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A criterion for selecting renewable energy processes

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ABSTRACT

We propose that minimum incremental cost per unit of greenhouse gas (GHG) reduction, in essence the carbon credit required to economically sustain a renewable energy plant, is the most appropriate social criterion for choosing from a myriad of alternatives. The application of this criterion is illustrated for four processing alternatives for straw/corn stover: production of power by direct combustion and biomass integrated gasification and combined cycle (BIGCC), and production of transportation fuel via lignocellulosic ethanol and Fischer Tropsch (FT) syndiesel. Ethanol requires a lower carbon credit than FT, and direct combustion a lower credit than BIGCC. For comparing processes that make a different form of end use energy, in this study ethanol vs. electrical power via direct combustion, the lowest carbon credit depends on the relative values of the two energy forms. When power is 70\$ MW h^{-1}, ethanol production has a lower required carbon credit at oil prices greater than 600\$ t^{-1} (80\$ bbl^{-1}).

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1. Introduction

Any society wishing to implement an increased share of renewable or low carbon energy to reduce the emission of greenhouse gases (GHG) faces a multitude of choices. Wind, solar and biomass, for example, are available as primary energy sources. Biomass in turn is available in numerous forms that include varieties of animal manures, agricultural and forest residues, and purpose grown crops. Biomass can be turned into electricity via direct combustion with a conventional steam cycle, or by integrated biomass gasification with air and a combined cycle power plant (BIGCC). It can also be turned into transportation fuel as lignocellulosic ethanol or as a syndiesel by oxygen gasification followed by the Fischer Tropsch (FT) reaction.

One response to the huge number of choices of renewable energy is an approach of "let's try everything". This approach often includes arbitrary targets that have no supporting economic analysis. Thus in Europe straw, an agricultural residue that is scarce relative to major grain growing regions of the globe, is intended as a feedstock for both ethanol and power generation [1]. Canada has adopted a target of 5% biomass ethanol in gasoline by the year 2012 with no analysis of the cost of this relative to alternate uses for grain and straw/corn stover, e.g. power production [2].

In the demonstration/early adoption stage of renewable energy "let's try everything" has minimal economic impact, because the fraction of energy derived from renewable sources is very small compared to the total energy used. Selecting the right technology becomes increasingly critical as the adoption of renewable energy grows. In this study we illustrate a criterion for making the best social choice of a renewable energy technology.

Most forms of renewable energy have a higher cost than a fossil fuel alternative, and this is precisely why fossil fuels grew to dominate much of the world's energy supply. Substitution of a renewable energy thus typically requires the integration of a higher cost source of energy into an existing

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energy economy. The three primary mechanisms for doing this are direct subsidy, mandated substitution, or emission caps that force producers to develop or purchase renewable offsets. The taxpayer pays for the first of these; the consumer pays directly for the second and indirectly for the third. Regardless of the choice of mechanism, there is a cost to society for the adoption of more expensive forms of energy. In most of the world the primary cited benefit from the adoption of renewable energy is the reduction in the risk of climate change due to the accumulation of GHG. (Independence from fossil fuel imports gets some weighting as a benefit, particularly in the United States, as discussed further below.) By applying weighting factors to various emissions [3] one can evaluate the reduction in GHG as a CO_2 equivalency.

In rare cases renewable energy has a lower cost than the fossil fuel it is replacing. One example is the use of biomass to generate power in remote communities in areas such as northern Canada, where the alternative is from diesel fuel transported by truck or plane. A second example could be lignocellulosic ethanol if the price of oil returns to and remains at the high prices experienced in the summer of 2008. When a renewable energy is more economic than fossil fuel traditional means of analyzing investment decisions, e.g. using net present value (NPV) and internal rate of return (IRR) are appropriate, since no social payment is required.

In the more frequent case that renewable energy is more expensive than fossil fuel, we suggest that the right criterion for selecting a technology is the lowest incremental cost per unit of reduction in GHG emissions. Calculation of this value requires both an economic and emissions assessment of a renewable energy source relative to the currently available fossil fuel choice. Application of this criterion will ensure that the most GHG reduction is being purchased per unit of social investment in energy. Failure to apply this criterion runs the risk of dissipating available social spending resources for less than optimum benefit.

In this study we illustrate the application of this criterion for one biomass resource, agricultural residues using straw/corn stover as an example, that can be processed to two different forms of usable energy, electrical power and transportation fuel, by the four processes discussed above, and we discuss the more general application of the criterion across all forms of renewable energy.

2. Methodology

Straw and corn stover are agricultural residues that are abundantly available in some regions, e.g. the corn belt in the central U.S. and the grain belt in western North America and the Ukraine. Straw/stover is produced annually and can be put into large bales for transport by truck over existing roads. This study draws on two previous studies of the cost of processing straw and the reduction in life cycle emissions from straw in a western North American setting [4,5]. Transportation cost is affected by trucking cost and distance. Truck shipment cost is drawn from Kumar et al. [6], adjusted (as with all costs in this work) to 2006 US$. Transportation distance for a given size of processing plant is set by the availability of biomass within a general region, i.e. how much biomass per overall ha occurs in a region, and what fraction of that biomass would be available to a biomass processing plant. Our assumed availability of 0.21 t ha^{-1} corresponds to a 25% availability of corn stover in the U.S. Midwest corn belt [7] and a 50% availability of straw in a western North American grain region [6]. Table 1 lists the properties of straw/stover and transportation cost factors used in this study.

All processing of field sourced biomass has competing cost factors: as plant size increases, the draw area from which biomass must be transported (and hence the cost of transportation) increases, while the processing cost per unit of throughput (plant operating cost and capital recovery) decreases. Competition between these cost factors leads to an optimum size for such plants at which total cost of produced energy is minimized [4,6,9–14]. In a prior study [4] we reported that acceptance of a product cost 3% above the theoretical minimum results in a plant size about half the optimum size, and that plant sizes below this level have a rapidly rising cost of production. Actual renewable energy projects would likely be developed at less than optimum size to reduce the amount of capital at risk. All plant sizes in this study are set at a size that gives a production cost 3% above the minimum.

A prior study [4] analyzed the yield and production cost for processing of straw/stover as a function of plant size for the four technologies discussed above. Values of plant size, biomass draw area, transportation cost, yield, processing cost and total production cost are summarized in Table 2. Costs incorporate both operating and capital recovery. An actual biomass plant would have a mix of debt and equity financing, with the equity portion likely requiring an after tax return of 10–15%. In this study we use a 12% pre-tax return on total capital as a proxy for the blend of debt and equity an actual plant would utilize. We note that the four processing alternatives are at different levels of development: power generation from biomass by direct combustion operates at a large commercial scale today [15], and six commercial scale lignocellulosic ethanol plants are under construction in the United States [16], whereas BIGCC and FT synthesis from biomass have not yet been reported as operating at a demonstration scale. Hence the cost values in Table 2 are subject to change over time as the quality and detail of cost estimates increases.

A second prior study [5] evaluated life cycle emissions for the four straw/stover processes relative to the future fossil fuel processes they would displace in a North American

Table 1 – Straw/stover properties and transportation cost factors [4].

Moisture Content	15	%
Hydrogen content	5.46	wt%
Bulk density	140	dry kg m^{-3}
HHV, dry basis	18	MJ kg^{-1}
LHV	13.9	MJ kg^{-1}
Transport form	Bale	
Distance fixed cost	4.39	\$ t^{-1}
Distance variable cost	0.12	\$ t^{-1} km^{-1}

[a]Basis one way driving distance .

Table 2 – Size, yield and cost factors for four processing alternatives for straw/stover.

	Ethanol	FT	Direct combustion	BIGCC
Optimum size (dry t d^{-1})	6750	12 750	4375	11 000
Plant size[a] (dry t d^{-1})	3250	6250	2750	5250
Draw area (km^2)	51 330	98 710	43 430	82 915
Transport cost	0.10\$ L^{-1}	0.19\$ L^{-1}	18.0 \$MW h^{-1}	18.4\$ MW h^{-1}
Processing cost[b]	1.4 $x^{-0.3}$	3.0 $x^{-0.3}$	151 $x^{-0.3}$	297 $x^{-0.3}$
Processing cost	0.23\$ L^{-1}	0.48\$ L^{-1}	31.2\$ MW h^{-1}	47.0\$ MW h^{-1}
Total production cost	0.42\$ L^{-1}	0.79\$ L^{-1}	64.2\$ MW h^{-1}	77.2\$ MW h^{-1}

a Plant size at which production cost is 3% above theoretical minimum size, used in this study.
b "x" is plant capacity. Capacity of ethanol and FT production facilities are in dam^3 yr^{-1}(ML yr^{-1}). In the power cost formula, capacity is in gross MW gross; net power output is 92% of gross due to internal consumption.

setting: supercritical coal fired power generation and the production of gasoline and diesel from petroleum. Results are summarized in Table 3. The primary factor in the LCA impact of straw/stover processing arises from the displacement of the fossil fuel itself (emissions from processing are relatively small in comparison). Assumed conversion yield is a critical factor; as with cost, yield data for direct combustion and ethanol are far better established than for BIGCC and FT.

The amount of social payment, either price of product or subsidy, that is required to sustain a straw/stover processing plant, i.e. ensure a 12% pre-tax return on total capital investment, is a function of the value of the commodity it displaces. For example, as wholesale power price in a region or the wholesale price of gasoline or diesel increase, the economic gap between the cost of a renewable fuel and the alternative renewable energy from straw/stover decreases. We calculate the required subsidy of the straw/stover plant, the carbon credit, as a function of the market price of the produced energy:

$$\mathrm{CC},\ \$\,t^{-1}CO_2e = \frac{\mathrm{TPC},\ \$\,yr^{-1} - (\mathrm{PV},\ L\,yr^{-1}\ \mathrm{or}\ MWh\,yr^{-1})\left(\mathrm{UP}\ ,\ \$L^{-1}\ \ \mathrm{or}\ \ MW\,h^{-1}\right)}{\mathrm{AE},\ t\,yr^{-1}CO_2e}$$

where CC is the carbon credit, TPC is the total annual production cost, PV is the net annual production volume, UP is the unit price of the produced energy, and AE is the annual avoided emissions. The carbon credit is the payment that the straw/stover processing scheme requires to achieve a 12% pre-tax return on total capital. A negative value means that no social payment is required to sustain a renewable technology: it can compete with fossil fuels on its own.

3. Results

Fig. 1 shows the required carbon credit for using straw/stover to produce electricity as a function of wholesale electricity price. Based on cost data in this study a biomass direct combustion power plant would not require a social payment at a power price of 73.9\$ MW h^{-1} for direct combustion and 83.9\$ MWh^{-1} for BIGCC. At all power prices the carbon credit required to sustain a direct combustion power plant is less than that for BIGCC; this is a function of the gross availability of straw/stover. A previous study [4] noted that at a biomass cost in excess of 300\$ t^{-1} BIGCC would generate power at a lower total cost than direct combustion. Note, however, that this biomass cost would have a power production cost of about 175\$ MW h^{-1}, well in excess of current market values.

Table 3 – LCA emission reductions at plant size for four processing alternatives for straw/stover [5].

	Emissions of CO_2e from biomass conversion[a](g)	Emissions of CO_2e from conventional fuel production & consumption[b](g)	Avoided CO_2e emissions[c](g)	Avoided CO_2e emissions (g t^{-1} dry biomass input)
Ethanol[d]	−260 L^{-1}	2730 L^{-1}	2060 L^{-1}	650
FT	650 L^{-1}	3090 L^{-1}	2440 L^{-1}	540
Direct combust.	56 kW h^{-1}	886 kW h^{-1}	830 kW h^{-1}	1400
BIGCC	47 kW h^{-1}	886 kW h^{-1}	839 kW h^{-1}	1680

a Including biomass production, transport, and conversion to product.
b For ethanol, FT syndiesel, and the two power technologies, the conventional alternative is conventional petroleum gasoline, conventional petroleum diesel, and coal power, respectively.
c Avoided emissions L^{-1} or MW h^{-1} of the biomass-based alternative.
d Including credit for the sale of power. See ref. [5] for details.

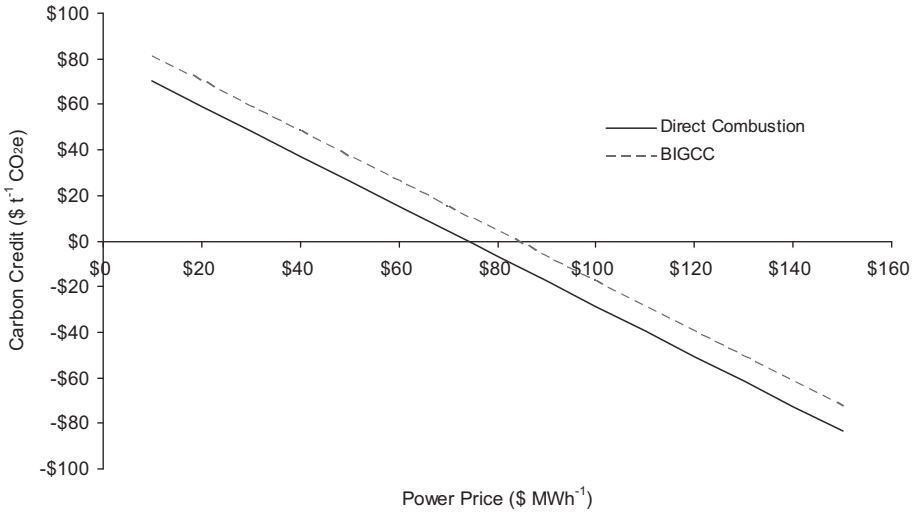

Fig. 1 – Carbon credit required for a 12% pre-tax return on total capital for four straw/stover power generation alternatives.

For the generation of a similar curve for the transportation fuels, it is useful to relate gasoline and diesel prices to the price of oil, although the relationship is confounded by other variables such as short-term supply and demand for each of the two transportation fuels. We relate oil price to gasoline and diesel price by two methods, illustrated in Fig. 2a and b. In the first, price data for oil, gasoline and diesel for the time period January 2005 to December 2007, drawn from the U.S. Energy Information Administration [17], is correlated. The best fit data over this time period gives a marginal value for gasoline (the slope) substantially in excess of that for diesel, which may reflect specific supply demand factors for the two fuels during the time period analyzed. In the second, we hold the gasoline line constant, fix the slope of the diesel regression curve to be proportional to the energy content of the two fuels, 32.0 MJ L^{-1} for gasoline and 36.4 MJ L^{-1} for diesel [18], and use a best fit technique to set the intercept.

We use the two relationships in Fig. 2a and b to determine the required carbon credit for the two transportation fuel alternatives as a function of oil price, shown in Fig. 3. Ethanol production is prorated to a gasoline equivalency based on an energy equivalency: 21.1 GJ L^{-1} of ethanol vs. 32.0 GJ L^{-1} for gasoline [18], based on the premise that vehicle distance traveled is proportional to energy content [19].

Note that the slope of the carbon credit required for power production by direct combustion and BIGCC is virtually identical, because the annual production volume per annual avoided emission is very close for the two processing technologies. This is a result of very low CO_2e emissions from the biomass processing, with the slight difference in this study between direct combustion and BIGCC arising from slightly different emissions from transportation of biomass [5]. The slope for producing gasoline and diesel is not identical because the LCA emissions avoided per unit of production are different for the two processes. For all power costs, at a gross availability of 0.21 t ha^{-1} dry basis the social payment required to support direct combustion and the power cost at which no social payment is required is lower than for BIGCC. At this availability of straw/stover, power via direct combustion has a lower social cost than BIGCC, and is the favored technology. For oil prices up to a range of 870–1350$ t^{-1} (115–180$ bbl^{-1}), depending on the correlation of oil price to gasoline and diesel price, the production of ethanol is favored over Fischer Tropsch production of diesel, for the same reason.

The selection between two processes that make different end products, in this study electricity and transportation fuel, depends on the relative pricing of the two products. Fig. 4 shows the line for oil and power price at which the calculated carbon credit for lignocellulosic ethanol and power production by direct combustion are equal. In the region above the line production of ethanol has a lower social cost, and below the line power production does. The energy prices at which no social subsidy is required are also identified. Fig. 4 also shows the approximate values of oil and power in North America for several time periods, showing that the selection of the end use form of energy to achieve a minimum social input per unit of avoided carbon dioxide would depend on relative energy pricing forecast far into the future.

4. Discussion

This study concludes that if the objective of a society is to reduce the accumulation of GHG in the atmosphere, then for straw/stover at availabilities expected in major grain and corn growing areas it is better to make electricity by direct combustion than BIGCC and better to make ethanol as a transportation fuel than FT syndiesel. ''Better'' is measured as having a lower cost to society, either the consumer or taxpayer, for the benefit received: a reduction in GHG. This study further concludes that for a typical North American wholesale power price of 70$ MW h^{-1}, if the long term oil price is below about 600$ t^{-1} (80$ bbl^{-1}) then production of electricity would have a lower social cost per unit of avoided GHG emissions. Several elements of this study warrant discussion.

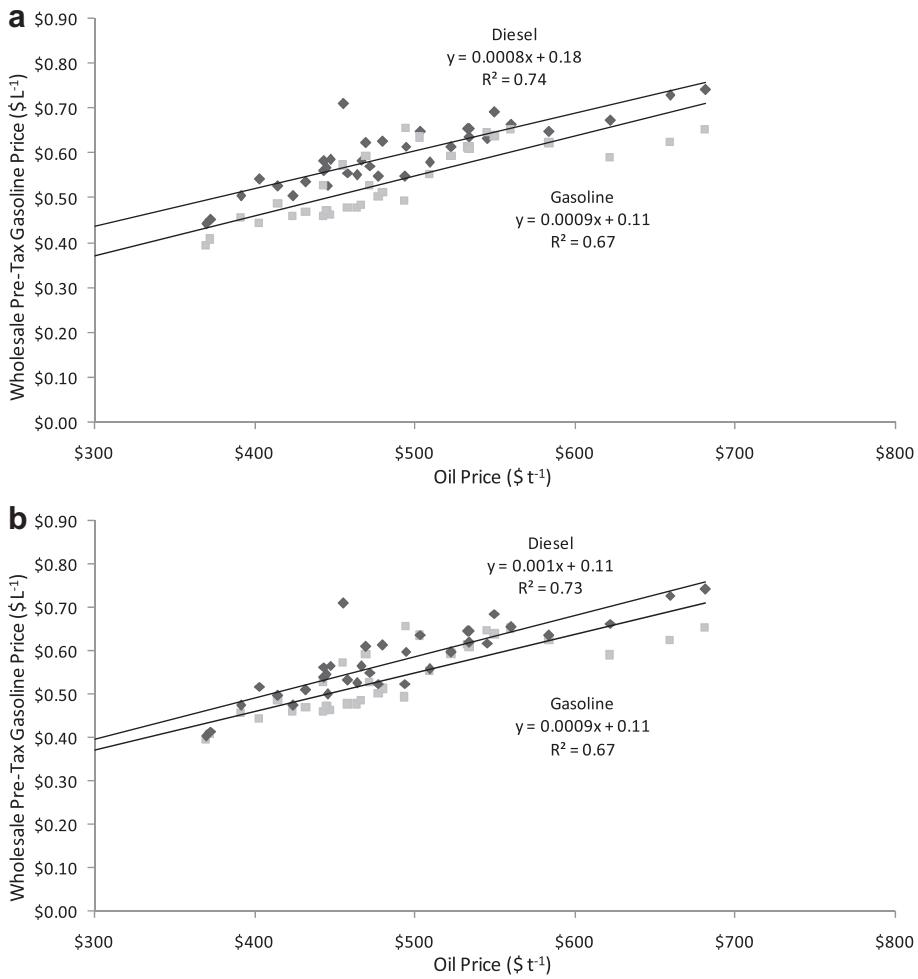

Fig. 2 – (a and b) Correlation between oil and U.S. gasoline and diesel price for 2005–2007 by best fit (a) and best fit with a slope proportional to the energy content of diesel vs. gasoline (b). As a reference note that 80$ bbl^{-1} oil is approximately equivalent to 600$ t^{-1}.

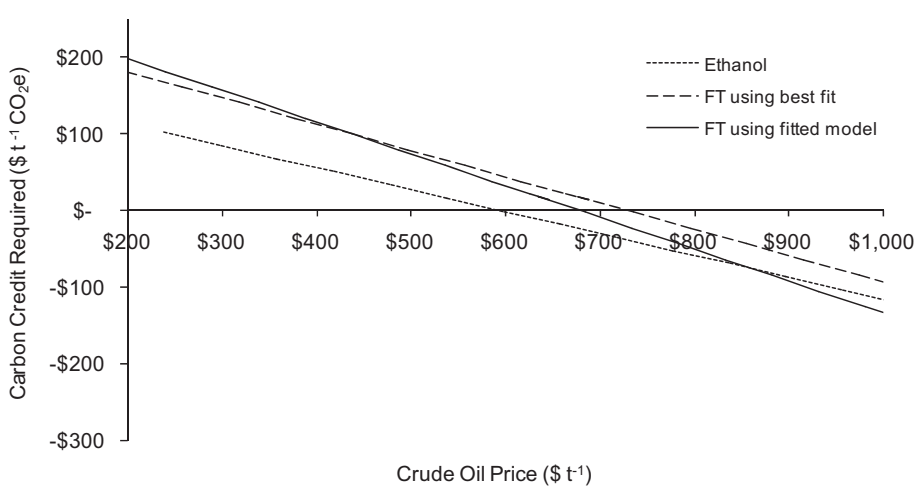

Fig. 3 – Carbon credit required for a 12% pre-tax return on total capital for two straw/stover transportation fuel alternatives. The results of two different models used for the relationship of gasoline and diesel to oil price are shown.

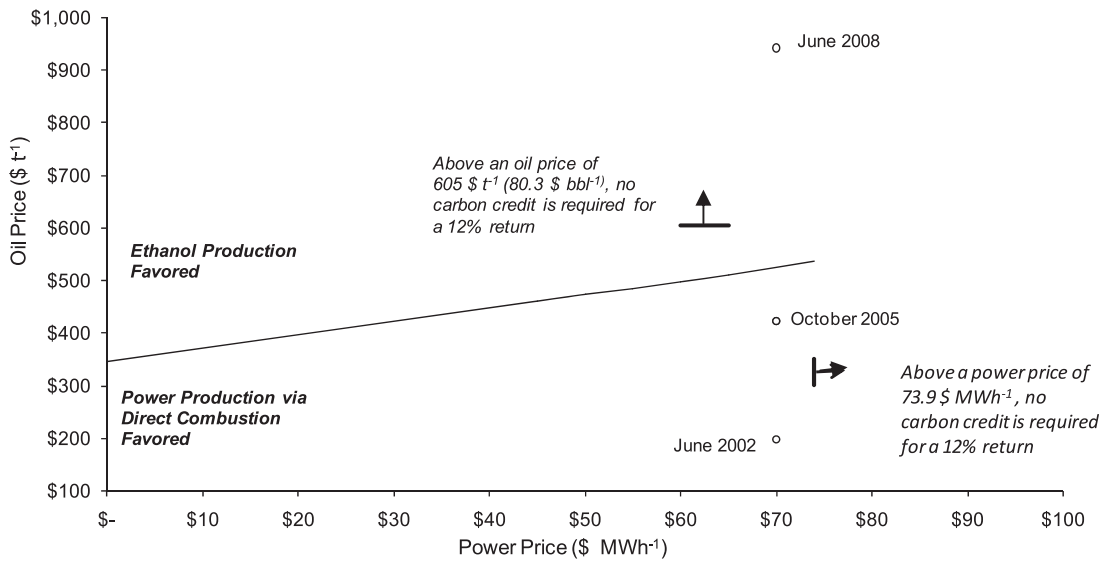

Fig. 4 – Oil and power price at which the carbon credit required for a 12% pre-tax return on total capital for the production of lignocellulosic ethanol and electricity from straw/stover are equal.

This study illustrates an approach to technology selection by applying it to one feedstock only. Good social decisions about selection of renewable energy technologies would calculate incremental cost per unit of avoided emissions for all renewable energy alternatives. This would give a basis for sorting through the myriad of alternatives for renewable energy and identifying a subset of desirable processes. Doing a little bit of everything is, we believe, a very poor social strategy as implementation of renewable energy becomes a substantial component of total energy production. To illustrate this, consider the generation of power from the anaerobic digestion (AD) of manure. AD is a well-demonstrated technology, but a previous study calculated that it would require a carbon credit well in excess of 100$ t^{-1} CO_2e to achieve a 12% pre-tax return on total capital investment [8]. Pursuing AD as a form of green energy has a high cost to achieve a minimal reward. AD of manure may sometimes be warranted to deal with an agricultural problem, such as odor, pathogen or phosphate control, but pursuing AD purely for its renewable energy benefit is a poor social decision.

Two cautions must be voiced about the quality of cost data in this study. First, as noted above, the four processes analyzed in this study are at substantially different stages of commercial development. The uncertainty in the cost estimates for BIGCC and FT are far higher than for direct combustion and lignocellulosic ethanol. We note, however, that further commercial development of a process more frequently increases the estimate of capital and operating cost than decreases it. Therefore the conclusion of this paper that direct combustion and lignocellulosic ethanol are preferred over BIGCC and FT for typical North American agricultural residue availability is not likely to be altered by additional data on the cost of BIGCC and FT. A second caution is that the production cost formulae used in this study were drawn from studies using cost estimates prior to 2005. Evidence supports that equipment cost, and hence total capital cost, went through a major increase in the period 2005 through 2008 [20–22], partly in response to high rates of development in China and India. The significance of this is that the estimates of carbon credits in this study, and the power and oil price at which no carbon credit is required for the renewable energies to achieve a 12% pre-tax return on total capital, are more likely to be biased low than high. Note again, however, that this would not likely affect the relative screening of the four processes, since an increase in capital cost would affect all four processes. Further, BIGCC and FT are more capital intensive processes than direct combustion and ethanol.

The United States has long cited a goal of reducing the import of oil, and more recently concerns have emerged in Europe about the extent of dependence on natural gas from Russia. In this study we calculate cost against the single social benefit of reduced CO_2e in the atmosphere. A social choice of technology would also be influenced by secondary goals related to energy dependency. In the U.S. this would bias process selection towards transportation fuel, while in Europe it might well bias the decision towards power production with heat recovery (co-generation), or a different process to produce a gaseous fuel from biomass.

The carbon credit required to sustain a renewable technology depends on the gross availability of biomass. We tested the impact of this by looking at a higher availability of straw/stover, 0.32 t ha^{-1}, corresponding to a 75/37.5% availability of straw/stover rather than the 0.21 t ha^{-1} (50%/25%) availability that is the basis of the results presented in this study. As expected, the required carbon credit for each of the four processes is lower as biomass availability increases, because the cost of transport of biomass decreases. However, there is negligible impact on the line that defines equal carbon credit for the production of power and ethanol (Fig. 4), because the impact on carbon credit runs in tandem for the four processing alternatives.

5. Conclusions

Key conclusions of this work are:

- Minimum carbon credit in \$ t^{-1} avoided CO_2e is an appropriate criterion for selecting a renewable energy processing technology.
- For availabilities of straw/stover that are representative of North American grain and corn growing regions, production of electricity by direct combustion is favored over BIGCC, and production of lignocellulosic ethanol is favored over FT syndiesel.
- For a power price of 70\$ MW h^{-1}, the carbon credit required by a direct combustion power plant is less than ethanol production for oil prices lower than about 600\$ t^{-1} (80\$ bbl^{-1}).
- Specific calculations of required carbon credits will be impacted by improved capital and operating cost estimates. Enhanced estimating data will have a lesser impact on the relative ranking of process alternatives.

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