215 K	Poor Road

where K is the distance in kilometers. The Good Road is level, straight and smooth, the Poor Road undulates, twists and is rough.

Appendix C.
Use of the Geographic Information System.

The Creation of Digital Maps

The first step in the analysis was to digitize the maps into a computer compatible form. The maps were manually traced using the "Roots" program with the digitization table in the Interactive Computer Graphics Laboratory (ICGL) at Princeton. The Roots files store the data in vector form. The application "Chopin" was then be used to convert the files from vector to raster form. Raster represents the file as a two dimensional matrix, in which each entry represents the characteristic of the corresponding area (for this application the raster areas were chosen to represent one acre each). Figure C-1 shows a schematic of the rasterized road system; Fig. C-2 shows a schematic of the no-grow map; Fig. C-3 shows a schematic of the soil map. The map of the facility position is a single dot. These raster files were transferred to a UNIX account ready for manipulation by the "MapBox" application.

				1						
				1						
				1						
			1	1	1	1	1			
1	1	1	1				1			
							1			
							1			
							1	1	1	1

Figure C-1. Digitized Raster Map of the Road System.

1	1	1	1	1	1	1	2	2	2	2
1	1	1	1	1	1	2	2	3	3	2
1	1	1	1	1	1	3	3	3	2	2
1	1	1	1	1	1	3	3	3	2	2
3	1	1	1	2	2	3	3	2	2	2
1	3	3	2	2	2	2	2	2	2	2
3	3	3	2	2	2	2	2	2	2	2
3	3	3	2	2	2	2	2	2	2	2
3	3	3	3	2	2	2	2	2	2	2

Figure C-2. Digital Raster Map of the Soil Types.

	1	1	1	1						
		1	1							
								1		

Figure C-3. Digital Raster Map of the No-Grow Areas.

The MapBox Application

The MapBox application is a raster based geographic modeler produced by Decision Images Inc.[Tomlin, 90]. Four different MapBox functions were used for the analysis:

1) Areas or points can be given new values, for example all areas with “soil type 1” can be relabled “production cost of $51/hectare”.
2) The values of corresponding cells in different layers can be added, subtracted, divided, or multiplied. For example a map layer showing the total cost per cell ($) can be divided by a layer showing the yield per cell (Tonnes) to give a map layer showing the $/Tonne in each cell.

3) The "focal-proximity-spreading-in" function moves out from a designated focal point (in this case, the plant site) and is constrained to spread through a given network (in this case the road system). As the process spreads through the network it calculates the shortest distance back to the starting point. This function is useful for calculating transport distances.

4) The "focal-neighbor" function relates each cell to the nearest point of a particular feature and gives the cell the attribute of the feature. This function is used to show the point in the road system to which a cell's fuel must be moved for loading and shows how far that load of fuel must be transported along the road to the plant.

Map Manipulation Sequence to Calculate Biomass Costs

Figure C-4 is a flow diagram showing the sequence of map manipulations necessary to characterize the topography of the Iowa site. Using the map of the road system, the focal-proximity-spreading-in function gives the transportation distances from the plant (Fig. C-5). Based on this map, the focal-neighbor function assigns a road transport distance to each cell (Fig. C-6). The rings of transport distance are then created by reassigning all distances between zero and one to be equal to one, etc., up to a maximum of 25 miles (Fig. C-7). Comparing this map with the soil maps and no-grow maps allows the calculation of the number of acres of each soil type within each ring.

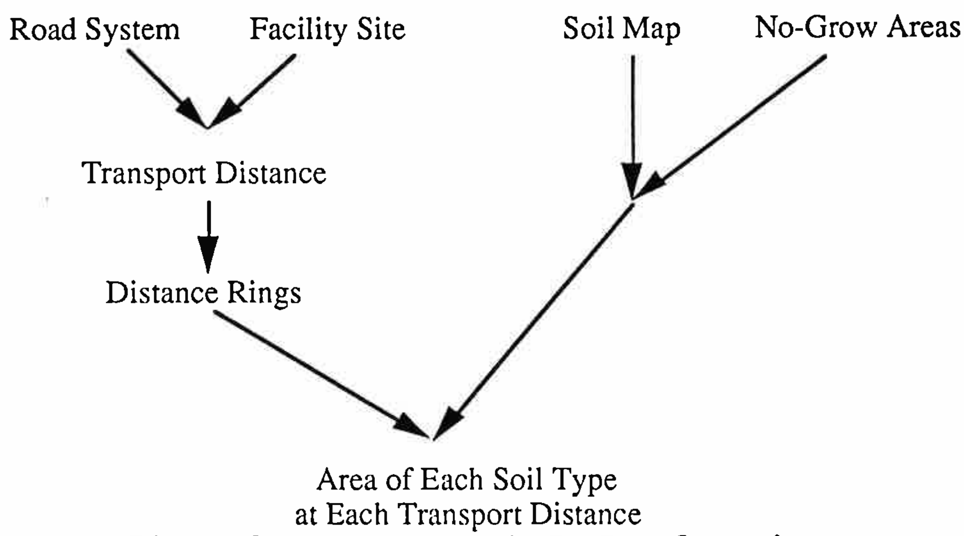

Figure C-4. Sequence of MapBox Operations.

				5						
				4						
				3						
			3	2	1	2	3			
7	6	5	4				4			
							5			
							6			
							7	8	9	10

Figure C-5. Map of Transport Distances from the Facility.

5	5	5	5	5	5	5	3	3	3	3
7	4	4	4	4	4	2	3	3	3	3
7	6	3	3	3	1	2	3	3	3	3
7	6	3	3	2	1	2	3	3	3	3
7	6	5	4	2	1	2	4	4	4	4
7	6	5	4	2	1	5	5	5	5	10
7	6	5	4	2	6	6	6	6	9	10
7	6	5	4	7	7	7	7	8	9	10
7	6	5	4	7	7	7	7	8	9	10

Figure C-6. Map of Transport Distances Related to Each Area.

2	2	2	2	2	2	2	1	1	1	1
2	2	1	1	1	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	1	1
2	2	2	1	1	1	1	1	1	1	1
2	2	2	1	1	1	2	2	2	2	3
2	2	2	1	1	2	2	2	2	3	3
2	2	2	1	2	2	2	2	2	3	3
2	2	2	1	2	2	2	2	2	3	3

Figure C-7. Map of Transport Distance Rings.
(for this schematic, assume 4 blocks equals one mile)

Appendix D
The Influence of Adjacent Biomass Energy Facilities

If two small facilities are collocated, the effect on the cost is equivalent to halving the biomass production density, ρ, because each facility will only have access to half the area it would otherwise have. If several facilities are evenly spread out across the country side, then the effect on costs is a little more complex.

If there is no limitation on the expansion of the production area, then there is a direct relationship between the price of biomass and the maximum transport distance for each soil type:

$$\begin{aligned} \text{BiomassPrice} &= \text{FixedCost}_{\text{SoilTypeA}} + \text{TD}_{\text{SoilTypeA}} \bullet \text{TC} \\ &= \text{FixedCost}_{\text{SoilTypeB}} + \text{TD}_{\text{SoilTypeB}} \bullet \text{TC} \\ &\vdots \end{aligned} \qquad \text{(D-1}$$

The transport distance varies approximately with the square root of the area, and the production of biomass varies linearly with the area:

$$\text{MaxTransportDistance}_{\text{SoilTypeA}} \approx K_A \sqrt{\text{Production}_A} \qquad \text{(D-2}$$

$$\text{Production}_A = \left(\frac{\text{MaxTransportDistance}_{\text{SoilTypeA}}}{K_A} \right)^2 \qquad \text{(D-3}$$

Where K_A is some constant. If the area is unrestricted the production on Soil Type A will be

$$\text{Production}_A = \left(\frac{\text{BiomassPrice} - \text{FixedCost}_{\text{SoilTypeA}}}{\text{CostPertonnekm} \bullet K_A} \right)^2 \qquad \text{(D-4}$$

However, if there are several biomass energy conversion facilities in the area, we can imagine the layout to be similar to Figure D-1 (the necessary spacing between each plant will be determined by the macro decision as to how much energy will be produced from biomass in the region). Once the spacing has been fixed, we can assume that each plant only takes fuel from its own area. In this case, there is a limitation on the maximum transport distance and therefore on the total area of each soil type that is available to each plant. In the unrestricted case, the least-cost solution is to increase the area of production according to eq. D-2. If expansion is restricted, areas of cheap biomass outside the allowed catchment area cannot be brought into production, and for the same feedstock price, the total supply will be less. The extent of this effect will depend on the ratio of the spacing of the facilities to the size of the facilities. The overall effect of limiting the catchment area is to reduce the production for a given price.

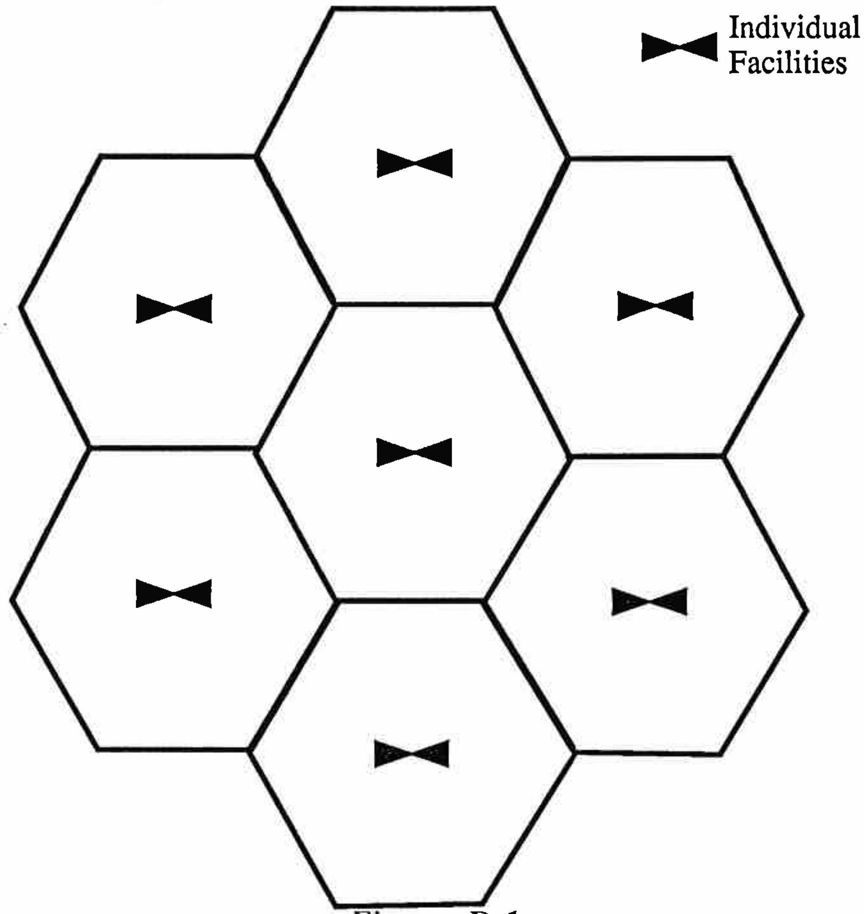

Figure D-1.
Supply Areas for the Case where Several Facilities are Located within a Region.

Appendix E.
Consideration of the Difference Between the Road Distance and the Direct Distance.

Calculation of F From GIS Data

In eq. 2.7-8, F was given as

$$F = \frac{TD}{\hat{r}} \quad \text{(E-1}$$

with

$$\hat{r} = \sqrt{\frac{\text{Area}}{\pi}} \quad \text{(E-2}$$

From the GIS analysis, we have 25 values for areas and corresponding transport distances. The factor F was calculated for each ring of transport distances and the corresponding area; the result is shown in Fig. E-1. At short transport distances, the factor is high because of the distortion of the lake near the center of the four-county area, but at large distances the factor settles out to be approximately 1.4.

Theoretical Calculations of F
Radial Road System

Transportation distances are minimized if the roads run radially from the energy conversion facility to the area of production. A dedicated energy plantation may therefore be laid out as in Fig . This approximates a radial road layout. For a perfectly radial layout, the transport distance is R and the production area is πr^2. From eq. E-2 $\hat{r}$ is equal to R and F is equal to 1.

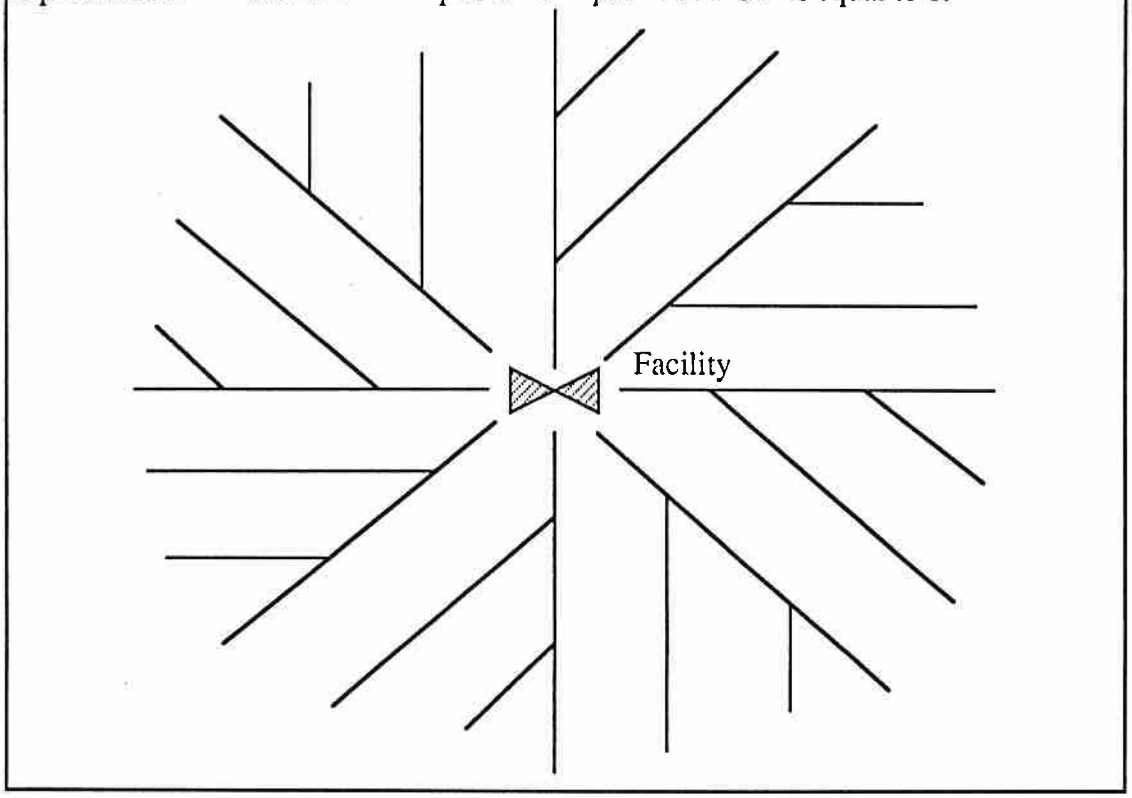

Figure E-2. A Road System that Approximately Minimizes the Transport Distances.

Grid Road Layout

Many areas (e.g., the Floryl plantation in Brazil) have square grid road layouts as in Fig. E-3. For a set road transport distance, the shape of the equal transport distance contour is a diamond. In Figure E-3 the shortest transport distance from the facility to the diamond is a constant, L:

$$L = x_1 + y_1 = x_2 + y_2 = \ldots \tag{E-3}$$

The area within the diamond is

$$\text{Area} = \left(2\frac{L}{\sqrt{2}}\right)^2 = 2L^2 \tag{E-4}$$

and the equivalent radius is

$$\hat{r} = \sqrt{\frac{\text{Area}}{\pi}} = \sqrt{\frac{2}{\pi}}L \tag{E-5}$$

giving

$$F = \frac{TD}{\hat{r}} = \frac{L}{\sqrt{\frac{2}{\pi}}L} = 1.25 \tag{E-6}$$

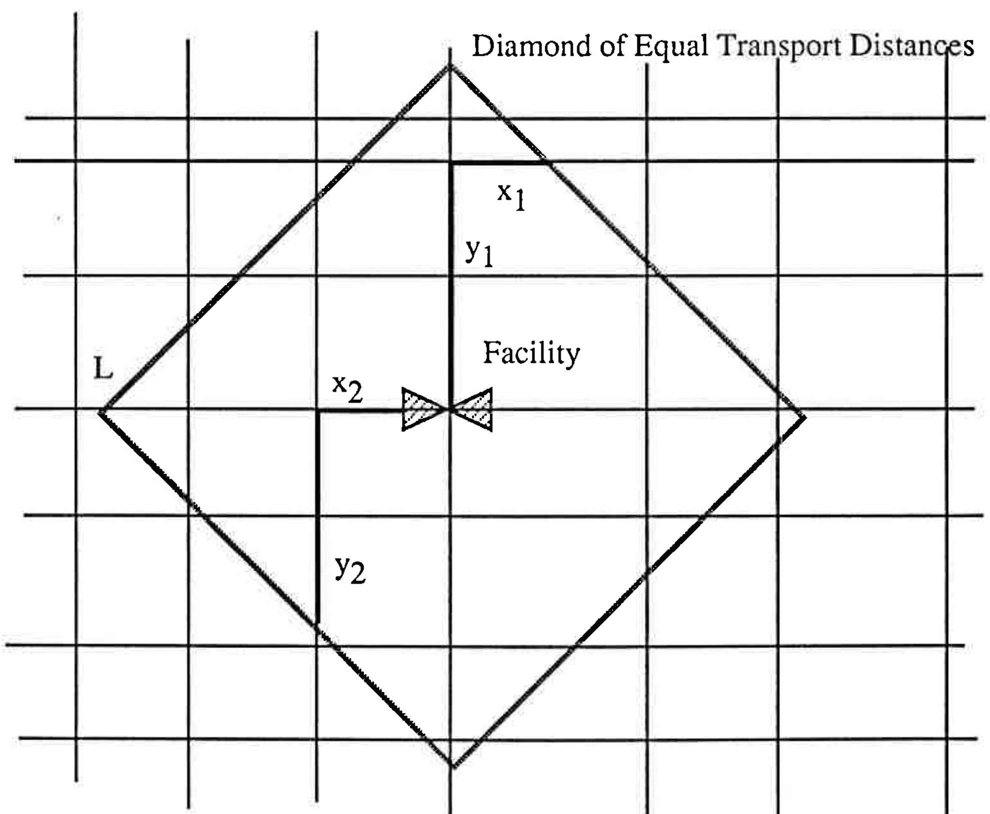

Figure E-3. Transport Distances for a Grid Road System.

Appendix F
Including the Effect on the Supply Curve of Different Soil Types

This analysis allows theoretical supply curves to be generated when there are significant differences between soil types. Figure F-1 shows a model of an area in which there are three soil types and a no-grow area. Each soil occupies a segment whose angle is such that

$$\frac{\theta_x}{2\pi} = \frac{\text{Area of Soil x in Region}}{\text{Total Area in Region}} \tag{F-1}$$

The radius of each segment is the maximum distance at which it is economic to produce biomass on that soil type, given a specific price per tonne. The price is

$$\text{Price} = \text{FixedCost}_x + R_x \bullet F \bullet TC \tag{F-2}$$

Where the Fixed Cost is the cost of biomass at the farmer's gate, and TC is the transport cost per tonne-km. For each soil type, the radius is given by

$$R_x = \frac{\text{Price} - \text{FixedCost}_x}{F \bullet TC} \tag{F-3}$$

For a given price, the production on soil x is

$$\text{Production}_x = \frac{\theta_x}{2\pi} Y_x \bullet \pi \bullet R_x^2 \tag{F-4}$$

and the total supply from the three soils will be

$$\text{Production} = Y_1 \frac{\Theta_1}{2} R_1^2 + Y_2 \frac{\Theta_2}{2} R_2^2 + Y_3 \frac{\Theta_3}{2} R_3^2 \tag{F-5}$$

In the cases when the price is less than the fixed cost, the radius will be zero and there will be no production on that soil type.

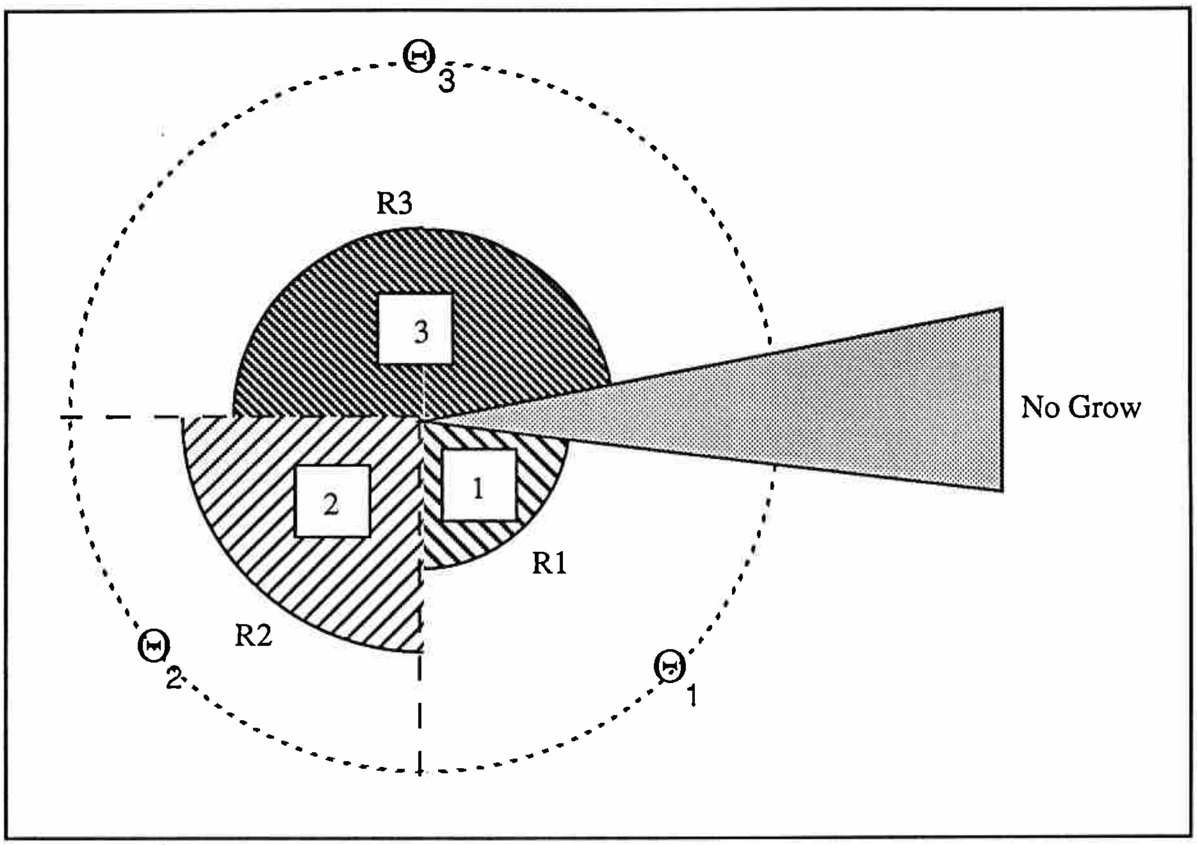

Figure F-1. Model of Biomass Production in an Area of Three Different Soil Types.

Appendix G.
Calculating the Optimal Capacity when Efficiency and O&M Costs are also Functions of Capacity.

In eq. 4.3-9, the optimal capacity was given for the case in which the O&M cost per kWh and the efficiency are not functions of the capacity. This appendix amends the analysis that led to eq. 4.3-9 and adds the small terms due to variations in O&M and efficiency. We model these functions as

$$\eta = \eta_o + fn_\eta(\text{Capacity}) \qquad \text{(G-1}$$

$$O\,\&\,M = O\,\&\,M_o + fn_{O\&M}(\text{Capacity}) \qquad \text{(G-2}$$

The first problem is to relate capacity to the annual feedstock supply. If the capacity is fixed then the supply is given directly by rearranging eq. 4.3-3:

$$\text{Supply}_n\left(\frac{\text{Tonnes}}{\text{year}}\right) = \frac{\text{Capacity(MW)} \bullet 3600 \bullet 365 \bullet 24 \bullet CF}{HHV(\frac{GJ}{\text{Tonne}}) \bullet 10^3 \bullet \left(\eta_o + fn_\eta(\text{Capacity})\right)} \qquad \text{(G-3}$$

However, with the GIS data, the capacity is not *a priori* fixed. Rather, the GIS gives the value of production, and the matching capacity must be derived. Again eq. 4.3-3 can be used to relate the supply to the capacity:

$$\text{Capacity(MW)} = \frac{\text{Supply}\left(\frac{\text{Tonnes}}{\text{year}}\right) \bullet HHV(\frac{GJ}{\text{Tonne}}) \bullet 10^3 \bullet \left(\eta_o + fn_\eta(\text{Capacity})\right)}{3600 \bullet 365 \bullet 24 \bullet CF} \qquad \text{(G-4}$$

Here the Capacity appears on both sides of the equation, therefore iteration is required to find a value for capacity that satisfies eq. G-4.. Starting from an initial guess of Capacity_o equals zero, we can iterate to the answer using the relationship

$$\text{Capacity}_{k+1}\text{(MW)} = \frac{\text{Supply}\left(\frac{\text{Tonnes}}{\text{year}}\right) \bullet HHV(\frac{GJ}{\text{Tonne}}) \bullet 10^3 \bullet \left(\eta_o + fn_\eta(\text{Capacity}_k)\right)}{3600 \bullet 365 \bullet 24 \bullet CF} \qquad \text{(G-5}$$

where k is the iteration index. This will converge quickly because $\eta_o >> fn_\eta(\text{Capacity})$. The relationships above allow us to produce the energy cost curves if the efficiency is a function of Capacity. The analysis below shows how to define the optimal Capacity in this case.

From eq. 4.3-4, the feedstock cost is

$$\text{FeedstockCost}\left(\frac{\$}{kWh}\right) = \frac{3600}{HHV \bullet 10^6 \bullet \eta}\left(A_{ton} + B_{ton} \bullet \sqrt{\frac{\text{Capacity} \bullet 3600 \bullet 365 \bullet 24 \bullet CF}{Y \bullet \rho \bullet \pi \bullet HHV \bullet 10^3 \bullet \eta}}\right) \qquad \text{(G-6}$$

We can group all the values that do not depend on capacity into the constants A_{kWh} and B_{kWh}:

$$\text{FeedstockCost}\left(\frac{\$}{\text{kWh}}\right) = A_{kWh} + B_{kWh} \bullet \sqrt{\frac{\text{Capacity}}{1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}}}$$

$$= A_{kWh} + B_{kWh} \bullet (\text{Capacity})^{0.5}\left(1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-0.5} \qquad \text{(G-7}$$

This is the same as eq. 4.3-5 but with a small additional term to account for variations in the efficiency. The total electricity cost is

$$\text{ElectricityCost} = A + B \bullet (\text{Capacity})^{0.5}\left(1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-0.5} + C + D(\text{Capacity})^{E} + O\,\&\,M_o + fn_{O\&M}(\text{Capacity}) \qquad \text{(G-8}$$

Differentiating with respect to Capacity gives

$$\frac{d\,\text{ElectricityCost}}{d\,\text{Capacity}} = 0.5B \bullet (\text{Capacity})^{-0.5}\left(1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-0.5} - B \bullet (\text{Capacity})^{0.5} \bullet 0.5\left(1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-1.5}\frac{\frac{d\,fn_{\eta}(\text{Capacity})}{d\text{Capacity}}}{\eta_o} + DE(\text{Capacity})^{E-1} + \frac{dfn_{O\&M}(\text{Capacity})}{d\text{Capacity}} \qquad \text{(G-9}$$

Setting this equal to zero and multiplying by $2\text{Capacity}^{0.5}$ we obtain

$$0 = B \bullet \left(1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-0.5} - B \bullet \text{Capacity} \bullet \left(1+\frac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-1.5}\frac{\frac{d\,fn_{\eta}(\text{Capacity})}{d\text{Capacity}}}{\eta_o} + 2DE(\text{Capacity})^{E-0.5} + 2(\text{Capacity})^{0.5}\frac{d\,fn_{O\&M}(\text{Capacity})}{d\,\text{Capacity}} \qquad \text{(G-10}$$

The optimal capacity must therefore satisfy

$$\text{Capacity} = \left(\frac{1}{-2DE}\right)^{\frac{1}{E-0.5}} \left[\begin{array}{l} B \bullet \left(1 + \dfrac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-0.5} \\ \quad - B \bullet \text{Capacity} \bullet \left(1 + \dfrac{fn_{\eta}(\text{Capacity})}{\eta_o}\right)^{-1.5} \dfrac{\dfrac{d\, fn_{\eta}(\text{Capacity})}{d\text{Capacity}}}{\eta_o} \\ \quad + 2(\text{Capacity})^{0.5} \dfrac{d\, fn_{O\&M}(\text{Capacity})}{d\, \text{Capacity}} \end{array} \right]^{\frac{1}{E-0.5}}$$

(G-11

This is similar to eq but with the addition to the right hand side of terms that are functions of capacity. These terms are, by their nature, small compared with the nominal values. Equation can therefore be used iterativly to find the optimal capacity:

$$\text{Capacity}_{k+1} = \left(\frac{1}{-2DE}\right)^{\frac{1}{E-0.5}} \left[\begin{array}{l} B \bullet \left(1 + \dfrac{fn_{\eta}(\text{Capacity}_k)}{\eta_o}\right)^{-0.5} \\ \quad - B \bullet \text{Capacity}_k \bullet \left(1 + \dfrac{fn_{\eta}(\text{Capacity}_k)}{\eta_o}\right)^{-1.5} \dfrac{\dfrac{d\, fn_{\eta}(\text{Capacity}_k)}{d\text{Capacity}_k}}{\eta_o} \\ \quad + 2(\text{Capacity}_k)^{0.5} \dfrac{d\, fn_{O\&M}(\text{Capacity}_k)}{d\, \text{Capacity}_k} \end{array} \right]^{\frac{1}{E-0.5}}$$

(G-12

where Capacity_k is the result of the previous iteration. As the convergence is rapid, it is viable to take the initial guess, Capacity_0, to be equal to zero.

Appendix H.
Description of EPRI TAG Calculations for Levelized Carrying Charge Fraction

This appendix gives the Matlab code used to calculate the capital recovery factor according to the equations in section 6.10.3 of the EPRI TAG, Volume 1 [EPRI, 93b] (the '%' symbol denotes a comment).

```
function AnnualizedCapitalCost =TAGCalculations

PropertyTaxandInsurance=0.02;                        % From Table 6-3 of the TAG
DebtRatio=0.46;         CostofDebt=0.048;           % From Table 6-3 of the TAG
PreferredRatio=0.08;    CostofPreferred=0.041;      % From Table 6-3 of the TAG
CommonRatio=0.46;       CostofCommon=0.085;         % From Table 6-3 of the TAG
weightedi=
     DebtRatio*CostofDebt+PreferredRatio*CostofPreferred+CommonRatio*CostofCommon;
TaxRate=0.38;                                        % From Table 6-3 of the TAG
inflation=0.041;                                     % From Table 6-3 of the TAG
ApparentDiscountRate=(1+wi)*(1+inflation)-1;         % From Table 6-3 of the TAG
ApparentCostDebt=(1+CostDebt)*(1+inflation)-1;       % Converts to Apparent Cost
ApparentReturnOnDebt=ApparentCostDebt*DebtRatio;
Deduction=TaxRate* ApparentReturnOnDebt /(1+inflation);
                                                     % Debt repayments are not subject to Tax
DiscountRateAfterTax=weightedi-Deduction;
ApparentDiscountRateAfterTax=ApparentDiscountRate-TaxRate*ReturnDebt0;
TCE=0.5+0.5/(1+ inflation);                          % Total Cash Expended over the last
                                                     % two years of construction.
TPI=0.5+0.5*(1+ ApparentDiscountRateAfterTax)/(1+ inflation);
                                                     % PV of Total Plant Investment, including
                                                     % the cost of money
AFDC=TPI-TCE                                         % Allowance for Funds used During
                                                     % Construction
Startup=71/1927;                                     % Startup Cost as proportion of Capital Cost,
                                                     % Table 6-6
ITC=0;                                               % Investment Tax Credit under old laws was
                                                     % non-zero
BookLife=30;
YearTaxDepreciation=TPI*[0.2*ones(1,5) zeros(1,25)];
                                                     % Renewable energy investments are allowed
                                                     % to depriciate over 5 years for tax purposes

DebtAFDC=AFDC*DebtRatio;                             % Annual Payments for AFDC
PreferredAFDC=AFDC*PreferredRatio;
CommonAFDC=AFDC*CommonRatio;

InvestGrossDep=TCE+DebtAFDC;                         % Initial Value of Depreciating Investments
InvestNonDep=Startup+PreferredAFDC;                  % Value of Non-Depreciating Investments
InvestTotal=InvestGrossDep+InvestNonDep;

InvestNet=InvestTotal-ITC*InvestGrossDep;            % In case of investment tax credit
ITCNormalized=ITC*InvestGrossDep/BookLife;

DebtBalance=InvestNet*DebtRatio;                     % Initial Value of remaining debts
PreferredBalance=InvestNet*PreferredRatio;
```

```
CommonBalance=InvestNet*CommonRatio;

InvestBookDeprec=InvestGrossDep/BookLife;        % Annual payback of capital
DebtBookDep=
    (DebtBalance-ITC*InvestGrossDep*DebtRatio)/BookLife;
PreferredBookDep=
    (PreferredBalance-ITC*InvestGrossDep*PreferredRatio-PreferredAFDC)/BookLife;
CommonBookDep=
    (CommonBalance-ITC*InvestGrossDep*CommonRatio-CommonAFDC-Startup)/BookLife;

PreferredAFDCRecov=PreferredAFDC/BookLife;
CommonAFDCRecov=CommonAFDC/BookLife;

% Now go through the calculations for each year
for n=1:BookLife

 DebtReturn=DebtBalance*CostofDebt;
 PreferredReturn=PreferredBalance*CostofPreferred;
 CommonReturn=CommonBalance*CostofCommon;
 DeferredIncomeTax=(YearTaxDepreciation(n)*InvestGrossDep- InvestBookDeprec)*TaxRate;
 CapitalRecovery=TPI*InvestBookDeprec+DeferredIncomeTax-ITCNormalized+
                    PreferredAFDCRecov+CommonAFDCRecov;
 IncomeTax=(PreferredReturn+CommonReturn+CapitalRecovery-
                    YearTaxDepreciation(n)*InvestGrossDep) *(TaxRate/(1-TaxRate));
 OtherTax=PropertyTaxandInsurance*TCE;
 AnnualCarryingCharge(n)=DebtReturn+PreferredReturn+CommonReturn+
                    CapitalRecovery+IncomeTax+OtherTax;
% Update the Balances
 DebtBalance=DebtBalance-DebtBookDep-...
  (DeferredIncomeTax+ITCNormalized)*DebtRatio;
 PreferredBalance=PreferredBalance-PreferredBookDep-...
  (DeferredIncomeTax+ITCNormalized)*PreferredRatio-PreferredAFDCRecov;
 CommonBalance=CommonBalance-CommonBookDep-...
  (DeferredIncomeTax+ITCNormalized)*CommonRatio-CommonAFDCRecov;
end

Discounts=(1+ AfterTaxDiscountRate).^[-1:-1:-BookLife];        % Annual Discounts
PVofAnnualCarryingCharge=Discounts.* AnnualCarryingCharge;
TotalPVofCarryingCharges=sum(PVofAnnualCarryingCharge);
CRF= AfterTaxDiscountRate / (1-(1+ AfterTaxDiscountRate).^-BookLife)
AnnualizedCapitalCost=CRF.* TotalPVofCarryingCharges;
```

Appendix

Matlab Calcs

Figure 2.5-1
Qualitative Map of Delivered Biomass Costs

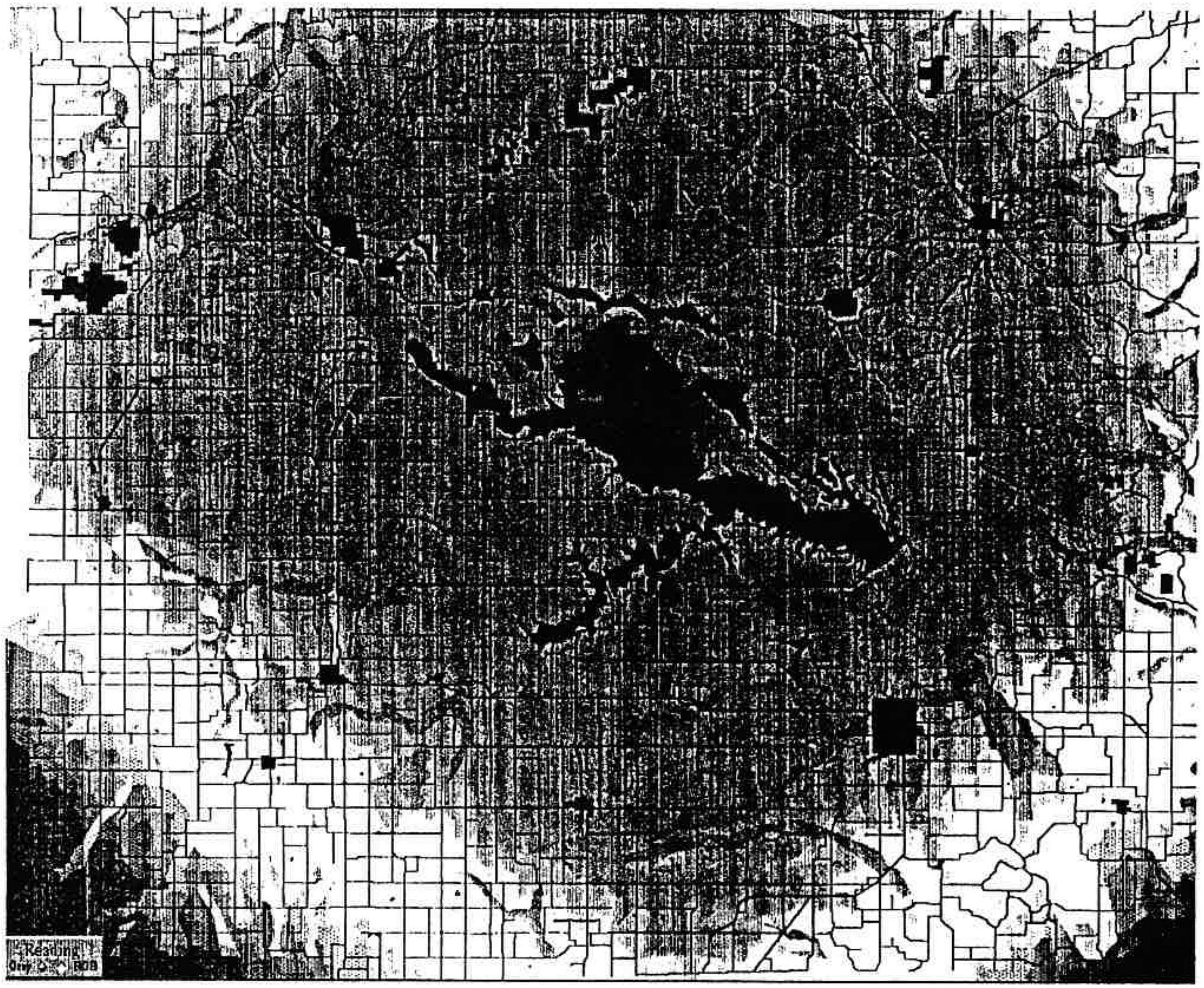

Figure 2.6-1
Marginal and Average Feedstock Costs from GIS Analysis for Iowa in 2000 and 2020

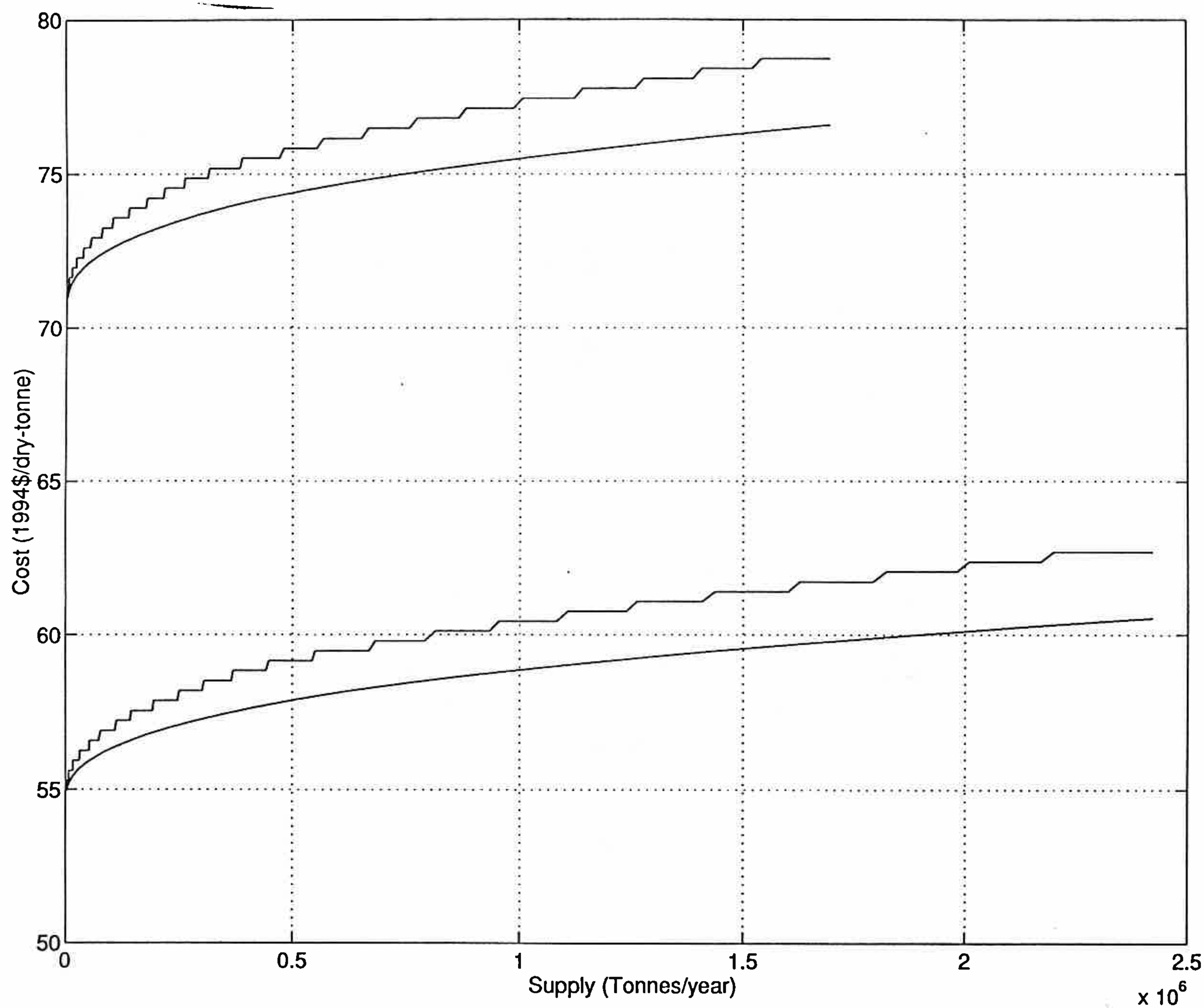

Figure 2.7-2
Comparison of Results from GIS and Simplified Theory

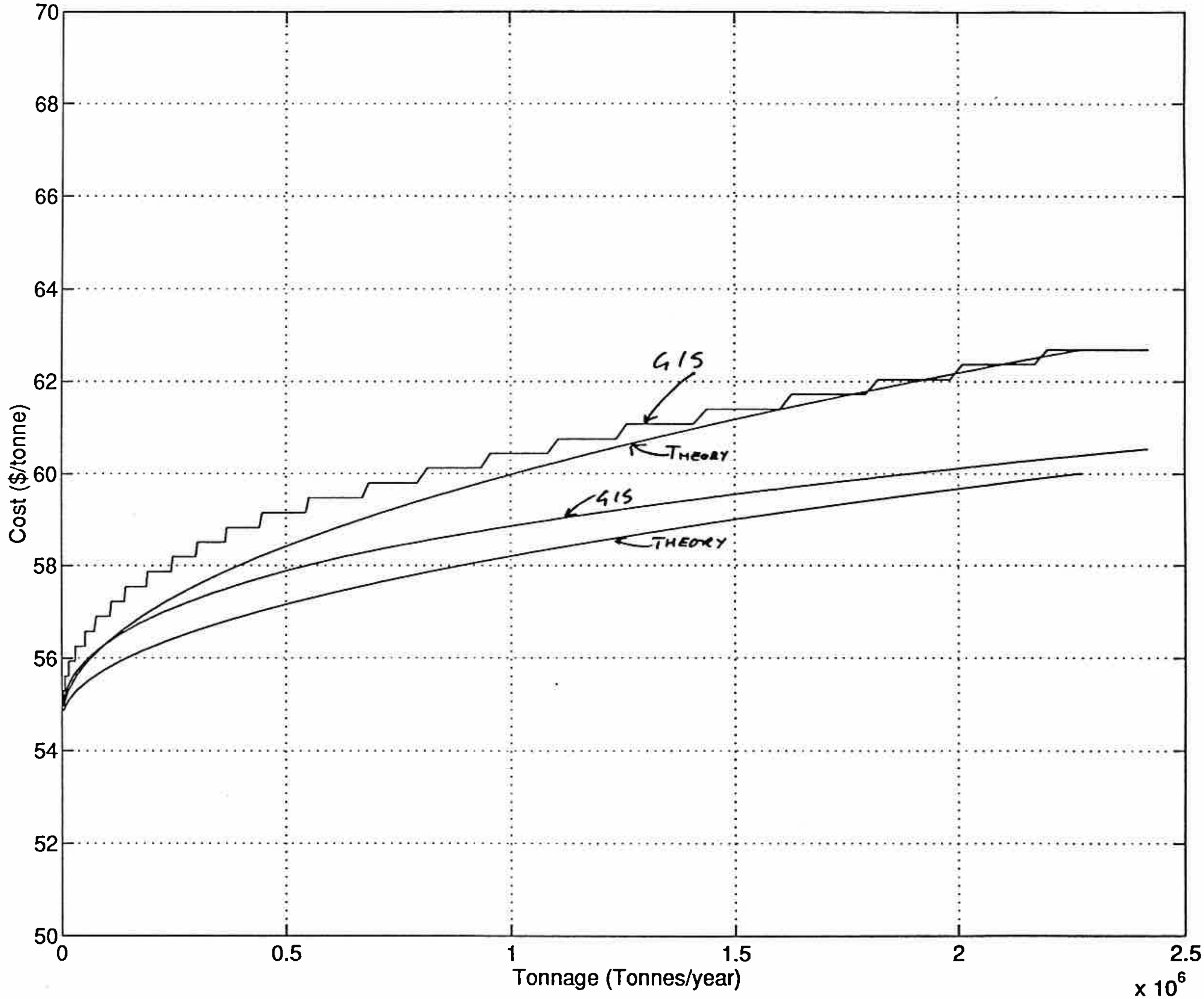

Figure 2.7-3
Projected Supply Curves for Brazil

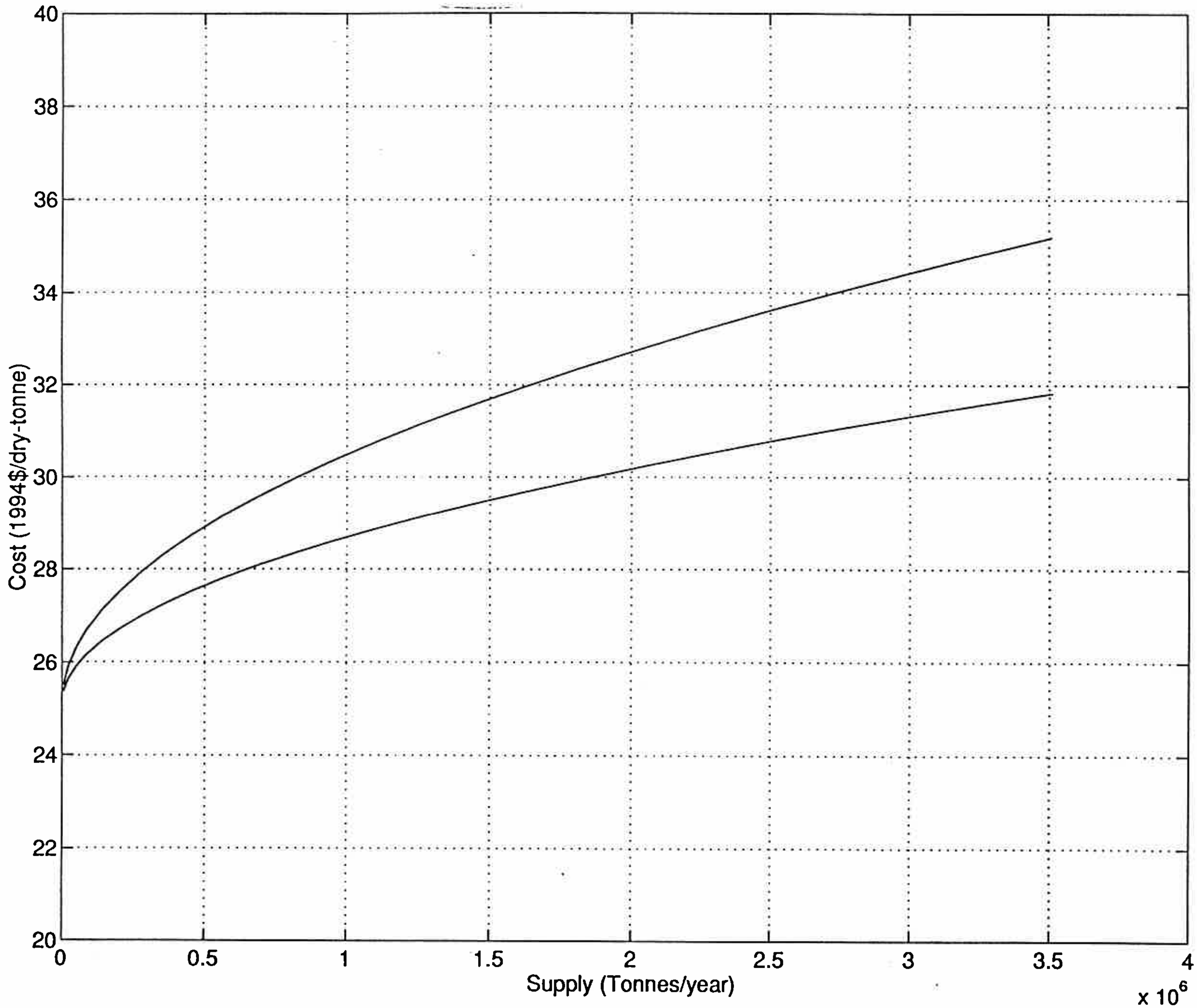

Figure 3.1-1
Capital Cost Curves for Electricity Generation

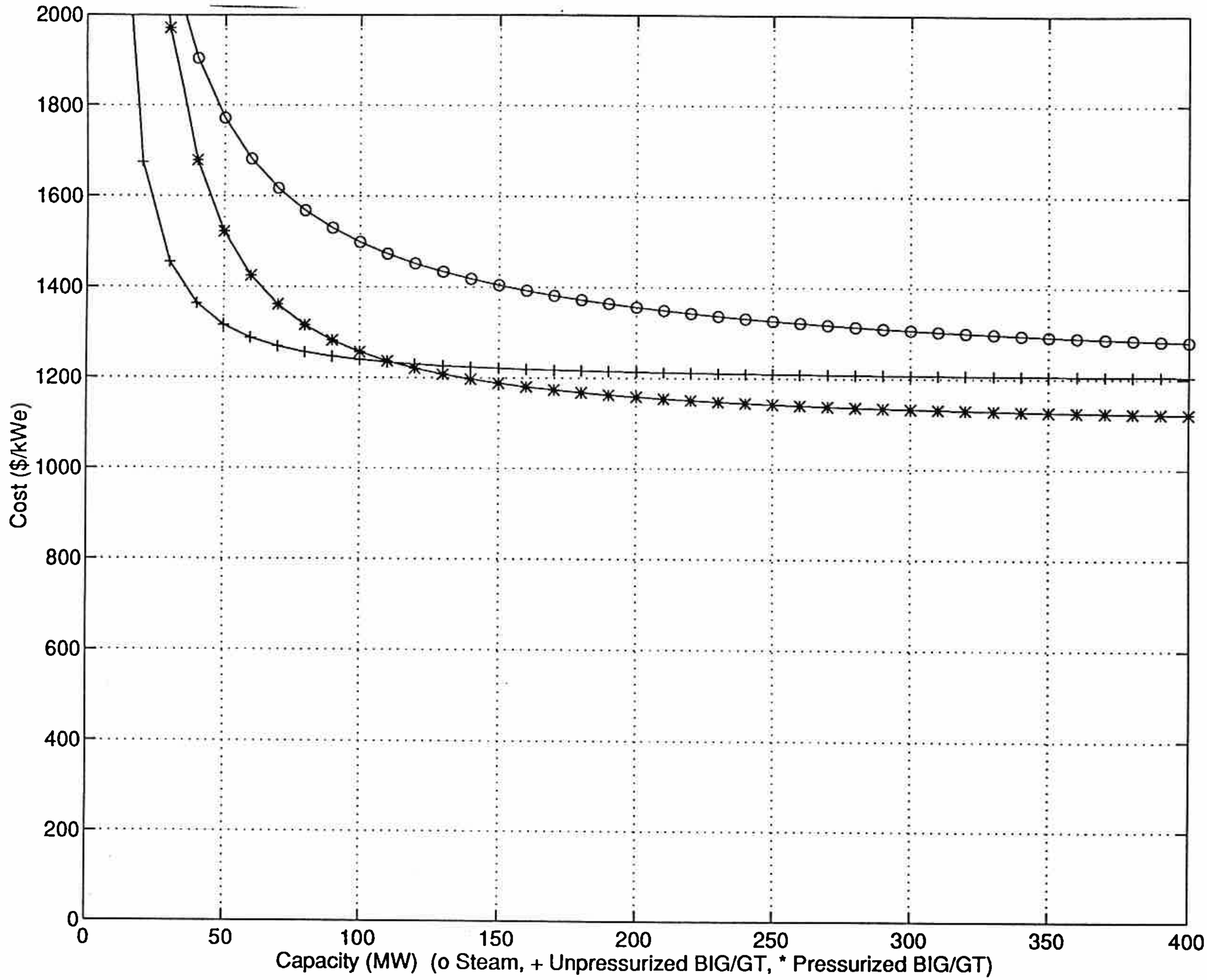

Figure 3.1-2
Capital Cost Curves for Fuel Production

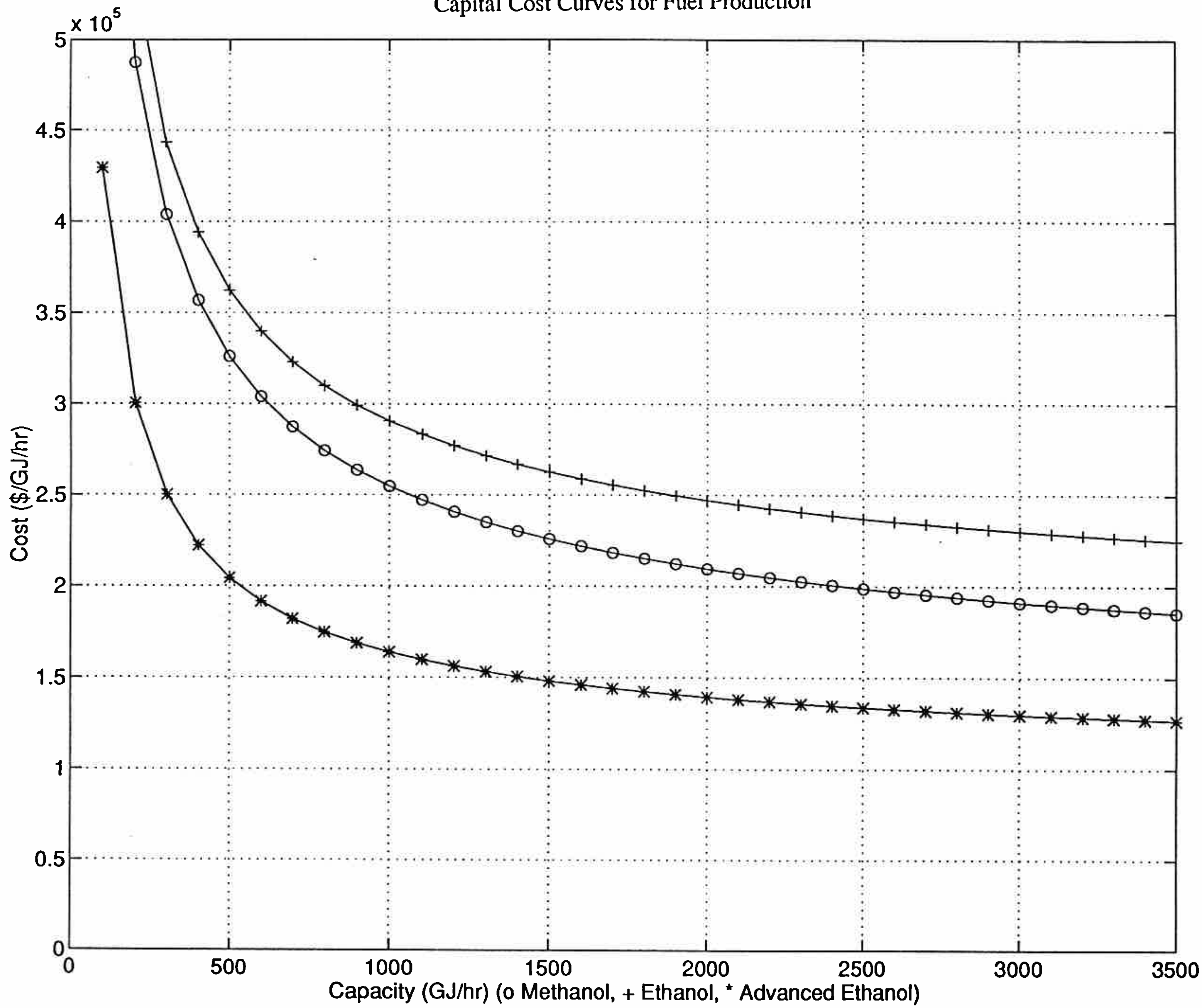

Figure 4.2-1
Electricity Costs in Iowa for 2000

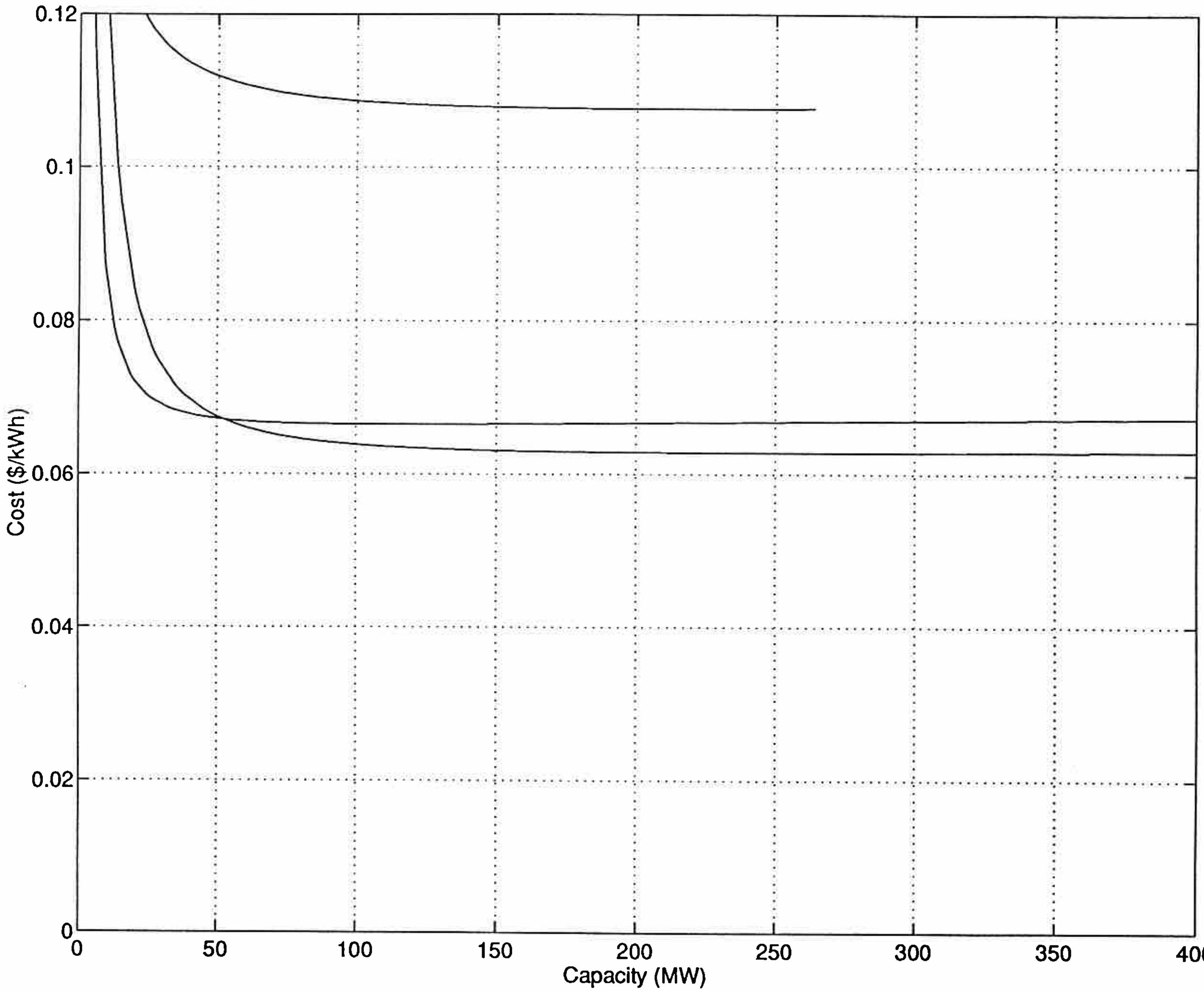

Figure 4.2-2
Electricity Costs in Iowa for 2020

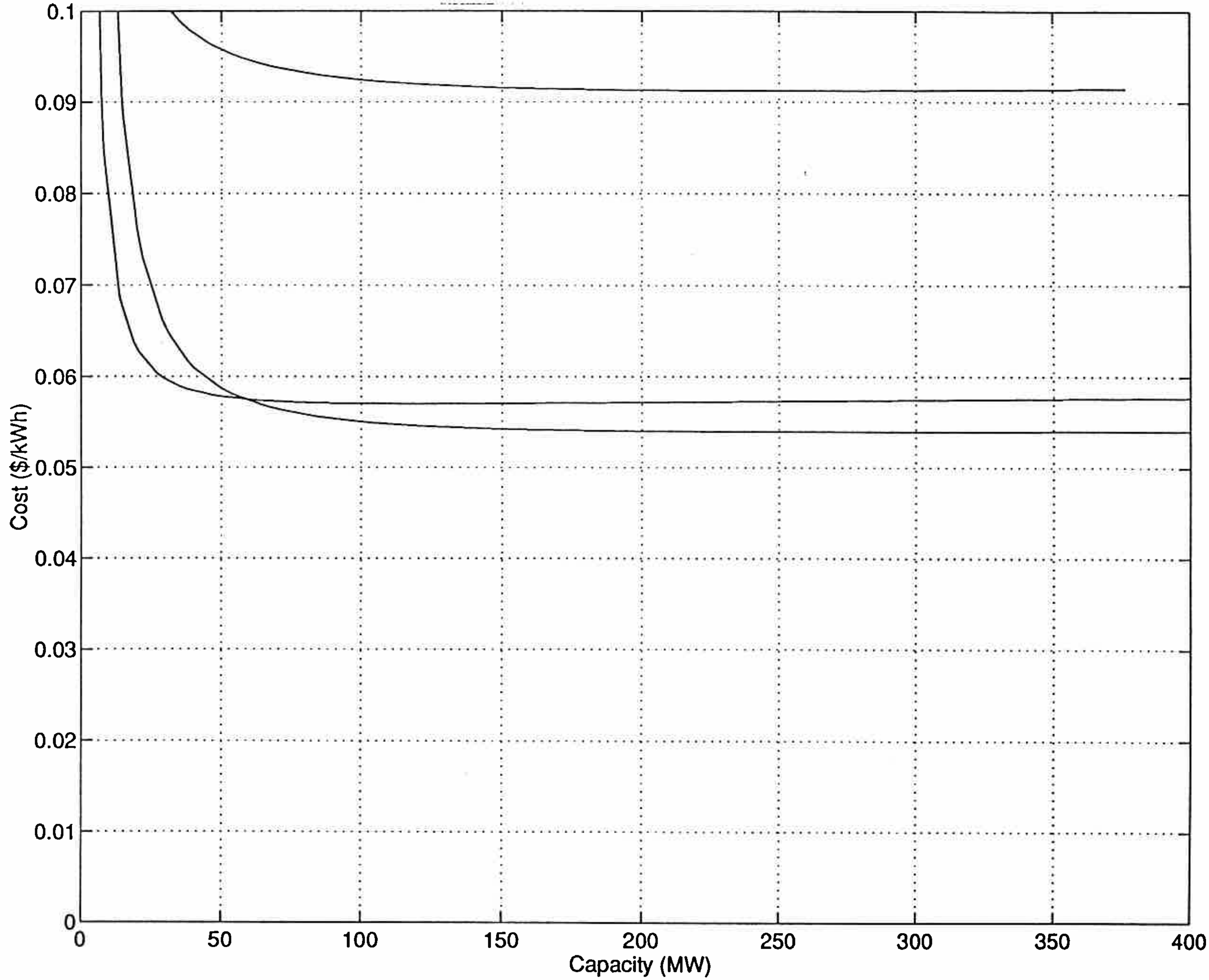

Figure 4.2-3
Fuel Costs in Iowa for 2000

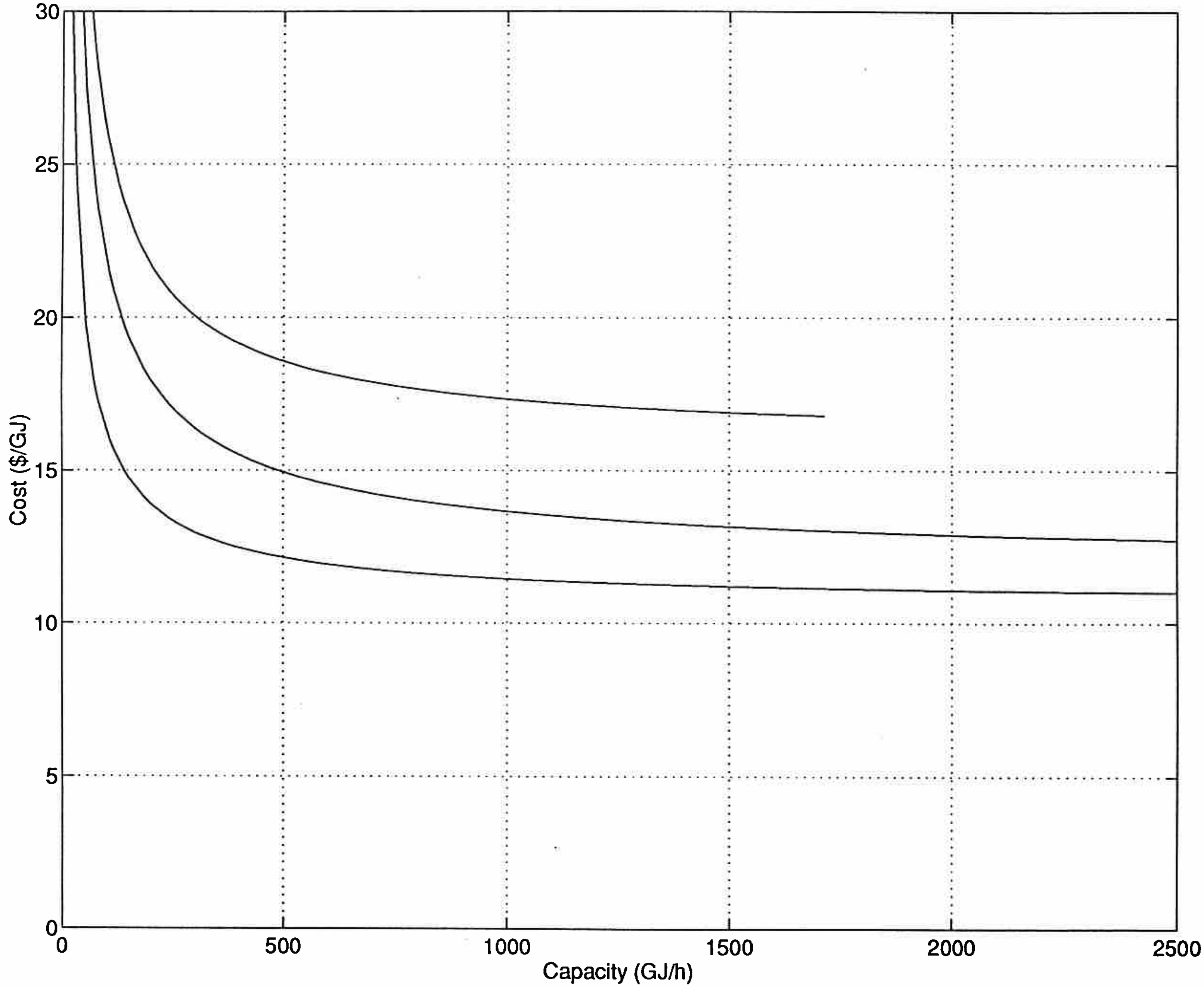

Figure 4.2-4
Fuel Costs in Iowa for 2020

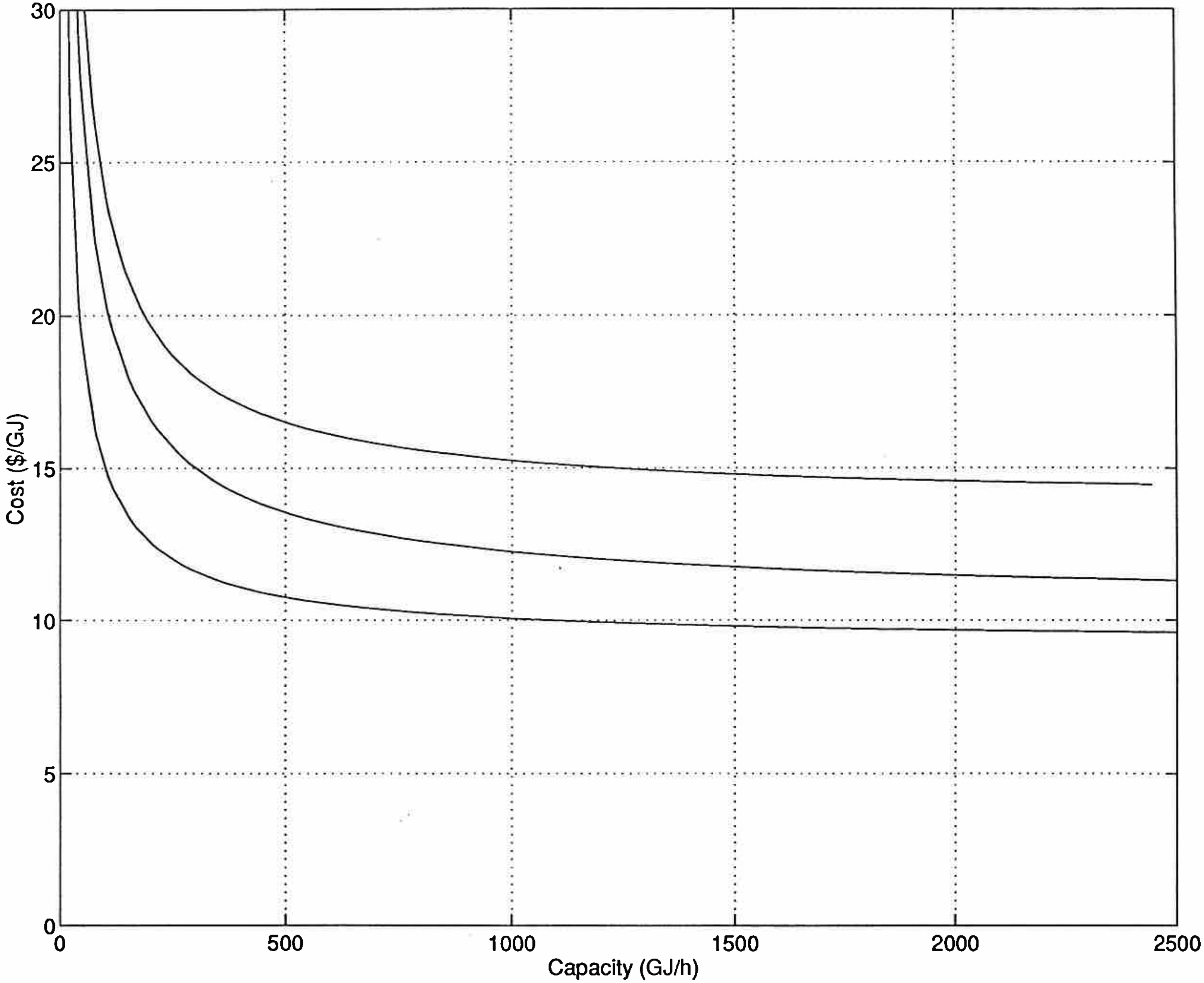

Figure 4.2-5
Electricity Costs in Brazil for 1994

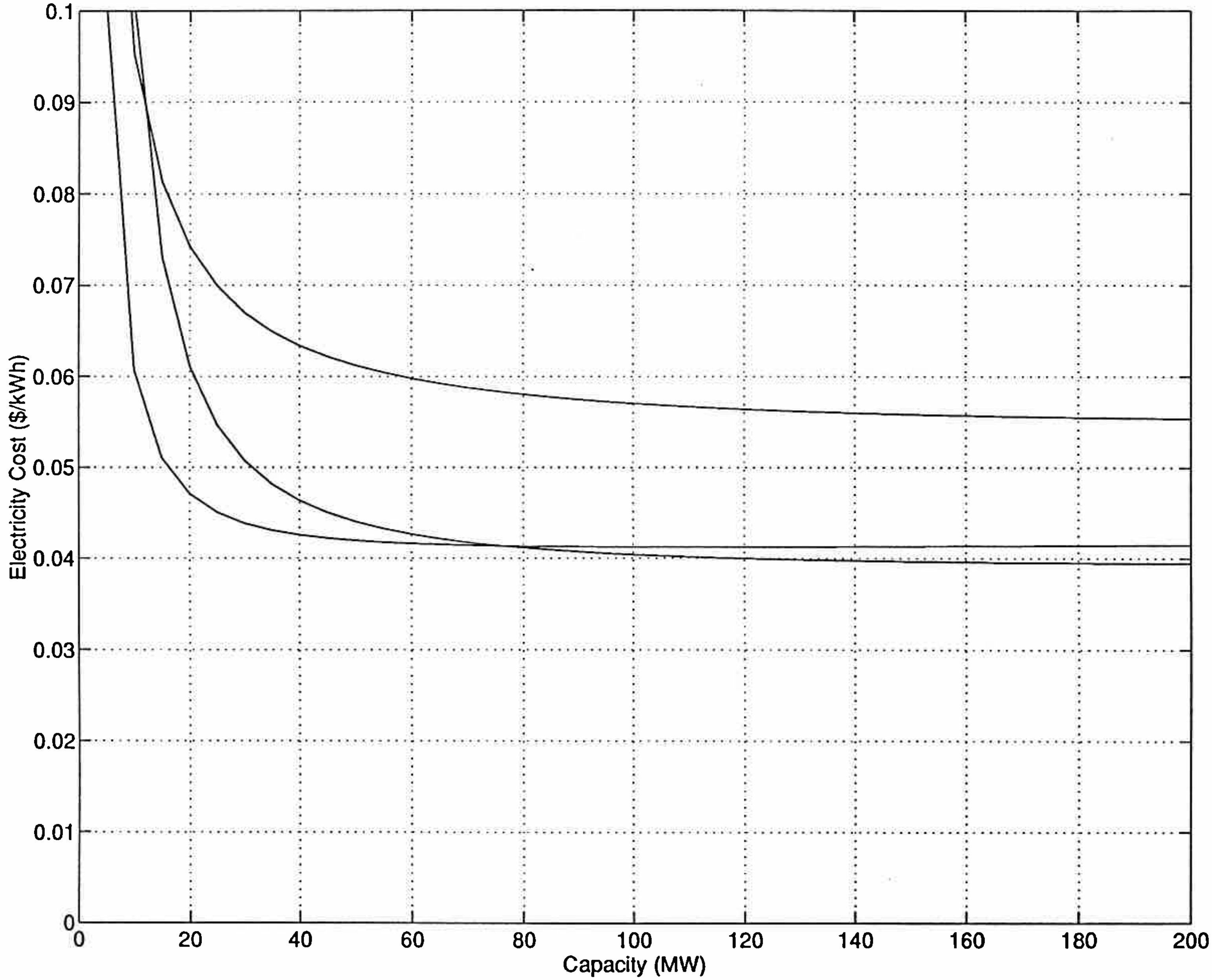

Figure 4.2-6
Fuel Costs in Brazil for 1994

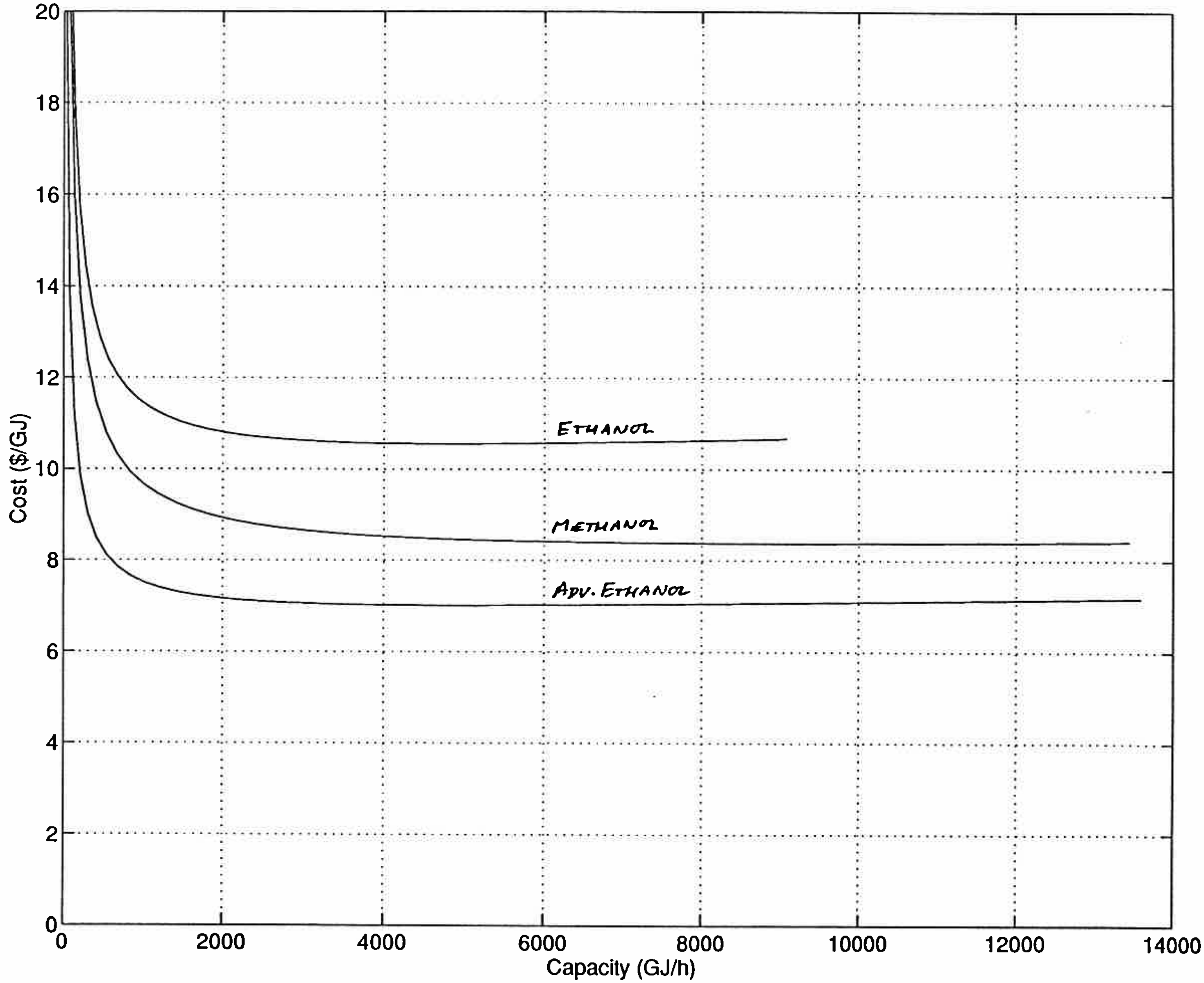

Figure 4.4-1
Sensitivity Analysis: Change in Transport Costs

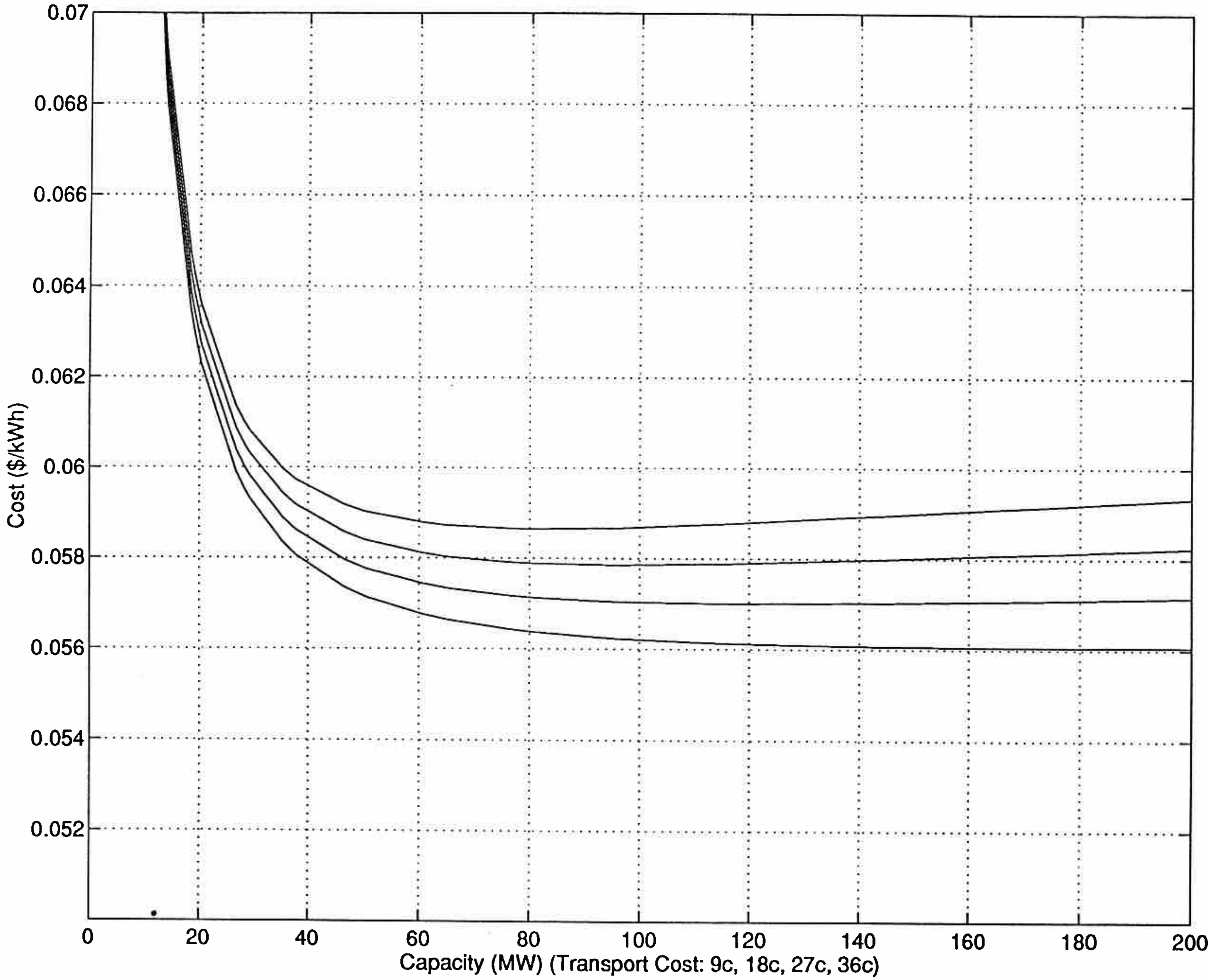

Figure 4.4-2
Sensitivity Analysis: Change in Planting Density

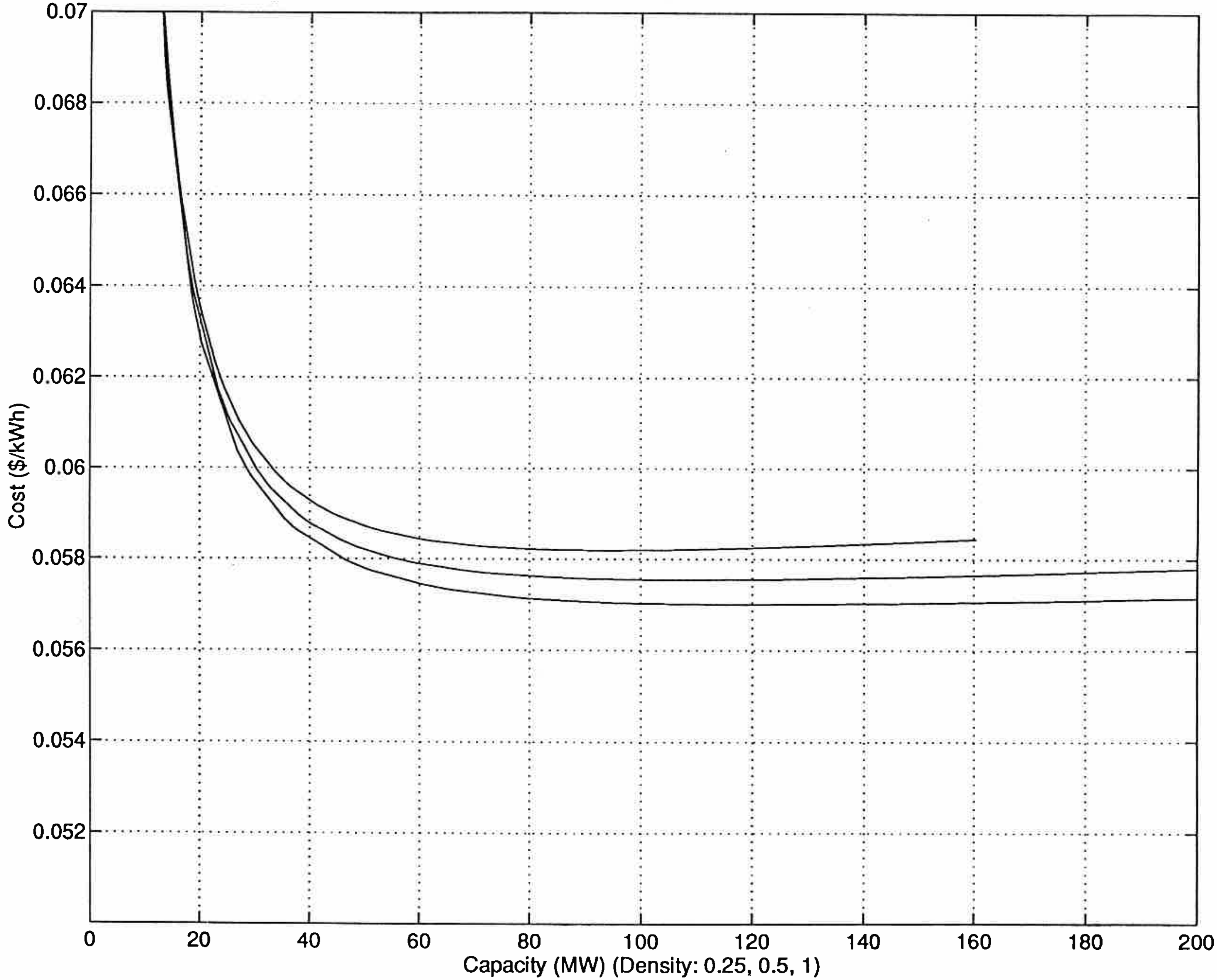

Figure 4.4-3
Sensitivity Analysis: Change in Land Rent