Methodology for Constructing Aggregate Ethanol Supply Curves

TAFV Model Technical Note

Draft, Revision 3

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Contents

1.0 Introduction

Ethanol for use as either a neat fuel or additive can be efficiently derived from two primary sources: grains (corn) and woody biomass. Feedstock preparation process facilities for corn include new wet mills, add-on wet mills, and new dry mills. Woody biomass feedstocks include short-rotation woody crops (SRWC), switchgrass, agricultural residues, hardwood waste, softwood waste.[1] This report describes ORNL's approach in constructing separate aggregate supply curves for ethanol from biomass and ethanol from corn. These curves are suitable for use in the Transition to Alternative Fueled Vehicles (TAFV) model (Leiby and Rubin, 1997). Moderate-scenario supply curves for the years 2000, 2005, 2010, and 2015 were estimated using a least-cost dispatching approach.[2] This approach uses GAMS, a nonlinear programming simulation software, to solve for the prevailing price and individual feedstock quantities that satisfy the aggregate ethanol supply requirements at the lowest cost given constraints on feedstock supply (Brooke et al., 1992). Supply curves for 1995 were extrapolated back from the final results.

Section 2.0 describes the information sources drawn upon for this study. Section 3.0 describes the model used to aggregate individual supply curves into aggregate supply curves. Section 4.0 presents the results for the moderate aggregate supply curves. Appendix A lists the estimates of feedstock parameters used to generate the aggregate curves. Appendix B displays the results of this analysis in graphical format. Finally Appendix C reports the model source codes used in constructing aggregate ethanol supply curves.

2.0 Information Sources

Production costs for corn and feedstock supply curves for corn, switchgrass, short rotation woody crops (SRWC), agricultural residues, hardwoods, and softwoods were provided by ORNL. These are detailed in Walsh et al. (1997) *Evolution of the Fuel Ethanol Industry: Feedstock Availability* and Perlack (1997) *Updated Supply Curves from Waste Wood*. Interim production costs for woody biomass were provided for by Tien Nguyen (1998).[3]

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[1] Refuse-derived fuel (RDF) is also considered a woody biomass feedstock for ethanol. However, due to the uncertainty of future supplies and competing resource uses, RDF is not included in this study.

[2] Previous versions of this document included optimistic as well as moderate cost scenarios. The data by which the optimistic case was constructed were deemed too unrealistic. The optimistic case is no longer reported.

[3] Previous versions of this document derived woody biomass production costs from NREL estimates. These estimates are now in the process of being revised. We are grateful to Tien Nguyen for providing preliminary results of the new data.

3.0 Model

Feedstock supplies are characterized by intercepts, slopes, and availability constraints. Ethanol supply from each feedstock type reflects feedstock supply curves and transportation and conversion costs as well as availability constraints. Aggregate supply curves are generated by minimizing the total cost of achieving ethanol supply requirements from 0.1 billion gallons of ethanol up to 33 billion gallons in increments of 100 million gallons based upon the availability and costs of the feedstocks. The minimization problem is given below.

$$\underset{\{q_i\}}{Min} \quad TC = \sum_{n=0}^{N} \sum_{f=1}^{F} \left[\int_0^{\bar{q}} CR_f \cdot (\alpha_f + \beta_f \cdot CR_f \cdot q_{nf})\,dq + CR_f \cdot TR_f \cdot q_{nf} + PG_f \cdot q_{nf} \right]$$

s.t.

$$feedstock\ limit\ constraint: \quad q_{nf} \le \bar{q}_f \quad \forall f$$

$$aggregate\ supply\ constraint: \quad \sum_{f=1}^{F} q_{nf} = Q_n \quad \forall n$$

$$nonnegativity\ constraint: \quad q_{nf} \ge 0$$

where:

- q_{nf} = *quantity of feedstock f (ethanol gal/yr) given an aggregate demand quantity n*
- CR_f = *conversion rate (dry tons/ethanol gallon)*
- α_f = *feedstock intercept* ($/*dt*)
- β_f = *feedstock slope* ($/*dt*)
- TR_f = *transportation cost* ($/*dt*)
- PG_f = *plant level conversion cost* ($/*gal*)
- $\bar{q}_f$ = *feedstock quantity limit (ethanol gal/yr)*
- Q_n = *aggregate quantity (ethanol gal/yr) stipulated for quantity iteratation n*

The resulting Lagrangian and partials are:

$$\mathcal{L} = \sum_{n=0}^{N} \sum_{f=1}^{F} \left[\int_0^{\bar{q}} CR_f \cdot (\alpha_f + \beta_f \cdot CR_f \cdot q_{nf})\,dq + CR_f \cdot TR_f \cdot q_{nf} + PG_f \cdot q_{nf} - \lambda_f (q_{nf} - \bar{q}_f) - \phi_f \cdot \left(\sum_{f=1}^{F} q_{nf} - Q_n \right) - \delta_f (q_{nf}) \right]$$

$$\frac{\partial \mathcal{L}}{\partial q_{nf}} = \begin{pmatrix} Plantgate\ price \\ of\ feedstock\ f \end{pmatrix} = \phi_f = CR_f \cdot (\alpha_f + \beta_f \cdot CR_f \cdot q_{nf}) + CR_f \cdot TR_f + PG_f - \lambda_f - \delta_f \quad \forall\ n,f$$

The prevailing price of ethanol for any total quantity supply requirement is then the accompanying shadow value of an additional unit of supply ($/gal). The plantgate price of ethanol from any feedstock is equal to the marginal cost of feedstock supply plus transportation and conversion costs, less the shadow values of the nonnegativity and feedstock limit constraints. The plant gate price is equal to the marginal cost of supply if and only if $0 < q_{nf} < \bar{q}_{nf}$. This implies 1) a nonnegative feedstock quantity is optimal and desired, and 2) a feedstock quantity is not at its limit.

In order to simplify the use of these results and provide for smooth supply paths, aggregate ethanol supply curves are then fitted to a variable elastic supply curve using the inverse form:

$$P_i = A + \frac{B}{C - Q_i}$$

Variables A, B, and C are chosen optimally as to minimize the mean squared error between the estimated curves resulting from the least cost minimization and the fitted curves. The new fitted price path for each year and scenario can then be fully described by three intervals (P1, 0), (P2, Q2), and (4, Q3).

4.0 Results

Results from the least-cost minimization ranged from approximately 200 to 500 data points for woody biomass to 40 data points for corn depending upon the total available quantity of feedstocks. Results for selected aggregate quantities appear in Tables 4.1 and 4.2. For woody biomass the aggregation of feedstocks on a least cost basis provided a smooth upward sloping curve with little irregularities. Generally hardwood was the lowest cost feedstock, however agricultural residues provided the bulk of ethanol production due to its immense availability. Due to the overwhelmingly lowest cost of the add-on wet mill processes, the results of the corn simulations tended to result in choppy supply curves, exhibiting discontinuous behavior as the add-on wet mill capacity reached full utilization.

Table 4.1 Results of Least-Cost Aggregate Ethanol Supply Curves from Woody Biomass

Price ($95/gal)	Total (bill gals)	SRWC (bill gals)	Switchgrass (bill gals)	Ag Residues (bill gals)	Hardwoods (bill gals)	Softwoods (bill gals)
Moderate Scenario, Year 2000						
1.294	5.00	0.00	0.24	3.52	0.93	0.31
1.362	10.00	0.00	0.24	8.08	1.24	0.44
1.577	15.00	0.00	0.24	11.66	2.22	0.88
NA	NA	NA	NA	NA	NA	NA
Moderate Scenario, Year 2005						
1.111	5.00	0.00	0.81	3.22	0.75	0.22
1.156	10.00	0.00	0.81	7.90	0.97	0.32
1.196	15.00	0.49	0.81	12.13	1.16	0.41
1.565	20.00	0.49	0.81	14.49	2.97	1.24
Moderate Scenario, Year 2010						
0.945	5.00	0.00	0.31	3.52	0.91	0.27
0.964	10.00	0.38	1.90	6.38	1.03	0.32
0.987	15.00	1.68	1.90	9.86	1.17	0.39
1.016	20.00	1.82	1.90	14.44	1.36	0.47
Moderate Scenario, Year 2015						
0.828	5.00	0.30	0.00	3.64	0.83	0.23
0.839	10.00	1.10	1.99	5.73	0.91	0.27
0.852	15.00	2.01	3.61	8.09	0.99	0.31
0.870	20.00	3.35	3.61	11.57	1.11	0.36

Table 4.2 Results of Least-Cost Aggregate Ethanol Supply Curves from Corn

Price ($95/gal)	Total (bill gals)	New Wet Mill (bill gals)	Add-on Wet Mill (bill gals)	New Dry Mill (bill gals)
Moderate Scenario, Year 2000				
1.052	1.00	0.00	1.00	0.00
1.190	2.00	0.00	1.00	1.00
Moderate Scenario, Year 2005				
1.059	1.00	0.00	1.00	0.00
1.239	2.00	0.46	1.00	0.54
Moderate Scenario, Year 2010				
1.036	1.00	0.00	1.00	0.00
1.222	2.00	0.62	1.00	0.38
Moderate Scenario, Year 2015				
1.017	1.00	0.00	1.00	0.00
1.206	2.00	0.73	1.00	0.27

The estimated results of the least cost minimization problem were then fitted to smooth upward-sloping curves as described above. The fitted results of the analysis are presented in Tables 4.3 and 4.4. Estimates for 1995 values were extrapolated back from the forecasted years[4].

Table 4.3: TAFV Woody Biomass to Ethanol Supply Parameters ($94/bbl, mill

Moderate Scenario

	1995	**2000**	**2005**	**2010**	**2015**
P_1	57.140	50.943	44.718	38.166	33.492
P_2	60.353	53.532	46.462	39.445	34.613
P_3	4	4	4	4	4
Q_1	0.000	0.000	0.000	0.000	0.000
Q_2	0.420	0.528	0.672	0.881	1.089
Q_3	1.100	1.230	1.441	1.869	2.282

Table 4.4: TAFV Corn to Ethanol Supply Parameters ($94/bbl, mill bbls/day)

Moderate Scenario

	1995	**2000**	**2005**	**2010**	**2015**
P1	42.896	41.221	42.839	41.954	41.155
P2	48.745	47.913	48.785	47.955	47.236
P3	4	4	4	4	4
Q1	0.000	0.000	0.000	0.000	0.000
Q2	0.130	0.130	0.130	0.130	0.130
Q3	4.200	4.243	4.830	4.944	5.031

[4] Extrapolation provides consistency with the generated results and provides a smooth path over the time horizon.

5.0 References

Brooke, A., D. Kendrick, and A. Meeraus (1992) *GAMS: A User's Guide, Release 2.25*, Scientific Press, Massachusetts.

Leiby, P. and J. Rubin (1997) The Transitional Alternative Fuels and Vehicles Model, Draft, Oak Ridge National Laboratory.

Nguyen, Tien (1998) *Ethanol Cost Projections for EE-34/PO Modeling Work with TAFV*, personal correspondence, July 30.

Perlack, B. (1997) *Updated Supply Curves from Waste Wood*, Draft, Oak Ridge National Laboratory.

Walsh, M., B. Perlack, D. Becker, R. Graham, and A. Turhollow (1997) *Evolution of Fuel Ethanol Industry: Feedstock Availability and Price,* Draft, Oak Ridge National Laboratory.

APPENDIX A

Feedstock Parameters used in the Model

Table A.1: Moderate Scenario Biomass Feedstock Supply Parameters

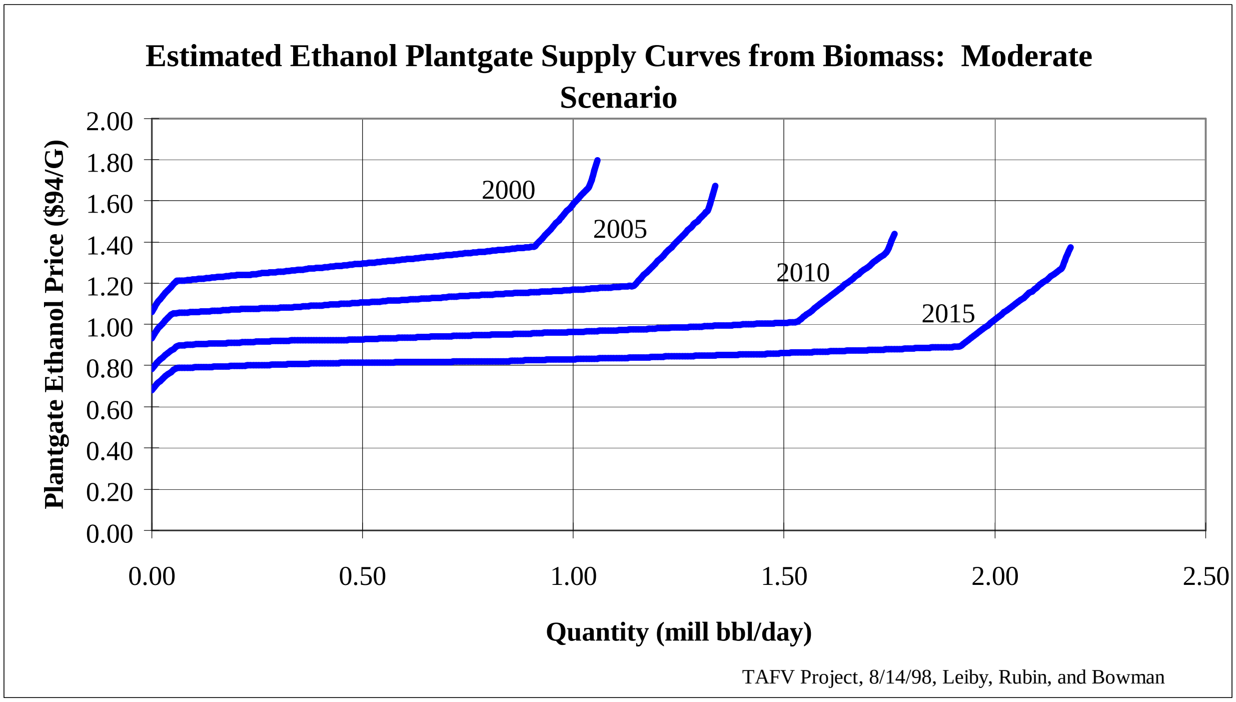
	2000	2005	2010	2015
SRWC				
Intercept ($95/ton)	NA	39.66	38.62	37.94
Slope	NA	0.379	0.225	0.195
Transportation Costs ($95/ton)	5.00	5.00	5.00	5.00
Conversion Costs ($95/gal)	0.843	0.709	0.575	0.460
Supply Limit (mill gals/yr)	0	485	1824	3894
Conversion Rate (gal/ton)	91	97	114	118
Switchgrass				
Intercept ($95/ton)	29.76	30.54	31.97	33.56
Slope	0.030	0.030	0.027	0.025
Transportation Costs ($95/ton)	5.00	5.00	5.00	5.00
Conversion Costs ($95/gal)	0.843	0.709	0.575	0.460
Supply Limit (mill gals/yr)	243	810	1900	3605
Conversion Rate (gal/ton)	81	90	100	103
Agricultural Residues				
Intercept ($95/ton)	27.31	28.47	29.76	30.87
Slope	0.097	0.077	0.065	0.057
Transportation Costs	5.00	5.00	5.00	5.00
Conversion Costs ($95/gal)	0.843	0.709	0.575	0.460
Supply Limit (mill gals/yr)	11664	14490	17700	19982
Conversion Rate (gal/ton)	81	90	100	103
Hardwood Wastes				
Intercept (including trans costs)	22.46	24.20	26.07	28.09
Slope	1.820	1.920	2.030	2.170
Transportation Costs ($95/ton)	0.00	0.00	0.00	0.00
Conversion Costs ($95/gal)	0.843	0.709	0.575	0.460
Supply Limit (mill gals/yr)	2871.05	3131.16	3751.74	3909.34
Conversion Rate (gal/ton)	91	97	114	118
Softwood Wastes				
Intercept (including trans costs)	27.30	29.59	31.94	34.38
Slope	4.090	4.180	4.430	4.570
Transportation Costs ($95/ton)	0.00	0.00	0.00	0.00
Conversion Costs ($95/gal)	0.843	0.709	0.575	0.460
Supply Limit (mill gals/yr)	1431.43	1604.38	1916.34	2069.72
Conversion Rate (gal/ton)	91	97	114	118

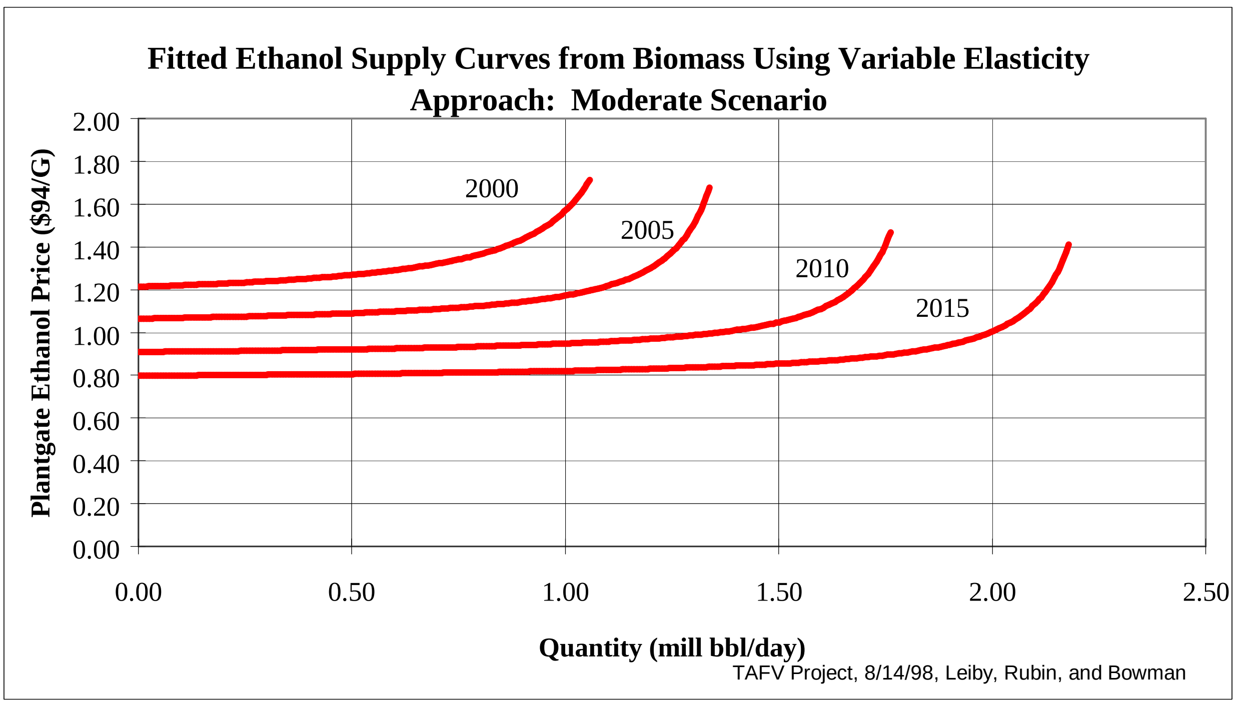
Table A.2: Moderate Scenario Corn Feedstock Supply Parameters

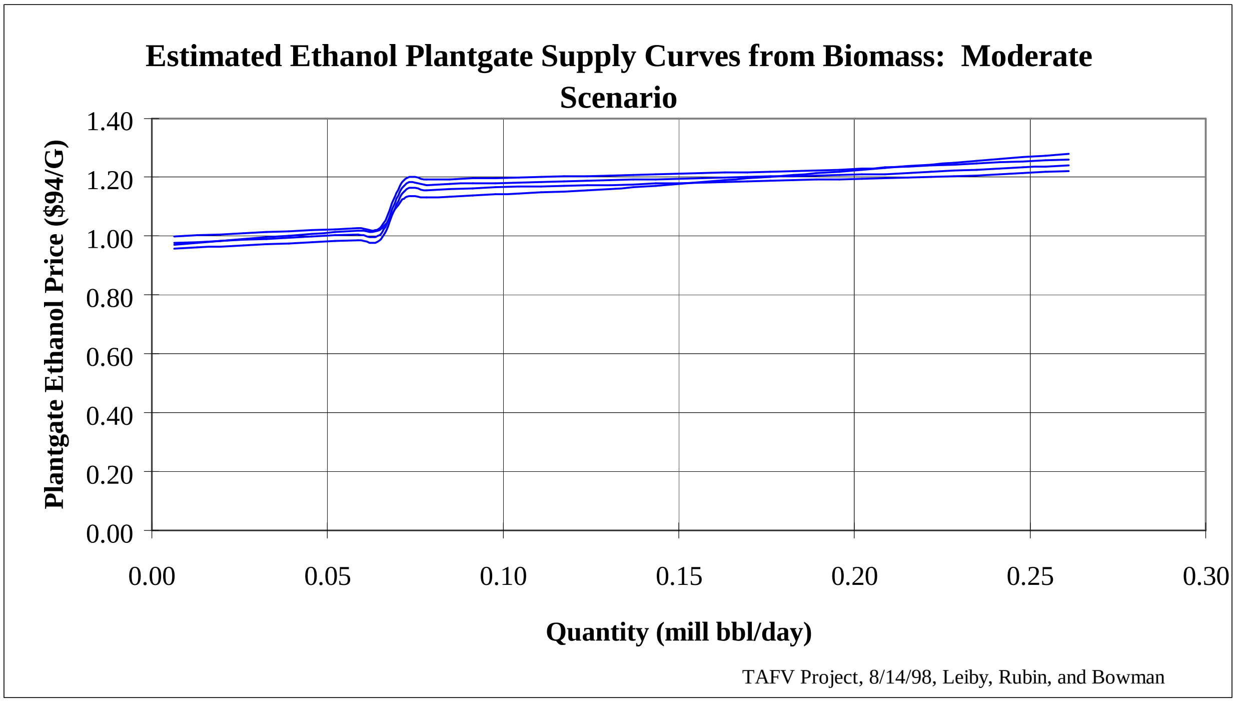
	2000	2005	2010	2015
New Wet Mill				
Intercept ($95/gal)	0.243	0.293	0.285	0.275
Slope	0.0615	0.0367	0.0371	0.0377
Transportation Costs ($95/gal)				
Conversion Costs ($95/gal)	0.920	0.905	0.890	0.880
Supply Limit (bill gals/yr)	2.0	2.0	2.0	2.0
Add-on Wet Mill				
Intercept ($95/gal)	0.243	0.293	0.285	0.275
Slope	0.0615	0.0367	0.0371	0.0377
Transportation Costs ($95/gal)				
Conversion Costs ($95/gal)	0.720	0.705	0.690	0.680
Supply Limit (bill gals/yr)	1.0	1.0	1.0	1.0
New Dry Mill				
Intercept ($95/gal)	0.377	0.46	0.464	0.468
Slope	0.0357	0.0387	0.0385	0.0385
Transportation Costs ($95/gal)				
Conversion Costs ($95/gal)	0.750	0.735	0.720	0.705
Supply Limit (bill gals/yr)	1.0	1.0	1.0	1.0

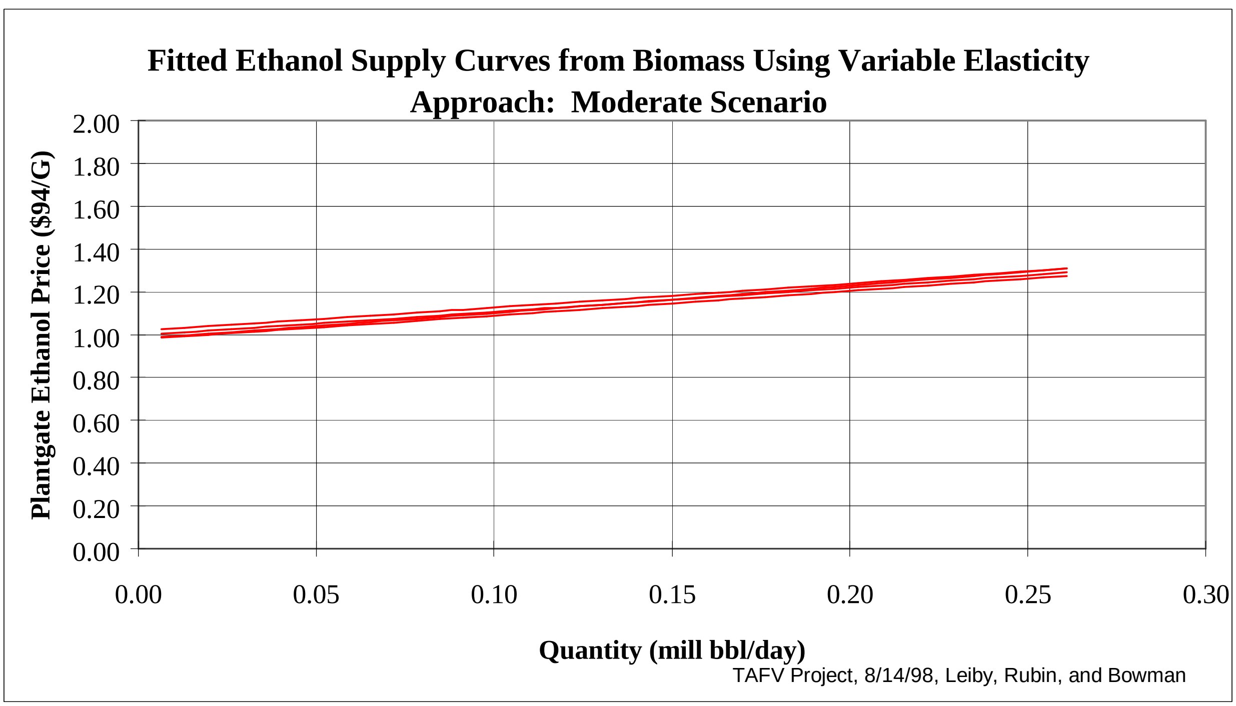
APPENDIX B

Result Graphs


Estimated Ethanol Plantgate Supply Curves from Biomass: Moderate Scenario
Plantgate Ethanol Price ($94/G)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2000
2005
2010
2015
0.00
0.50
1.00
1.50
2.00
2.50
Quantity (mill bbl/day)
TAFV Project, 8/14/98, Leiby, Rubin, and Bowman


Fitted Ethanol Supply Curves from Biomass Using Variable Elasticity Approach: Moderate Scenario
Plantgate Ethanol Price ($94/G)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2000
2005
2010
2015
0.00
0.50
1.00
1.50
2.00
2.50
Quantity (mill bbl/day)
TAFV Project, 8/14/98, Leiby, Rubin, and Bowman


Estimated Ethanol Plantgate Supply Curves from Biomass: Moderate Scenario
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Plantgate Ethanol Price ($94/G)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Quantity (mill bbl/day)
TAFV Project, 8/14/98, Leiby, Rubin, and Bowman


Fitted Ethanol Supply Curves from Biomass Using Variable Elasticity Approach: Moderate Scenario
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Plantgate Ethanol Price ($94/G)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Quantity (mill bbl/day)
TAFV Project, 8/14/98, Leiby, Rubin, and Bowman

APPENDIX C

Model Source Code

```
Moderate Scenario
$INLINECOM{ }
OPTION SOLPRINT =  ON;
OPTION LIMCOL = 50;
OPTION LIMROW = 50;

*SETS    N       Total 2000 Quantity {millions}    /1*162/
*SETS    N       Total 2005 Quantity {millions}    /1*205/
*SETS    N       Total 2010 Quantity {millions}    /1*270/
SETS    N       Total 2015 Quantity {millions}    /1*334/

*SETS    N       Corn  2000 Quantity {millions}    /1*40/
*SETS    N       Corn  2005 Quantity {millions}    /1*40/
*SETS    N       Corn  2010 Quantity {millions}    /1*40/
*SETS    N       Corn  2015 Quantity {millions}    /1*40/


*SETS    N       Trees 2000 Quantity {millions}    /1*182/
*SETS    N       Trees 2005 Quantity {millions}    /1*203/
*SETS    N       Trees 2010 Quantity {millions}    /1*253/
*SETS    N       Trees 2015 Quantity {millions}    /1*290/
*SETS    N       AGSG  2000 Quantity {millions}    /1*114/
*SETS    N       AGSG  2005 Quantity {millions}    /1*139/
*SETS    N       AGSG  2010 Quantity {millions}    /1*177/
*SETS    N       AGSG  2015 Quantity {millions}    /1*208/

        F       Feedstocks       / CornNWM,
                                   CornAWM,
                                   CornNDM,
                                   SRWC,
                                   Sgrass,
                                   AgRes,
                                   Hwoods,
                                   Swoods,
                                   RDF /

        Fsub(F) Feedstock subset / SRWC,
                                   Sgrass,
                                   AgRes,
                                   Hwoods,
                                   Swoods,
                                   RDF /
```

```
        T       Year              /  FY2000,
                                     FY2005,
                                     FY2010,
                                     FY2015 /

        Tsub(T) Year subset       /  FY2015 /;

TABLE  ALPHA(F,T)  Feedstock Supply Intercept

            FY2000         FY2005       FY2010       FY2015
CornNWM      0.243          0.293        0.285        0.275
CornAWM      0.243          0.293        0.285        0.275
CornNDM      0.377          0.460        0.464        0.468
SRWC        100000         39.658       38.619       37.941
Sgrass      29.761         30.542       31.966       33.558
AgRes       27.310         28.470       29.760       30.870
Hwoods      22.460         24.200       26.070       28.090
Swoods      27.300         29.590       31.940       34.380
RDF         26.612         28.669       30.885       33.272


TABLE TRANS(F,T) Transportation Costs

            FY2000         FY2005       FY2010       FY2015
CornNWM     0.028          0.024        0.024        0.024
CornAWM     0.028          0.024        0.024        0.024
CornNDM     0.027          0.023        0.023        0.023
SRWC        5.000          5.000        5.000        5.000
Sgrass      5.000          5.000        5.000        5.000
AgRes       5.000          5.000        5.000        5.000
Hwoods      0.000          0.000        0.000        0.000
Swoods      0.000          0.000        0.000        0.000
RDF         5.000          5.000        5.000        5.000

TABLE   BETA(F,T)      Feedstock Supply Slope

            FY2000         FY2005       FY2010       FY2015
```

CornNWM	0.0000615	0.0000367	0.0000371	0.0000377
CornAWM	0.0000615	0.0000367	0.0000371	0.0000377
CornNDM	0.0000357	0.0000387	0.0000385	0.0000385
SRWC	0.0000000	0.3786000	0.2248000	0.1945000
Sgrass	0.0303000	0.0299000	0.0268000	0.0251000
AgRes	0.0970000	0.0770000	0.0650000	0.0570000
Hwoods	1.8200000	1.9200000	2.0300000	2.1700000
Swoods	4.0900000	4.1800000	4.4300000	4.5700000
RDF	0.7916051	0.8527835	0.9186900	0.9896901

TABLE PG(F,T) Plantgate price woFS and trans

	FY2000	FY2005	FY2010	FY2015
CornNWM	0.920	0.905	0.890	0.880
CornAWM	0.720	0.705	0.690	0.680
CornNDM	0.750	0.735	0.720	0.705
SRWC	0.843	0.709	0.575	0.460
Sgrass	0.843	0.709	0.575	0.460
AgRes	0.843	0.709	0.575	0.460
Hwoods	0.843	0.709	0.575	0.460
Swoods	0.843	0.709	0.575	0.460
RDF	0.843	0.709	0.575	0.460

TABLE CR(F,T) Conversion Rate

	FY2000	FY2005	FY2010	FY2015
CornNWM	1.00000	1.00000	1.00000	1.00000
CornAWM	1.00000	1.00000	1.00000	1.00000
CornNDM	1.00000	1.00000	1.00000	1.00000
SRWC	0.01099	0.01031	0.00877	0.00847
Sgrass	0.01235	0.01111	0.01000	0.00971
AgRes	0.01235	0.01111	0.01000	0.00971
Hwoods	0.01099	0.01031	0.00877	0.00847
Swoods	0.01099	0.01031	0.00877	0.00847
RDF	0.01429	0.01111	0.01000	0.00971

TABLE UB(F,T) Upper bounds on gallons of ethanol output

	FY2000	FY2005	FY2010	FY2015

```
CornNWM      2000          2000          2000        2000
CornAWM      1000          1000          1000        1000
CornNDM      1000          1000          1000        1000
SRWC            0           485          1824        3894
Sgrass        243           810          1900        3605
AgRes       11664         14490         17700       19982
Hwoods       2871          3131          3752        3909
Swoods       1431          1604          1916        2070
RDF             0             0             0           0

*Total with corn
*           20209       24520       31092       37460

*Total without corn
*           16209       20520       27092       33460



PARAMETER   QTSUM(N)   Quantity of Total Feedstock
;

QTSUM(N) = ORD(N)*100
*QTSUM(N) = ORD(N)*500/CARD(N);
*QTSUM(N)=ORD(N);

POSITIVE VARIABLES
            Q(N,Fsub,Tsub)           Quantity
                    ;
VARIABLES
            COST                Total Supply and Conversion Cost
;

EQUATIONS   QEQ(N)               Total Quantity Constraint
            COSTEQ               Total Cost Equation;


QEQ(N)..          QTSUM(N) =E= SUM((Fsub,Tsub) , Q(N,Fsub,Tsub));

COSTEQ..
    COST =E= SUM((N,Fsub,Tsub),
        (ALPHA(Fsub,Tsub) + TRANS(Fsub, Tsub) +
BETA(Fsub,Tsub)*Q(N,Fsub,Tsub)*CR(Fsub,Tsub)/2)*CR(Fsub,Tsub)*Q(N
,Fsub,Tsub)
       + PG(Fsub,Tsub)*Q(N,Fsub,Tsub) ) ;
```

```
Q.up(N,Fsub,Tsub) = UB(Fsub,Tsub);

option iterlim = 99900;
option reslim = 99999;
option solprint = off;
option limrow = 0;
option limcol = 0;
model curves/all/;
curves.optfile= 1;

* Initialize values to equal share for each feedstock
*Q.L(N,FSub,Tsub) = QTSUM(N)/(CARD(FSub));
*Q.L(N,Fsub,Tsub) = 0;
DISPLAY Q.L;

solve curves minimizing COST using nlp;

DISPLAY QTSUM, Q.l;
```