Coupling Life-cycle Analysis with Supply Chain Optimization in Determining Biofuel Plant Size

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Objectives

- To develop a generic framework for determining the optimal biofuel plant size, feedstock supply radius, and production cost via cost minimization with inclusion of life-cycle GHG offset; and

- To demonstrate the applicability of the theoretical model using the case of bioethanol production in the U.S.

Presentation outline

- Importance of considering both GHG and biofuel production cost
- Theoretical derivation of the optimal biofuel plant size, feedstock supply radius, and production cost
- Empirical application: Bioethanol in the U.S.
  - Energy efficiency and GHG balance (life-cycle analysis results)
  - Ethanol plant size, feedstock supply radius, and production cost

Need for integrating GHG with biofuel production cost

- GHG offset is one of the key drivers/expectations of biofuels. Yet, GHG offset potential differs across biofuels and is highly debatable.

- Example: Recent publications in *Science*
  - Seachinger et al. Use of U.S. cropland for biofuels increases greenhouse gases through emissions from land use change*. Science* 2008; 319:1238-1240.
  - Kennedy, D. The bioenergy conundrum. *Science* 2007; 316:515.

Biofuel production cost and GHG offset

- Total production cost = feedstock cost + conversion cost
- Counting GHG offset benefits could improve the cost-competitiveness of biofuels that generate a positive offset.
- Feedstock transport cost, feedstock-to-biofuel conversion cost, and GHG offset potential could be sensitive to the scale of a conversion plant.

Scale vs. Radius vs. Cost & GHG

Scale (S) ↑

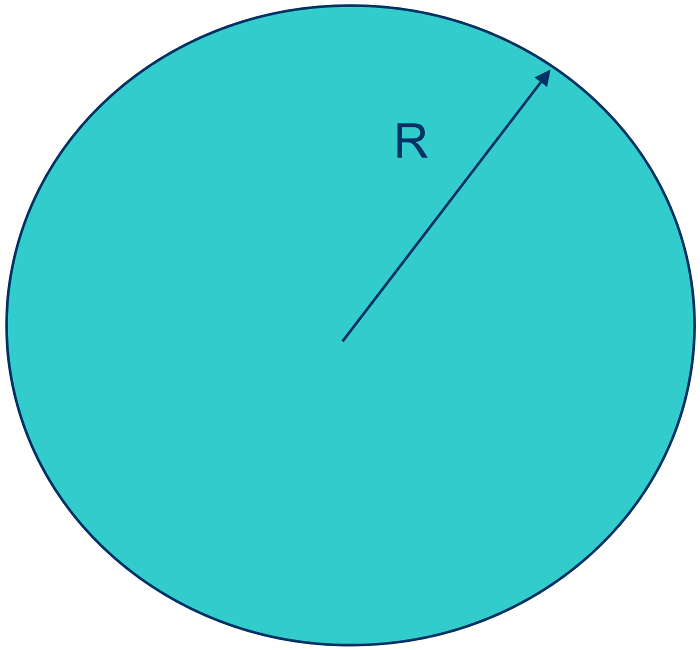
⇨

Feedstock supply radius (R) ↑

⇨

Biofuel production cost

& GHG offset ↓↑



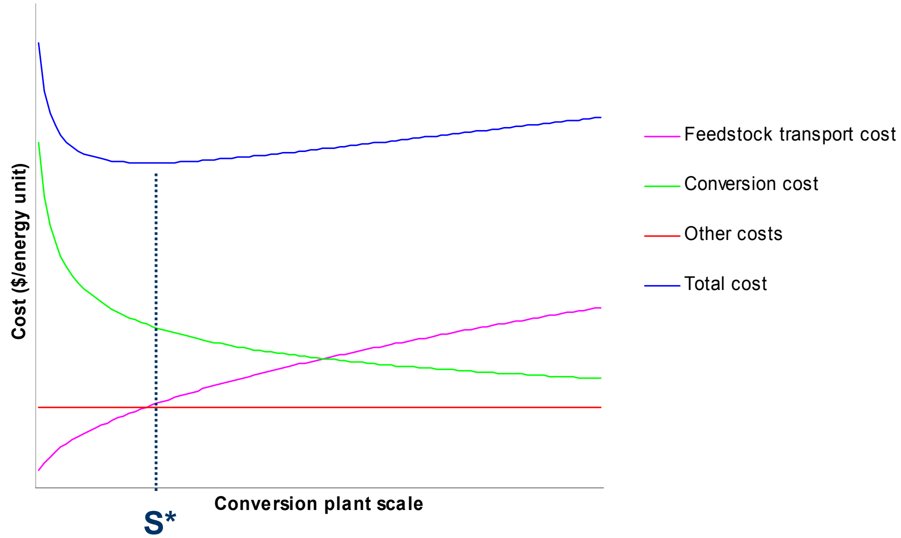
Biofuel production cost/GHG emissions vs. plant scale

- Scale ↑ ⇨ per-unit conversion cost ↓
  ⇨ GHG emissions per unit biofuel from conversion ↓

- Scale ↑ ⇨ Transport distance and per-unit transport cost ↑
  GHG emissions per unit biofuel from feedstock transport ↑

Thus, there exists an optimal conversion plant scale that minimizes (a) the per-unit cost of feedstock and conversion and (b) associated GHG emissions, and subsequently determines the optimal feedstock supply radius.

Biofuel production cost/GHG emissions vs. plant scale



S* = the optimal conversion plant scale, which minimizes the total per-unit cost of biofuel.

Total cost = Feedstock transport cost + Biomass-to-biofuel conversion cost + Other costs

Obviously, the decision on plant size based on minimizing the total cost is different from that based on minimizing feedstock cost or conversion cost. The same is true for GHG offset.

Derivation of the optimal biofuel plant scale

$$\underset{S}{Min}\, TC(S) = FSC(S) + CC(S) - P_c NCO(S) + FC$$

where

S = the scale of the conversion plant

TC = the total production cost less GHG offset credit (per unit biofuel)

FSC = the cost of delivered feedstock

CC = the cost of converting feedstock to biofuel products

P_c = the price of GHG emissions offset

NCO = net GHG (CO_2 equivalent) offset

FC = fixed costs

Biomass transportation work (BTW)

$$BTW = \int_0^R \frac{100\phi M(1+\lambda) r\tau \times 2\pi r dr}{n} = 209.44 \frac{\tau\phi M(1+\lambda)R^3}{n} \quad (t\ km)$$

where

R = the radius of the biomass supply circle (km)

1/n = the fraction of the circle that is harvested for biomass

ϕ = the proportion of the land where biomass is grown in the circular area

M = the spatial distribution density of biomass (bdt/ha)

λ = the moisture content of biomass

τ = the tortuosity factor (ratio of actual distance traveled to sight distance) of roads

Required land area (A_1) to meet annual feedstock need of the plant with capacity S

$$A_1 = \frac{365\,(days) \times 24\,(hours)\,\theta S}{100 M \phi \varepsilon \eta} \quad (km^2)$$

where

θ = the conversion plant factor (operation rate)

ε = the energy content of biomass (energy unit/bdt)

η = the efficiency of the conversion plant

Area suitable for biomass harvest (A_2)

$$A_2 = \frac{\pi R^2}{n} \quad (km^2)$$

- Letting A1=A2, we get:

$$R = 5.28\sqrt{\frac{n\theta S}{M\phi\varepsilon\eta}} \quad (km)$$

The relationship between the supply radius (R) and the conversion plant scale (S)

Feedstock supply radius

According to

$$R = 5.28\sqrt{\frac{n\theta S}{M\phi\varepsilon\eta}} \quad (km),$$

the radius increases with

- an increase in plant scale, or plant operation rate;
- a decrease in feedstock spatial distribution density, energy content of feedstock, plant efficiency, or fragmentation of lands growing biomass.

Cost of transporting feedstock to meet one-hour operation of the plant

$$HC(S) = \frac{c_h \, BTW}{365\,(days) \times 24\,(hours)\, \theta S}$$

$$= 3.52\, c_h \tau (1+\lambda) \sqrt{\frac{n\theta S}{M\phi \varepsilon^3 \eta^3}} \quad (\$ \; per\ unit\ biofuel)$$

where

c_h is the cost per unit of biomass transportation work ($/t km).

Biofuel conversion cost

$$CC(S) = CC_o \left(\frac{S}{S_o} \right)^{\alpha - 1}$$

where

CC_o = the cost per unit of biofuel converted from biomass at a base scale (S_o) of the conversion plant;

α = the conversion plant scale factor ($0<\alpha<1$) (Note: The cost is more responsive to scale for a smaller α).

GHG offset

$$NCO(S) = a - bBTW_1 - e_o \left(\frac{S}{S_o} \right)^{\alpha - 1}$$

where

a = GHG emissions per unit of fuel to be displaced

b = GHG emissions from feedstock production/transport (per unit biofuel)

BTW1 = Biomass transport work for producing one unit of biofuel

e_o = GHG emissions per unit of biofuel converted from biomass at the base plant scale (S_o)

α = the conversion plant scale factor ($0<\alpha<1$).

Total cost

$$\underset{S}{Min}\, TC = 3.52\,\tau(1+\lambda)(c_h + bP_c)\sqrt{\frac{n\theta S}{M\phi\varepsilon^3\eta^3}} + (CC_o + e_o P_c)\left(\frac{S}{S_o}\right)^{\alpha-1} - aP_c + FC$$

Solving this problem will derive S*, the optimal conversion plant size.

Optimal conversion plant size

$$S^* = \left[1.76 \frac{\tau(1+\lambda)(c_h + bP_c)}{(1-\alpha)(CC_o + e_o P_c) S_o^{1-\alpha}} \sqrt{\frac{n\theta}{M\phi\varepsilon^3\eta^3}} \right]^{\frac{2}{2\alpha-3}}$$

For $0<\alpha<1$,
S^* increases with a decrease in c_h, b, τ, λ, n, and θ or an increase in ε, ϕ, η, M, CC_o, and e_o.

S^* increases (decreases) with an increase P_c, if $c_h e_o$ >(<) bCC_o.

Optimal feedstock supply radius

$$R^* = 5.28\left[1.76\,\frac{\tau(1+\lambda)(c_h + bP_c)}{(1-\alpha)(CC_o + e_oP_c)\varepsilon^{\alpha}\eta^{\alpha}}\left(\frac{M\phi}{n\theta S_o}\right)^{1-\alpha}\right]^{\frac{1}{2\alpha-3}} \quad (km)$$

For $0<\alpha<1$,

R^* increases with a decrease in c_h, b, τ, λ, M, and ϕ or an increase in ε, η, n, θ, CC_o, and e_o.

R^* increases (decreases) with a increase P_c, if c_he_o >(<) bCC_o.

Biofuel production cost

$$TC^{*} = \frac{3-2\alpha}{1-\alpha}\left\{\frac{1.76\left[\tau(1+\lambda)(c_h + bP_c)\sqrt{\frac{n\theta S_o}{M\phi\varepsilon^3\eta^3}}\right]^{2(\alpha-1)}}{(1-\alpha)(CC_o + e_o P_c)}\right\}^{\frac{1}{2\alpha-3}} - aP_c + FC$$

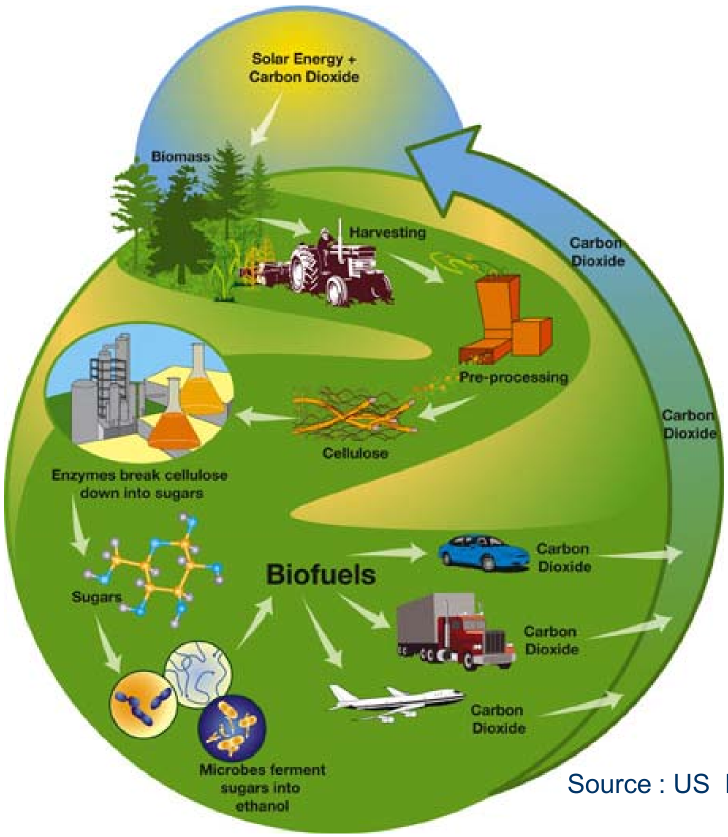
For $0<\alpha<1$,

TC^{*} increases with an increase in τ, λ, c_h, b, n, θ, CC_o, and e_o or a decrease in M, ϕ , ε, η, and P_c.

Elasticity comparisons with and without considering GHG offset

Factor	Plant Scale	Feedstock supply radius	Production cost
c_h	2/(2α-3) < 0 (↓)	1/(2α-3) < 0 (↓)	2(α -1)/(2α-3) > 0 (↓)
τ, (1+ λ)	2/(2α-3) < 0 (0)	1/(2α-3) < 0 (0)	2(α -1)/(2α-3) > 0 (0)
CC_o	-2/(2α-3) > 0 (↓)	-1/(2α-3) > 0 (↓)	-1/(2α-3) > 0 (↓)
n, θ	1/(2α-3) < 0 (0)	(α -1)/(2α-3) > 0 (0)	(α -1)/(2α-3) > 0 (0)
M, Φ	-1/(2α-3) > 0 (0)	(1- α)/(2α-3) < 0 (0)	(1- α)/(2α-3) < 0 (0)
ε, η	-3/(2α-3) > 0 (0)	- α/(2α-3) > 0 (0)	3(1-α)/(2α-3) < 0 (0)

Application: Bioethanol in the U.S.



Source : US DOE

Why ethanol?

- The nation's need
- Technology evolves

Well-to-pump energy efficiency and fossil fuel use (GREET simulation results, bioethanol)

Fuel type	Energy efficiency (%)	Fossil fuel use (MJ/MJ fuel available at pumps)
Forest residues	52.1	0.235
Woody biomass	45.8	0.061
Corn	46.0	0.627
Corn stover	52.7	0.145
Switchgrass	51.0	0.135
Sugar cane	50.2	0.180
Diesel	84.9	0.175
Gasoline	81.1	0.214

Well-to-wheel GHG (CO_2 equivalent) emissions (GREET simulation results, bioethanol)

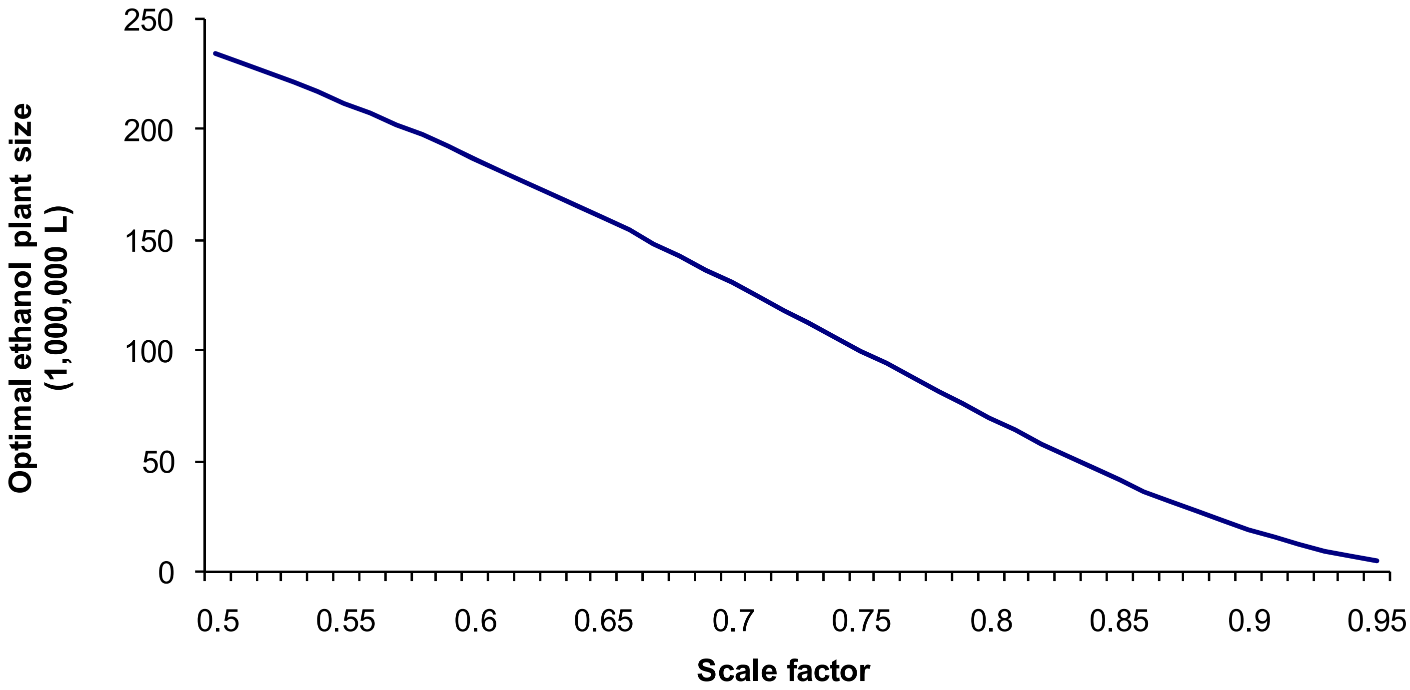
Fuel type	Feedstock (g/MJ)	Fuel conversion (g/MJ)	Vehicle operation (g/MJ)	Total (g/MJ)	% change in net GHGs vs. gasoline
Forest residues	-41	9	72	41	-55
Woody biomass	-57	9	72	25	-73
Corn	-31	36	72	78	-15
Corn stover	-46	9	72	36	-61
Switchgrass	-41	9	72	40	-56
Sugar cane	-35	9	72	47	-49
Diesel	5	9	67	81	-12
Gasoline	4	14	74	92	0

ϕ

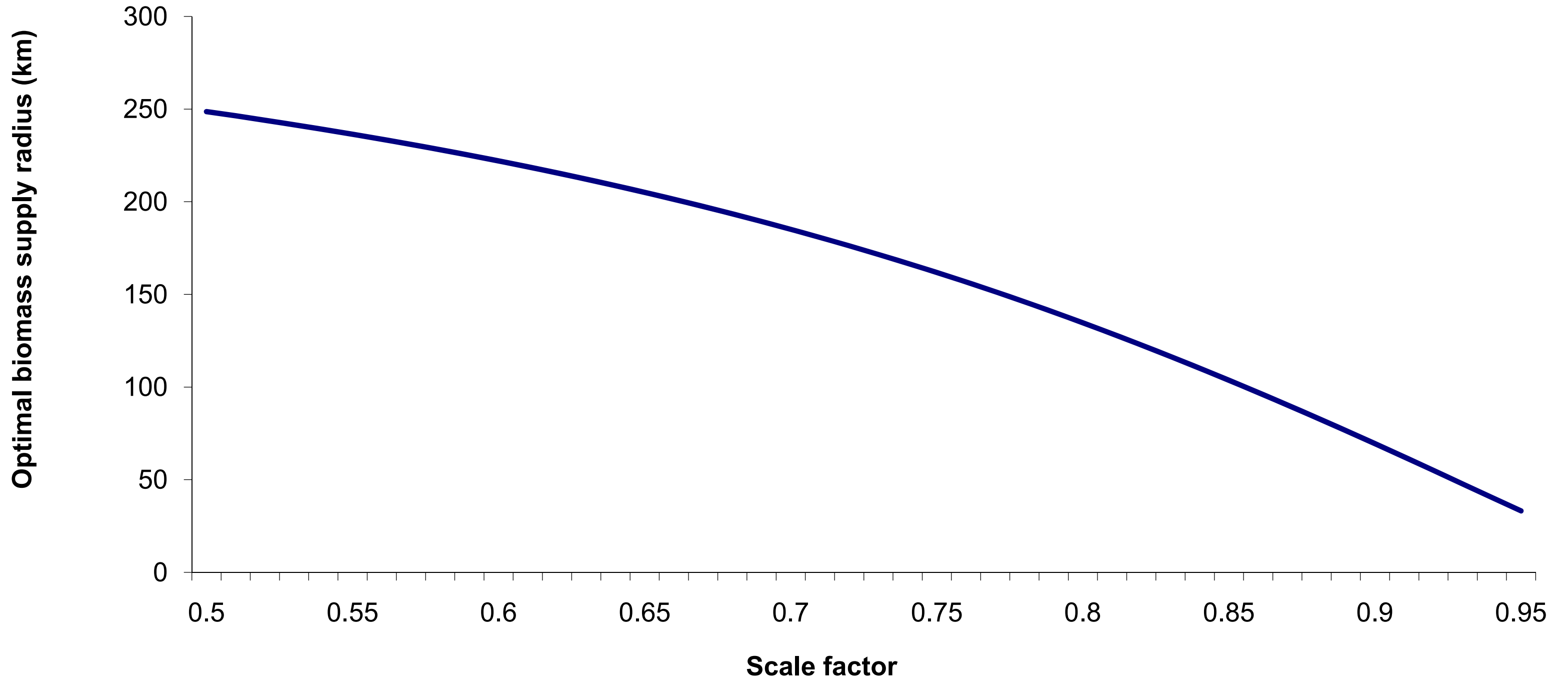
Coefficient values used in simulations

Coefficient	Description	Value
Φ	Proportion of the land where biomass is grown	0.30
λ	Moisture content of biomass (wet base)	0.45
M	Spatial distribution density of annually available biomass (based on the total area used to grow biomass)	0.50 bdt ha^{-1}
1/n	Fraction of a circle where biomass can be harvested	1/4
τ	Tortuosity factor of the road system	1.50
θ	Conversion plant factor (operation rate)	0.90
ε	Energy content of biomass	19 GJ bdt^{-1}
η	Efficiency of converting feedstock to biofuel	285 L bdt^{-1}
c_h	Cost per unit of biomass transportation work	\$0.20 t^{-1} km^{-1}
S_o	Base scale of the conversion plant	50×10^6 L
CC_o	Per unit feedstock-to-energy conversion cost at the base scale of the conversion plant	\$0.35 L^{-1}
α	Conversion plant scale factor	0.6~0.9
b	GHG emissions (CO_2 equivalent) from transporting the amount of biomass needed to produce one liter of ethanol for one km	1.41 g
e_o	GHG emissions (CO_2 equivalent) from converting biomass to produce one liter of ethanol	191 g
P_c	CO_2 price	\$25 t^{-1}

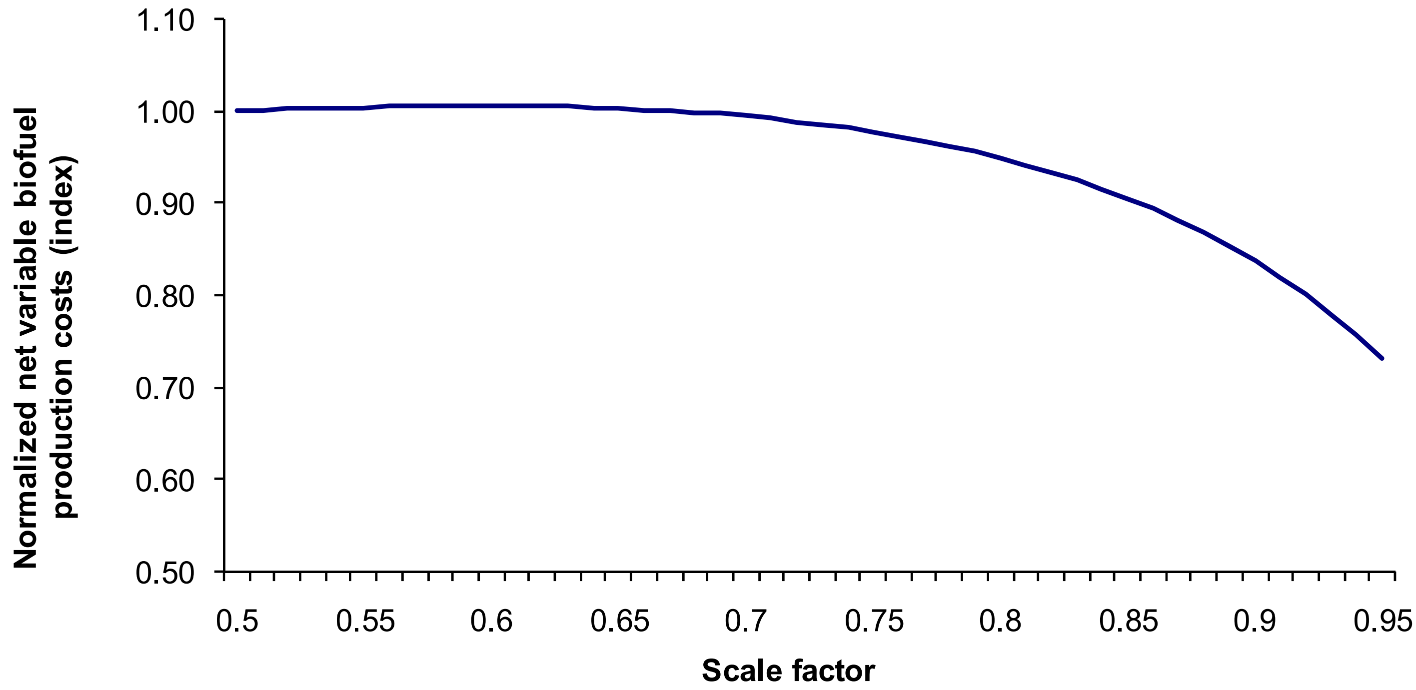
Optimal plant size vs. scale factor



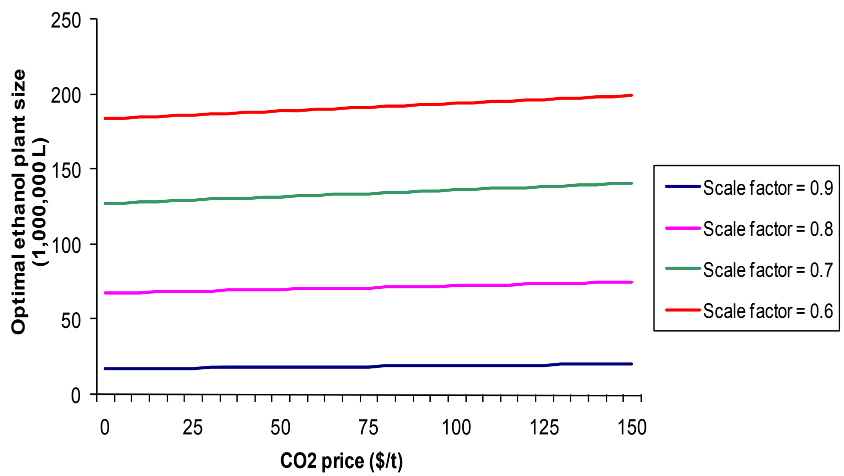
Optimal feedstock supply radius vs. scale factor

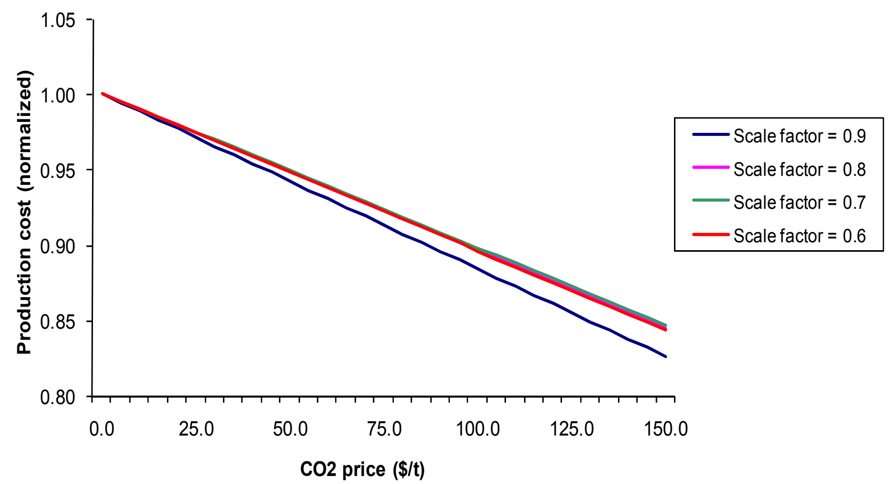


Variable ethanol production cost vs. scale factor



Ethanol plant size and production cost vs. CO_2 price and scale factor





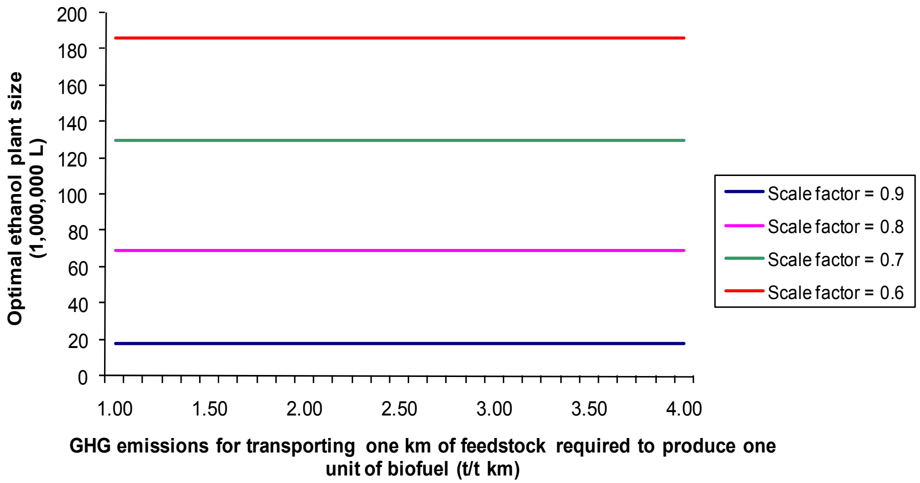
Plant size vs. CO_2 price

Production cost vs. CO_2 price

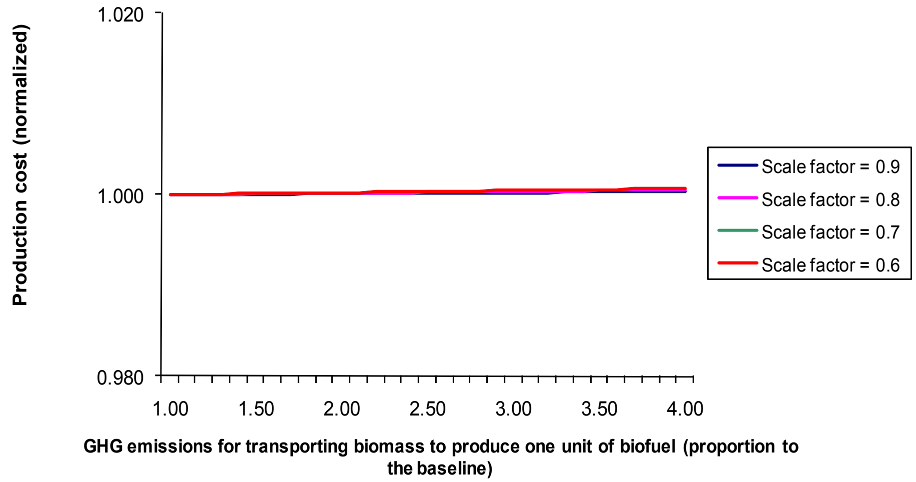
Plant size increases but production cost decreases as the CO_2 price goes up. Ethanol production cost is highly and more sensitive to CO_2 price changes than plant size.

Plant size is more irresponsive to scale factor changes than ethanol production cost.

Ethanol plant size and production cost vs. GHG emissions from feedstock transport and scale factor



Plant size vs. GHG emissions from feedstock transport

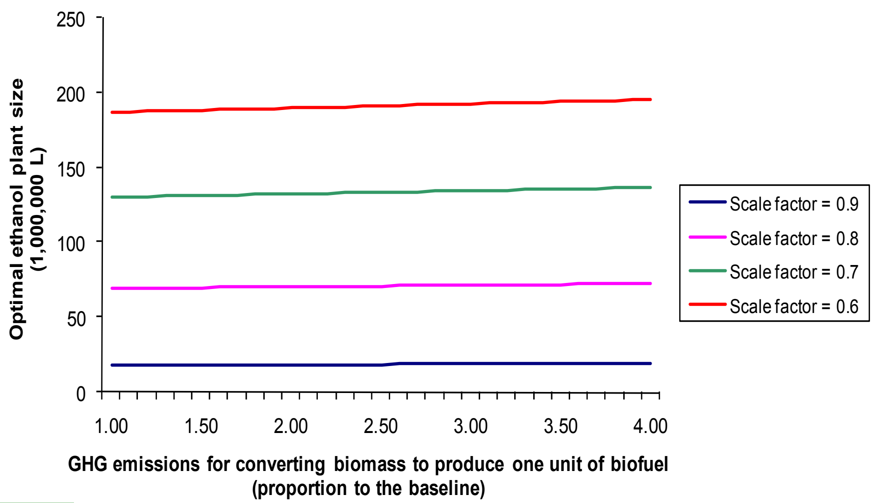


Production cost vs. GHG emissions from feedstock transport

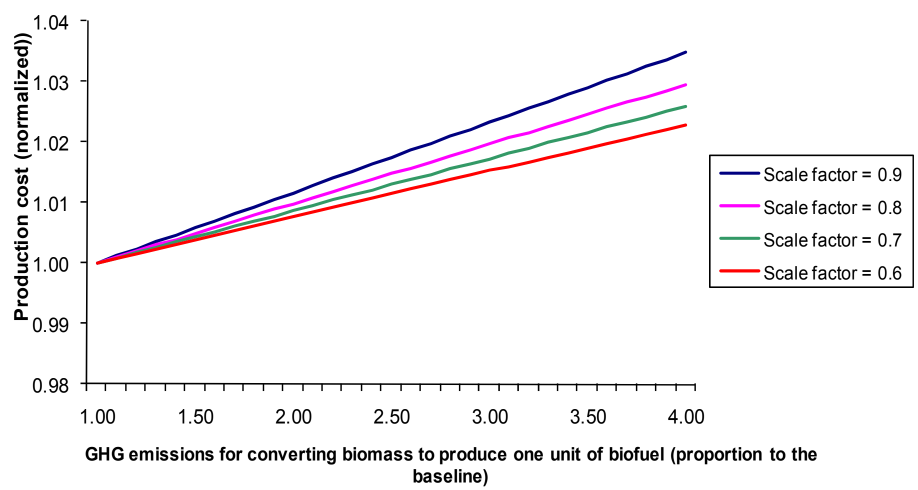
Ethanol plant size and production cost are relatively irresponsive to changes in GHG emissions from feedstock transport.

Plant size is more responsive to scale factor changes than ethanol production cost.

Ethanol plant size and production cost vs. GHG emissions from ethanol conversion and scale factor



Plant size vs. GHG emissions from feedstock-to-ethanol conversion



Production cost vs. GHG emissions from feedstock-to-ethanol conversion

Ethanol plant size and production cost increase slightly with GHG emissions from ethanol conversion.

Plan size is more responsive to GHG emissions from ethanol conversion than production cost.

Conclusions

- Biofuel plant size (S*) and feedstock supply radius (R*) should increase as
  - biomass moisture content, tortuosity factor, and feedstock transport cost decrease;
  - biomass energy content, conversion efficiency, and conversion cost increase;
  - GHG offset potential is accounted for;
  - GHG emissions from feedstock transport decrease; and
  - GHG emissions from ethanol production increase.

Conclusions (cont'd)

- Biofuel production cost (TC*, cost less C benefits) increases as
  - biomass moisture content, tortuosity factor, and land fragmentation increase;
  - biomass spatial distribution density, energy content, and conversion efficiency decrease;
  - GHG emissions from feedstock transport and ethanol production increase; and
  - GHG price decreases (assume the biofuel offers a positive GHG offset).

Conclusions (cont'd)

- Incorporating GHG offset would not dramatically alter S* and R* because $c_h >> bp_c$ and $CC_o >> e_o P_c$.
- Biofuel production cost is more responsive to a change in the GHG price than the optimal plant size and feedstock supply radius.
- S*, R*, and TC* become less sensitive to changes in feedstock transport cost and feedstock-to-biofuel conversion cost with accounting for GHG offset.

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Thanks

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