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Incorporating the Effect of Price Changes on CO_2-Equivalent Emissions from Alternative Fuel Lifecycles: Scoping the Issues

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ACRONYMS and TERMS

AF = alternative fuel
AFL = alternative-fuel lifecycle
BTU = British Thermal Unit
CARB = California Air Resources Board
CEF = CO2 equivalency factor
CO2 = carbon dioxide
Commodities = fuels such as oil and gas or non-fuel goods such as steel or crops
DOF = [California] Department of Finance
DSM = demand-shift method
EIA = Energy Information Administration
GHG = greenhouse gas
HDV = heavy-duty vehicle
LDV = light-duty vehicle
LEM = lifecycle emissions model
LCGE = lifecycle CO2-equivalent greenhouse-gas emissions
NEMS = National Energy Modeling System
PACUs = price-affected commodity uses
PRLEF = price-related emission factor
PM = particulate matter
SO2 = sulfur dioxide
SSM = supply shift method
UCB = University of California Berkeley

INTRODUCTION

Human activities associated with the production and use of energy and materials can pollute the air and water. Since the late 1960s concern about regional and local air pollution has led to the adoption of environmental laws and regulations regarding major polluting human activities, such as fuel use for transportation or electricity production. More recently, concern about the impact of human activities on global climate has led to discussions about ways to reduce emissions of the so-called “greenhouse gases” that affect global climate.

In the United States and worldwide, the transportation sector is one of the largest sources of urban air pollutants and greenhouse-gases (GHGs). As a result, policy makers and analysts often evaluate the impact of transportation policies on urban air quality and on global climate. The tools available for evaluating impacts on urban air quality (emission-factor models, travel models, and air-quality models) are reasonably well developed, but some of the tools for evaluating impacts on global climate (namely, lifecycle emissions models) are rudimentary and incomplete. This report discusses ways of improving one of the tools – lifecycle emissions analysis – often used in evaluating the impacts of transportation on global climate.

BACKGROUND: CURRENT PRACTICE

A lifecycle emissions model represents the energy use and environmental impacts of a set of production and consumption activities linked to the use of a particular commodity. Thus, in the case of transportation fuels and technologies, a lifecycle emissions analysis captures more than just emissions associated with the burning of fuel by vehicles: it accounts for emissions associated with making the fuel and vehicles, distributing fuels and vehicles, and so on. In an analysis of the impacts of transportation on global climate it is important to account for all emission sources in a lifecycle because -- unlike in the analysis of the impacts on urban air quality-- the effect of a pollutant on global climate generally is independent of the location and the timing of the emission[1]. (In an analysis of urban air quality, only the emissions that occur

[1]This is true at least for CO2, N2O, and CH4, which have long lifetimes and are mixed over large scales. It may not be true for PM and ozone, which have shorter lifetimes and are mixed over regional scales.

within a specified period of time within the air basin of interest matter.) For this reason, analysts have used lifecycle emissions models, rather than just estimates of end-use emissions, to evaluate the effect on energy use and global climate of alternative transportation fuels and technologies.

Unfortunately, lifecycle models have not been as well developed and cogently applied as one might like. Indeed, when we begin to examine the development and application of lifecycle models for transportation we find right away that it is not clear what precise questions the models are supposed to answer. This, of course, is a near-fatal flaw, because if we don't know what question a model is meant to answer, we cannot comprehend the answers that the model provides. In the case of transportation, we are forced often to infer a question from the nature of the outputs and the methods used. What we find, generally, is an unrealistic and irrelevant research question and a limited modeling method. These problems are serious: if the research question is not clear or realistic, and the method of analysis is overly limited, then the answers – the outputs of the models – are difficult to interpret or apply.

Often if not nearly always the research questions to be evaluated by transportation lifecycle analysis are not put clearly. The questions must be inferred from the conclusory statements and the methods of analysis. In transportation, the conclusory statements of lifecycle analysis typically are of the sort: "the use of fuel F in light-duty vehicles has X% more [or less] emissions of CO2-equivalent GHG emissions per mile than does the use of gasoline in light-duty vehicles". The method of analysis usually is a limited input-output representation of energy use and emissions for a relatively small number of activities linked together to make a lifecycle, with no parameters for policies or the function of markets[2]. Recalling that CO2-equivalent emissions are equal

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[2] By "input-output," I mean simply that each "stage" of a lifecycle (e.g., petroleum refining) is represented in these terms: "X units of commodity A, Y units of commodity B...are input for each unit of output of a commodity of interest". By "linked," I mean that the output of one stage is the input to another stage. This is similar to but generally far less extensive and complex than a comprehensive economic input-output (I-O) model.

Note that comprehensive economic I-O models assume fixed input/output ratios, whereas in the real world input/output ratios change with prices. Hence, comprehensive economic I-O models used for transportation LCAs (e.g., H. L. MacLean and L. B. Lave, "Environmental Implications of Alternative-Fueled Automobiles: Air Quality and Greenhouse-Gas Tradeoffs," *Environmental Science and Technology* 34 (2): 225-231, 2000) do appropriately expand the scope of an LCA to the universe of relevant activities, but do not account for the effects of price changes. Note, too, that economic I-O models often have less technology detail than traditional "engineering" LCAs, because the cost of sectoral breadth is sectoral detail. See to emissions of CO2 plus equivalency-weighted emissions of non-CO2 gases, where the equivalency weighting usually is done with respect to temperature change over a 100-year time period, we then can infer that the question being addressed by most transportation lifecycle modeling is something like:

> "What would happen to climate forcing over the next 100 years if we simply replaced the set of activities that we have defined to be the gasoline lifecycle with the set of activities that we have defined to be the fuel F lifecycle, with no other changes occurring in the world"?

The problem here is that this question is irrelevant, *because no action that anyone can take in the real world will have the net effect of just replacing the narrowly defined set of gasoline activities with the narrowly defined set of fuel-F activities*. Any action that involves fuel F will have complex effects on production and consumption activities throughout the world, via global political and economic linkages. These effects *will* occur, and a priori cannot be dismissed as insignificant. To omit them, therefore, is to introduce into the analysis an error of unknown sign and magnitude. The main objective of this report is to discuss ways of improving this deficiency of lifecycle models[3].

BACKGROUND: A MORE REALISTIC FRAMEWORK

If we wish the results of lifecycle analysis of transportation to be interpretable and relevant, then lifecycle models must be designed to address clear and realistic questions. In the case of lifecycle analysis comparing the energy and environmental impacts of different transportation fuels and vehicles, the questions must be of the sort: "what would happen to [some measure of energy use or emissions] if somebody did X instead of Y," where – *and here is the key* – X and Y are *specific and realistic alternative courses of actions.* These alternative courses of actions ("actions," for short) may be related to public

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H. S. Matthews and M. J. Small, "Extending the Boundaries of Life-Cycle Assessment Through Environmental Economic Input-Output Models," *Journal of Industrial Ecology* 4: 7-10 (2001), for a good short discussion of I-O LCA.

[3] There are other deficiencies in lifecycle models, which will not be addressed in this report. Among the most important are omitted emission-generating activities and overly simplistic treatment of CO2-equivalency calculations.

policies, or to private-sector market decisions, or to both. Then, the lifecycle model must be able to properly trace out all of the differences – political, economic, technological -- between the world with X and the world with Y. Identifying and representing all of the differences between two worlds is far more complex than simply representing the replacement of one narrowly defined set of activities with another.

As noted above, current lifecycle models do not put the questions they address clearly, and are not capable of tracing out all of the effects of clearly put questions. A major part of the problem is that there always will be *economic* differences between world X and world Y that do affect energy and emissions but that present lifecycle models do not account for.

The central claim of this report is that any action regarding transportation --- a vehicle production mandate by government, a public subsidy to fuels, or a market decision by a private company to make a new kind of diesel fuel -- will affect the prices of important commodities, such as oil, natural gas, or steel. The effects on prices ultimately will affect emissions, which are what lifecycle emissions models wish to estimate. However, most lifecycle emissions models, including my own, do not now include prices or supply and demand functions, and hence cannot account for price-induced changes in production, consumption, and ultimately emissions. If these price effects are important – and I believe that they can be -- then it will be useful to incorporate them into lifecycle emission models.

To begin to develop a more realistic lifecycle evaluation framework, we must understand how public or private actions regarding transportation fuels might affect prices and ultimately emissions. In general, actions may affect prices directly, for example by changing tax rates, or indirectly, by affecting the supply or demand curves for commodities[4] used in transportation. In an integrated and complex global economy, changes in the prices of important commodities ultimately will affect production and consumption of all commodities in all sectors throughout the world. In the final equilibrium of prices and quantities, there will be a new global pattern of production and consumption. Associated with this new pattern of production and consumption will be a new pattern of emissions of criteria pollutants and greenhouse gases. The difference between

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[4] Actions may affect demand or cost functions directly, for example by mandating production or consumption, or indirectly, for example by affecting incomes and hence household consumption decisions.

the global emissions pattern associated with the transportation action being evaluated and the global emissions pattern without the action may be said to be the "emissions impact" of the action being evaluated.

Hence, I propose that rather than ask what would happen if we replaced one very narrowly set of defined activities with another, and then use a technology lifecycle model to answer the question, we instead ask what would happen in the world were we to take one realistic course of action rather than another, and then use an integrated economic and engineering model to answer the question. This juxtaposition reveals three key differences between what we may call the "traditional" approach and the expanded approach that I believe is likely to be more accurate (Table 1):

TABLE 1. COMPARISON OF THE TRADITONAL LIFECYCLE APPROACH IN TRANSPORTATION WITH AN EXPANDED APPROACH

Issue	Traditional approach	Expanded approach
The aim of the analysis	Evaluate impacts of replacing one limited set of activities with another	Evaluate worldwide impacts of one realistic policy or market action compared with another
Scope of the analysis	Narrowly defined chain of material production and use activities	All major production and consumption activities globally
Method of analysis	Simplified input/output representation of technology	Input/output representation of technology with dynamic price linkages between all sectors of the economy

Of course, one sees right away that the scope and methods of analysis proposed for the "expanded approach" really are not expansive enough. If our objective is to evaluate how the world changes if we take one action rather than another, then in principle our scope needs to include more than the global economy and our method more than price-dynamic input-output representations, because there is more to the world than markets and prices. For example, public or private sector actions regarding transportation or transportation fuels can via a complex series of political and economic events influence sensibilities in the Middle East, which in turn can affect oil production and use and associated emissions. A theoretically complete model would include these sorts of effects. However, for the sake of manageability I leave modeling of political effects for a later project, and focus here on the omitted economic effects.

i) Outline of the remainder of the report. The remainder of this report deals mainly with incorporating price effects into "traditional" engineering (input-output) lifecycle emission models such as mine, as opposed to incorporating technology and emissions details into general- or partial-equilibrium models of the economy. Although it is possible in principle to have a completely detailed economic and engineering model, and to work towards this either by adding economic representations to engineering models or by adding technology and emissions details to economic models, I assume in this project that we will not be able to build such a *complete* model either from scratch or by expanding existing engineering or economic models. Thus, as a practical matter, an engineering-type lifecycle-emissions model expanded to include economics will have less economic detail than does an economic equilibrium model, and an economic equilibrium model expanded to include more technology sectors and detail will have less technology and emissions detail than does an engineering lifecycle model. This report focuses mainly on expanding "engineering" lifecycle emissions models because in order to analyze new fuel and vehicle pathways one must have fairly specific technology characterizations, and lifecycle models such as mine have this kind of detail.

I offer first an extended discussion of the ways in which the Lifecycle Emissions Model (LEM) might be expanded to account for the effects of price changes on emissions. I develop general methods for estimating the effect on emissions of changes in prices related to commodity production and use in alternative fuel lifecycles (AFLs). After presenting the general methods, I talk briefly about the possibility of expanding an economic-equilibrium model to include technology and emissions details. I then turn to the major parameters in the LEM. I discuss how the parameter is treated presently in the LEM, the importance of the parameter to the final lifecycle emissions results, the extent to which the parameter *in principle* depends on prices in the economy, and how any such economic dependency might be represented.

WAYS OF EXPANDING THE LEM TO ACCOUNT FOR THE EFFECTS OF PRICE CHANGES ON EMISSIONS

As mentioned in the section "background: a more realistic framework", a public or private action regarding transportation may affect prices in three ways:

i) directly, for example via a policy that changes price subsidies (such as for ethanol) or taxes (such as on gasoline);

ii) indirectly, by shifting demand curves for input commodities used in transportation-related lifecycles (e.g., a public mandate to use electric vehicles will shift the demand curve for electricity, and a policy promoting private-sector production of diesel-like fuels from natural gas will shift the demand curve for natural gas); and

iii) indirectly, by shifting the supply curve for output commodities produced in transportation-related lifecycles (e.g., a policy promoting the production of ethanol from wood will result in additional production of electricity which will shift the supply curve for electricity).

The indirect effects of shifts in demand can be represented by what I will call the "demand shift method" (DSM). The DSM uses price elasticities and estimates of demand and supply curves to estimate the effects on prices (and ultimately emissions) of shifts in demand for major input commodities in AFLs. The DSM also can be used to estimate the effects of direct changes in prices (such as via changes in taxes or subsidies).

A similar method will be used to represent the indirect effects of changes in supply. This method also will require the use of supply and demand curves for the commodities produced by AFLs in order to determine the equilibrium changes in prices and quantity. I will refer to this as the "supply-shift method" (SSM).

GENERAL DISCUSSION 1: A WAY OF EXPANDING THE LEM TO INCLUDE THE PRICE EFFECTS OF SHIFTS IN DEMAND FOR INPUT COMMODITIES IN AFLs

I believe that the most important expansion to the LEM to incorporate price effects would be to add a simple price-elasticity and supply/demand framework in which the incremental use of (or demand for) a major commodity in any AFL would shift the demand curve for the commodity and thereby affect its price.

This effect on price in turn would affect *all* uses of the commodity. For example, the incremental use of (demand for) natural gas as a feedstock to make methanol would shift the demand curve for natural gas, which would affect the price of natural gas, which in turn would affect other consumption of natural gas, such as for electricity generation or heating and cooking. The change in this other consumption would change emissions, and this change in emissions -- due ultimately to the incremental use of (shift in demand for) natural gas in the methanol AFL -- would be added to calculated CO2-equivalent emissions for the AFL.

Thus, the essence of my proposed expansion is to add to the LEM an independent calculation that produces an estimate of the change in lifecycle emissions worldwide due to changes consumption a commodity (due to changes in prices due to shifts in demand), per unit of the commodity used in an AFL. *I will refer to these new calculated emissions-per-unit as price-related lifecycle emission factors, or PRLEFs.* This effect of price changes on lifecycle emissions would be estimated for commodity uses directly affected by the price change and for commodity uses that are substitutes for the directly affected uses. These PRLEFs would be calculated for and attached to each major commodity input in AFLs.

The units of PRLEFS would be grams of CO2-equivalent lifecycle emissions in all price-affected commodity uses per unit (BTU, lb, acre, etc.) of commodity input to (demanded by) AFLs. Each major commodity in the LEM would have a PRLEF attached to it, and each PRLEF would represent the effect on price (and ultimately emissions) of other uses of the commodity.

The “demand-shift method” (DSM) is discussed here in several sections:

- Decide on the fuels and non-fuel commodities in AFLs to which PRLEFs will be attached
- Determine where in the LEM to attach the PRLEFs
- Identify the price-affected commodity uses (PACUs) to be included in PRLEFs
- Delineate the method of estimating PRLEFs

Note that this will be a static, partial, analysis: static because prices and other economic variables not will change over time, and partial because only part of the economy will be represented.

i) Decide on the fuels and non-fuel commodities in AFLs to which a PRLEF will be attached. Because the ultimate objective is to estimate changes in AFL emissions due to changes in prices, per incremental unit of major commodity input to an AFL, the first task is to decide on the major fuels and commodities for which this will be done. Obviously we should attach a PRLEF to each of the major inputs to AFLs in the LEM, *and* to commodities that might be substitutes for any of these major inputs. In this context, "major" inputs are those that account directly or indirectly for significant energy use and emissions of GHGs worldwide. These include at least:

- Crude oil
- Petroleum products (gasoline, diesel fuel, jet fuel, fuel oil)
- Natural gas
- Coal
- Electricity
- Steel
- Plastics
- Aluminum
- Concrete
- Generic chemicals
- Fertilizer
- Crops (corn and soybeans)
- Biomass (grass and trees)
- Land

These I propose are the commodities in AFLs in the LEM to which a PRLEF would be attached.

ii) Determine where in the LEM to attach the g/BTU or g/lb PRLEF for each commodity. Because AFLs in the LEM are relatively complex and connected to one another circularly, it is not a straightforward matter to determine where in each AFL to attach the g/BTU or g/lb PRLEFs to commodities. In making this determination, there are at least four requirements to consider:

a) Any use of a major input commodity in an AFL should have one and only one PRLEF attached to it;

b) the units of the PRLEF should be consistent with the units of commodity use (i.e., if a commodity is input to an AFL in BTUs, the PRLEF must be in grams of CO2-equivalent emissions per BTU of the commodity);

c) Any PACU *included* in a PRLEF (see iii below) should *itself* have a PRLEF attached to it;

d) the application of PRLEFs should not compound circularities in the LEM so much that the model does not solve.

The LEM might have to be restructured in order to facilitate this.

Note that requirement c) results in circularities, and that these circularities may prevent the model from solving (in violation of requirement d). The circularity arises from the fact the lifecycle emission factor for a PACU (say, heating and cooking) on the one hand is used in the calculation of PRLEFs but on the other hand includes emissions from the use of commodities (say natural gas) that themselves have a PRLEF attached – a PRLEF that as just noted comprises emission changes in the "original" use, heating and cooking. Diagrammatically:

Heating and cooking lifecycle emissions -----> part of PRLEF ------> PRLEF attached to use of natural gas -----> natural gas input to heating and cooking sector (a PACU) ----> heating and cooking lifecycle emissions

A major task in follow-on work to this project will be to determine precisely how to incorporate PRLEFs into the LEM.

<u>iii) Identify the affected PACUs that will be included in a PRLEF.</u> A PRLEF is an emission factor. It expresses grams of lifecycle CO2 equivalent missions of GHGs in various PACUs per incremental unit of fuel or commodity input to (or demanded within) an AFL. Now, any emission factor depends on the type of activity as well as the type of commodity: Natural gas used for home heating has a different lifecycle emission factor than does oil used for home heating (different commodity, same end use) or natural gas used for power generation (same commodity, different end use). In step i) above we identified the input commodities in AFLs to which a PRLEF would be attached. In this step we must identify the PACUs to be included in PRLEFs.

The LEM characterizes emissions from many fuel combustion processes, industrial process areas, and agricultural activities. In order to ensure internal consistency in the calculation of lifecycle emissions, a PRLEF should include any PACUs already characterized in the LEM and used in the calculation of lifecycle CO2-equivalent emissions from AFLs. For example, if commercial heating is to be a PACU included in a PRLEF, then the commercial-heating emission factors actually used in AFLs in the LEM -- not newly calculated commercial-heating factors that would be independent of and therefore perhaps inconsistent with the commercial-heating emission factors already used in the LEM – should be the ones included in the PRLEF.

The PACUs included in PRLEFs should encompass most if not nearly all of the major GHG-producing fuel and commodity uses. This will ensure that no significant emission sources (and hence price-related emission effects) are omitted.

However, in order to keep the data requirements manageable and the model solvable, the PACUs should not be too disaggregated. For example, we do need to include as a PACU every piece of equipment included in the LEM (offroad tractors, offroad trucks, etc.) -- a generic "offroad" PACU that uses some representative or average emissions will suffice.

With these considerations, I propose the following PACUs to be included in PRLEFs:

- Energy: power generation; lifecycle of generating fuels through combustion at power plant
- Energy: electricity use; lifecycle to end use of electricity
- Energy: petroleum refining; lifecycle of fuels through use at refinery
- Energy: other industrial processes; lifecycle of fuels through combustion
- Energy: heating and cooking; lifecycle of fuels through end use
- Energy: highway transportation; lifecycle of fuels through end use
- Energy: aviation; lifecycle of fuels through end use
- Energy: marine transportation; lifecycle of fuels through end use
- Energy: rail transportation; lifecycle of fuels through end use
- Energy: offroad (including agriculture); lifecycle of fuels through end use
- Materials: steel use; lifecycle of steel through end use including recycling
- Materials: aluminum use; lifecycle of aluminum through end use including recycling
- Materials: plastics use; lifecycle of plastic through end use including recycling
- Materials: concrete use; lifecycle of concrete through end use including disposal
- Materials: miscellaneous chemical use; lifecycle of chemicals through end use including disposal
- Agriculture: fertilizer use; lifecycle of fertilizer through end use including environmental fate
- Agriculture: crop use; lifecycle of crops through end use

- Agriculture: biomass use; lifecycle of biomass through end use
- Agriculture: land use; changes in emissions associated with changes in land use

We can now group the commodities to which a PRLEF is attached with the affected PACUs to be included in a PRLEF. This grouping is done two ways in Table 2.

TABLE 2A. PRLEFS: INPUT COMMODITIES TO WHICH A PRLEFS WILL BE ATTACHED, PACUS INCLUDED IN PRLEFS, AND UNITS OF PRLEFS

Input commodity	Price-affected commodity use	Units
Crude oil	Energy use: petroleum refining, other industrial processes, materials production	g/BTU
Petroleum products	All except agriculture: land use and agriculture: crop production	g/BTU
Natural gas	Energy use: power generation, petroleum refining, other industrial processes, heating and cooking	g/BTU
Coal	Energy use: power generation, petroleum refining, other industrial processes, heating and cooking	g/BTU
Electricity	Energy: electricity use	g/kWh
Steel	Materials: steel use	g/lb
Plastics	Materials: plastics use	g/lb
Aluminum	Materials: aluminum use	g/lb
Concrete	Materials: concrete use	g/lb
Generic chemicals	Materials: chemicals	g/lb

Fertilizer	Agriculture: fertilizer use	g/lb
Crops (corn and soybeans)	Agriculture: crop use	g/bu
Biomass (grass and trees)	Agriculture: biomass use	g/ton
Land	Agriculture: land use	g/acre

TABLE 2B. PRLEFS: PACUS INCLUDED IN PRLEFS, INPUT COMMODITIES TO WHICH PRLEFS WILL BE ATTACHED, AND UNITS OF PRLEFS

Price-affected commodity use	Input commodity	Units
Energy: power generation	Residual fuel	g/BTU
	Coal	g/BTU
	Natural gas	g/BTU
Energy: electricity use	Oil power	g/kWh
	Coal power	g/kWh
	Natural gas power	g/kWh
	Hydropower	g/kWh
	Nuclear power	g/kWh
	Other power	g/kWh
Energy: petroleum refining	Fuel oil	g/BTU
	Natural gas	g/BTU
	Coal	g/BTU
	Generic power mix	g/kWh
Energy: other industrial processes	Fuel oil	g/BTU
	Natural gas	g/BTU
	coal	g/BTU
Energy: heating and cooking	Fuel oil	g/BTU
	Natural gas	g/BTU
	coal	g/BTU

Energy: highway transportation	Diesel fuel Gasoline	g/BTU g/BTU
Energy: aviation[5]	Jet fuel	g/BTU
Energy: marine transportation	Bunker fuel	g/BTU
Energy: rail transportation	Diesel fuel	g/BTU
Energy: offroad (including agriculture)	Diesel fuel	g/BTU
Materials: steel use	Steel	g/lb
Materials: aluminum use	Aluminum	g/lb
Materials: plastics use	Plastics	g/lb
Materials: concrete use	Concrete	g/lb
Materials: miscellaneous chemical use	Generic chemicals	g/lb
Agriculture: fertilizer-use	Fertilizer	g/lb
Agriculture: crop use	Corn Soybeans	g/bu g/bu
Agriculture: biomass use	Grass Trees	g/ton g/ton
Agriculture: land use	Land	g/acre

Note that power generation and electricity end use are separate PACUs. We need power generation as a PACU to estimate the effects in the power generation sector of using more of a particular fuel, such as coal, in an AFL. We

[5] Because emissions from airplanes at high altitudes can have a different impact on climate than emissions of the same pollutants at ground level, I would have to develop new CO2-equivalency factors for the calculation of CO2-equivalent emissions from the use of energy for aviation.

need electricity end use as a PACU to estimate the effects of using electricity itself in an AF lifecycle.

The next steps are to estimate the PRLEFs themselves, using estimates of price elasticities and representations of supply and demand curves. Each PRLEF for an commodity input of interest (see section i above) will include up to eight components:

- the direct effect on the commodity of interest (the commodities of interest are shown in section i here) on prices and emissions in PACUs (the PACUs are shown in Table 2);
- the effect on products derived from the commodity of interest (call these "derivative" products);
- the effect on commodities from which the commodity of interest is derived (call these "generative" commodities);
- same as the previous, except that the effect is on other products derived from the commodities from which the commodity of interest is derived (call these "parallel" products)
- the effect on *substitutes* for the commodity of interest;
- the effect on *substitutes* for products derived from the commodity of interest;
- the effect on *substitutes* for the commodities from which the commodity of interest is derived;
- same as the previous, except that the effect is *substitutes* for the other products derived from the commodities from which the commodity of interest is derived;

The total PRLEF will be the sum of these eight components, some of which may not be applicable for some commodities of interest. (For example, not all commodities of interest have significant emission-relevant derivative products, or generative commodities, or parallel products.) Recall again that each component will be in units of grams of CO2-equivalent emission changes, throughout the economy, due to price effects arising from the use of a unit of the commodity of interest.

iv). Direct effects on the use of the commodity of interest. An example of a simple direct effect is: an incremental input of (demand for) natural gas (the commodity of interest in this example) in any AFL shifts the demand curve for natural gas and thereby affects the price and hence consumption of natural gas in all of the PACUs that include natural gas in Table 2. The object here is to estimate the direct emissions changes in all of these PACUs due to an initial one-unit shift in the natural-gas demand curve (as an example) in any AFL.

a) define the incremental "unit" of the commodity input of interest (e.g., a BTU of natural gas);

b) estimate the supply and demand curves for the commodity of interest in the largest pertinent market area (e.g., North America), in terms of the incremental unit defined in a) (e.g., a slope expressed in $/BTU/BTU);

c) estimate a functional relationship between shifts in the demand curve and changes in price for the commodity in the same market (Figure 1 and discussion below);

d) use the relationship from c) and the estimates from b) to estimate the change in the price of the commodity (Figure 1 and discussion below)

e) estimate the price elasticity of demand, the baseline price, and the baseline consumption of the commodity for each of the direct PACUs for the commodity within the pertinent market;

f) with the change in price from d) and the quantities from e), estimate the change in quantity consumed (along the PACU demand curve) for the commodity in each PACU (see discussion below);

g) identify the appropriate lifecycle emission factors for the use of the commodity in each PACU;

h) multiply the change in quantity consumed for the commodity from f) by the lifecycle emission factor from g) to obtain the change in emissions, for each PACU;

i) sum the emissions changes from h) over all PACUs.

The result in iv-i) is the total change in emissions in all sectors (PACUs) directly effected by price changes due to an initial one-unit shift in the demand curve of the commodity of interest. This is the first of the eight components of the overall PRLEF for a commodity of interest.

Two things are important to note here. First, the initial incremental use of (or demand for) the commodity of interest is modeled as an exogenous shift in the demand curve, not as a change in consumption along a fixed demand curve. This shift in demand results in a new intersection with the supply curve and hence in a new equilibrium price (c and d above) (Figure 1). (By contrast, the final change in consumption of the commodity in each PACU due to the estimated change in price is estimated by moving up or down a PACU [sectoral] demand curve.) Assuming linear supply and demand curves, the change in price can be estimated formally as a function of the slope of the demand curve and the slope of the supply curve. In Figure 1, demand shifts outward by the quantity Q'-Q, from D to D*, and price increases from P to P*. (Note that the increase in price causes the equilibrium increase in consumption to be less than the amount of the shift in demand by the quantity Q'-Q*.) Referring to the derivation done for Figure 2, in the context of the SSM, we find that:

$$\Delta P/\Delta Q = -D/(1-D/S)$$
$$\Delta P/\Delta Q \equiv \Delta P\hat{}$$

where:
$\Delta P/\Delta Q$ = the change in price per unit of commodity input (i.e., per unit shift in demand), which is the quantity we are interested in (call this ΔP^).
ΔP = P*-P (change in price)
ΔQ = Q-Q (shift in demand)
D = slope of demand curve (a negative number)
S = slope of supply curve (a positive number)

ΔP^ is the change in price associated with a unit demand shift mentioned in step iv-d) above. The change in consumption of the commodity in the PACU (step iv-f) above) is:

$$\Delta Q_{PACU} = E_{PACU} \cdot \Delta P\hat{}/P \cdot Q_{PACU}$$

where:
ΔQ_{PACU} = the change in consumption of the commodity in the PACU
E_{PACU} = the price elasticity of demand for the commodity in the PACU
P = the baseline (pre-change) price of the commodity
Q_{PACU} = the baseline consumption of the commodity in the PACU

Second, because the change in price depends on demand and supply curve characteristics in the largest pertinent market (iv-b above), and the change in consumption in the PACUs depend on price elasticities and baseline prices and quantities in PACUs, it is important to define pertinent markets and PACUs carefully and consistently. PACUs are sectors of the largest pertinent market; thus, quantities estimated for PACUs must be consistent with the characterization of the largest pertinent market.

Both of these notes apply generally to the estimation of all eight components of a PRLEF.

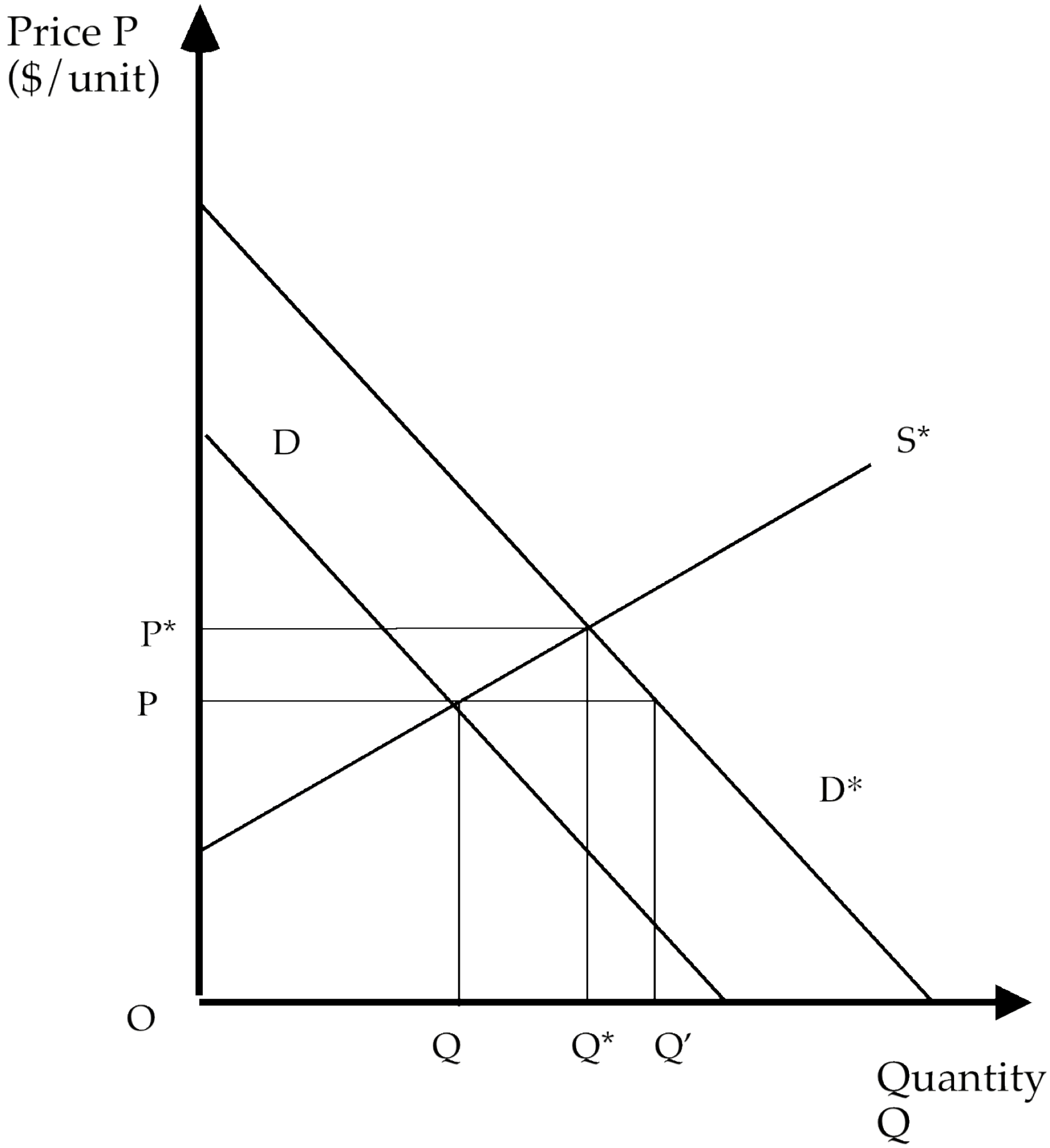

FIGURE 1. THE EFFECT ON PRICE OF A SHIFT IN DEMAND

<u>v) Effects on the use of products derived from the commodity of interest.</u> An example of this is: the incremental use of (demand for) crude oil in any AFL shifts the demand curve for crude oil and affects the price and hence the consumption of products derived from crude oil in all of the PACUs that include petroleum products. The object here is to estimate these emission changes in all of these sectors due to an initial one-unit shift in the crude-oil demand curve (for example) in an AFL.

a) to d) same as iv-a) to iv-d) above

e) estimate the relationship between a change in price of the commodity of interest and a change in price of derivative products;

f) with the change in commodity price from d) and the relationship from e), estimate the change in price of derivative products;

g) estimate the price elasticity of demand, the baseline price, and the baseline consumption of the derivative products in each of the PACUs;

h) with the change in product price from f) and the estimates from g), estimate the change in consumption of the derivative products in each PACU (see discussion above);

i) identify the appropriate lifecycle emission factors for the use of the derivative products in each PACU;

j) multiply the change in consumption of the commodity from h) by the lifecycle emission factor from i) to obtain the change in emissions, for each PACU;

k) sum the emissions changes from j) over all PACU.

The result in v-k) is the total change in emissions in derivative-product PACUs effected by price changes due to an initial one-unit shift in the demand curve of the primary commodity of interest. This is the second of the eight components of the overall PRLEF for a commodity of interest.

<u>vi) The effect on commodities from which the commodity of interest is derived (generative commodities).</u> An example of this is: gasoline derived from crude oil can affect the price and hence the direct consumption of the generative commodity, crude oil. (Note that here we estimate the effect on the direct use of crude oil; in the next component we estimate the effect on other products derived from the affected generative commodity.)

a) define the incremental “unit” of the commodity of interest (e.g., a bbl of gasoline);

b) estimate the relationship between a change in the use of the commodity of interest and a change in the use of the generative commodity (e.g., crude oil) in the largest pertinent market (e.g., the world);

c) use the relationship in b) to estimate the incremental shift in demand for the generative commodity (crude oil) per incremental one-unit shift in demand for the commodity of interest (gasoline);

d) estimate the supply and demand curves for the generative commodity in the pertinent market (e.g., the world oil market);

e) estimate a functional relationship between shifts in demand and changes in price for the generative commodity in the pertinent market (Figure 1 and discussion above);

f) use the relationship from e) and the estimates from d) to estimate the change in price of the generative commodity (Figure 1 and discussion above);

g) estimate the price elasticity of demand, the baseline price, and the baseline consumption of the generative commodity in each of the direct PACUs for the generative commodity, within the pertinent market;

h) with the change in price from f) and the estimates from g), estimate the change in consumption of the generative commodity in each of the direct PACUs (e.g., crude oil used as a process fuel by refineries) (see discussion above);

i) identify the appropriate lifecycle emission factors for the use of the generative commodity in each PACU;

j) multiply the change in consumption of the generative commodity from h) by the lifecycle emission factor from i) to obtain the change in emissions, for each PACU;

k) sum the emissions changes from j) over all PACUs.

The result in vi-k) is the total change in emissions in generative-product PACUs affected by price changes due to a one-unit shift in the demand curve for the commodity of interest. This is the third of the eight components of the overall PRLEF for a commodity of interest.

<u>vii) The effect on products derived from a commodity from which the commodity of interest is derived (parallel products).</u> An example of this is: the incremental use of gasoline derived from crude oil can affect the price of crude oil, which in turn can affect the price and direct consumption of other products derived from crude oil, such as home heating fuel.

a) to f) same as vi-a) to vi-f) above.

g) estimate the relationship between the change in price of the generative commodity and the change in price of the derivative commodities, in each PACU of a derivative commodity (e.g., fuel oil for home heating; gasoline for highway vehicles);

h) with the change in price from f) and the relationship from g), estimate the change in price of derivative commodities in each PACU;

i) estimate the price elasticity of demand, baseline price, and baseline consumption of the derivative commodities in each of the direct PACUs;

j) with the change in price from h) and the estimates from i), estimate the change in consumption of the derivative commodities in each of the direct PACUs (see discussion above);

k) identify the appropriate lifecycle emission factors for the use of the derivative commodities in each PACU;

l) multiply the change in consumption of the derivative commodity from j) by the lifecycle emission factor from k) to obtain the change in emissions, for each PACU;

m) sum the emissions changes from l) over all PACU.

The result in vii-m) is the total change in emissions in derivative-product PACUs affected (via generative commodities) by price changes due ultimately to a one-unit shift in the demand curve of the commodity of interest. This is the fourth of the eight components of the overall PRLEF for a commodity of interest.

viii) The effect on substitutes for the commodity of interest, derivative products, generative commodities, or parallel products. The next four components of the overall PRLEF involve substitutes for the original commodities estimated in the first four PRLEF components. With cross-elasticities we can capture this next-order effect. For all of the final four components the procedure is the same:

a) start with the change in price of what I will call the "original" commodity from step iv-d (commodity of interest), v-f (derivative products), vi-f (generative commodities), or vii-h (parallel products);

b) delineate substitutes for the original commodities in the relevant PACUs (call these "substitute commodities");

c) estimate the baseline price of the original commodity and the cross-price elasticity of demand and the baseline consumption of the substitute commodities, in each PACU;

d) with the change in the price from a) and the estimates from c), estimate the change in consumption of substitute commodities in each PACU;

e) identify the appropriate lifecycle emission factor for the use of a substitute commodity in each PACU;

f) multiply the change in consumption of the substitute commodity from d) by the lifecycle emission factor from e) to obtain the change in emissions, for each PACU;

g) sum the emissions changes from f) over all PACUs.

The quantity estimated in viii-g) is the price-related change in emissions in PACUs that use substitutes for the commodities, derivative products, generative commodities, or parallel commodities affected by the initial shift in the demand curve of the commodity of interest.

These four quantities of type viii-g) are the final four components of the PRLEF for a commodity of interest. Of course, there are further ramifications of the price changes throughout the economy, but to keep the analysis manageable I propose truncating it here.

In summary, each commodity of interest (section i) will have attached to it one PRLEF comprising as many as eight components, as delineated above. The PRLEF attached to each commodity of interest will not change from lifecycle to lifecycle; it will be unique to each commodity of interest, and will be the same regardless of the AFL in which the commodity of interest is used.

The method is the same whether the commodity of interest is an energy commodity, such as oil or gas, a material commodity, such as steel or plastic, or an agricultural commodity, such as fertilizer or crops. In the case of energy commodities (crude oil, petroleum products, natural gas, coal, electricity), one estimates the price effect of the commodity in the pertinent *energy* PACUs of Table 2. In the case of material commodities (steel, plastics, aluminum), one estimates the price effect of the commodity in the *material production* PACU of Table 2. In the case of agricultural commodities (crops, fertilizer, land) one estimates the price effect of the commodity in the pertinent *agriculture* PACUs of Table 2.

<u>ix) A variation on the DSM: evaluating the impacts of actions that directly change the price of commodities.</u> In the DSM as outlined above, changes the use of input commodities (i.e., shifts in the demand curve) result in changes in commodity prices which in turn result in changes in emissions. This chain of events represents the effects of public or private actions that affect commodity use, or demand curves, in AFLs. However, it is possible for public policies or private actions to "start" the chain differently, by affecting prices directly (as opposed to indirectly via affects on demand curves). An example of this would be the imposition of a carbon tax on fuels. The increase in price would reduce demand for the fuel and ultimately reduce emissions in PACUs

To model the effect of changing prices directly, I would use the following variation on the DSM:

a) create an option for model users to directly change the prices of commodities, for example to represent the effect of a CO2 tax. This could be done by having the price change term comprise two parts: one stemming from the indirect effect of shifts in demand (as discussed above), and the other representing the direct effect of a price-changing policy;

b) estimate the price elasticity of demand for the commodities subject to the tax;

c) with the change in price input in a) and the price elasticity of demand from b), estimate the change in consumption of the taxed commodity;

d) estimate the resultant change in emissions, following the method of the DSM above (e.g., iv-g to iv-i)

e) estimate the emissions effects related to the use of substitute fuels, following viii-a to viii-g of the DSM

With this method, one could model (for example) how a carbon tax or a price subsidy effects LCGE for different AFLs. However, this method does not capture all of the economic effects of actions that directly changes prices: it does not capture any effects on household income or effects of deadweight losses. To the extent that both of these economic effects ultimately affect emissions, the simplified method proposed here will not capture all of the relevant price/emission effects of directly changing the prices of commodity inputs in the LEM.

<u>x) Conclusion.</u> I believe that it will be useful to expand the capability of the LEM to include the effects of price changes on emissions, because such effects cannot easily be captured by calculations "outside" of the LEM. The proposed expansion amounts to adding a highly simplified (or aggregated) price-effect structure to the LEM, with all of the engineering/emission calculations fully intact. Moreover, once we establish the formal method, the only limits to expanding the number of PACUs and commodities of interest represented in the LEM are those of data and of the ability of the model to solve the system. As regards the last, I do not know the limits of Excel. If Excel turns out to be too limiting, we will have to consider reconstructing the LEM in a different modeling software.

I note again that the DSM does not address all potentially policy-relevant price or economic considerations in lifecycle emissions modeling. It is a simplified method for representing the emissions effects of demand-induced changes in price or price-induced changes in quantities produced and consumed. To do this, the main "economic" parameters it uses are price elasticities, representations of demand and supply curves, and baseline prices and quantities.

In order to represent the effects on prices and emissions of changes in the *production* of (or supply curves for) commodities in AFLs (as opposed to changes in demand curves or direct changes in prices), we will need a slightly different method. I turn to this momentarily.

xi) Note on compatibility of elasticity and supply/demand curve estimation. The DSM requires the use of price elasticities and the representation of supply and demand curves. The simplest representation of supply and demand curves is linear, and the simplest assumption for price elasticities is a constant value. However, a linear demand curve generates a varying price elasticity of demand and hence is technically inconsistent with a constant price elasticity of demand.

This inconsistency could be corrected by assuming either variable elasticities or, alternatively, nonlinear demand curves. However, either of these corrections would complicate the analysis. Moreover, the difference between a linear and logarithmic demand curve in the narrow region of interest probably is minor. Thus, I believe that simplicity here is not had at a very great cost.

GENERAL DISCUSSION 2: A WAY OF EXPANDING THE LEM TO INCLUDE PRICE EFFECTS OF COMMODITIES SUPPLIED BY (OR OUTPUT FROM) AFLs.

Many fuel-production processes produce more than just one commodity. For example, petroleum refining produces a wide range of petroleum products, and the production of ethanol from corn produces material that can be used as animal feed. Thus, a world in which we produce more gasoline may also be a world in which we produce more of other petroleum products, such as residual fuel, and a world in which we produce more ethanol is also a world in which we produce more animal feed.

A *change* in production of these other products (in the preceding examples, residual fuel or animal feed) will affect the markets for these products and ultimately emissions related to activities in these markets. This effect is analogous to the one discussed in DSM, in which demand for commodities as inputs to the fuel production processes (e.g., crude oil to petroleum refining, and coal to ethanol production) affect the markets for the input commodities and ultimately emissions: in the case of the DSM, we represent the effect of a shift in the demand curve, whereas in this case (the supply-shift method, or "SSM") we represent the effect of a shift in the supply curve.

Because these other products are produced along with the primary fuel commodity of interest, I will refer to them as "coproducts". Presently there are several kinds of coproducts in the LEM:

- Coproducts of processes that convert agricultural crops to fuels (e.g., distiller's dried grains and solids produced by corn-to-ethanol plants)
- Coproducts of processes that convert cellulosic material to fuels (e.g., electricity produced by wood-to-ethanol plants)
- Coproducts of processes that convert fossil fuels (coal, natural gas), or crude oil to gasoline or diesel-like fuels (e.g., residual fuel produced by refineries that produce mainly gasoline)[6]

The method for analyzing the price-related emissions effects of these coproducts (the SSM) is similar to the DSM proposed for analyzing the effects of the use of commodities in AFLs[7]. The general similarity is that a change in the production of these coproducts will affect prices and hence consumption and ultimately emissions in co-product markets. The main methodological similarity is that I propose that price or quantity changes be estimated on the basis of the slope of the supply and demand curves. The main difference is that with the SSM we start with a shift in the supply curve, whereas with the DSM we start with a shift in the demand curve.

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[6] I recognize that refineries do not necessarily produce products in fixed ratios, but can within limits vary the proportions of the products derived from a barrel of crude oil. Thus, it is not necessarily the case that a change in the production of gasoline results in a change in the production of residual fuel oil. And if there is no change in the production of residual fuel, there is no displacement of original products and no emissions changes to estimate.

[7] Most engineering-type lifecycle models represent the effect of coproducts in one of two ways. Some models "allocate" the emissions from the fuel production process across all of the products on the basis of energy content, mass, or value. This method is incoherent, because in the real world no such allocation or its equivalent happens. Other models attempt to estimate the emissions "displaced" by the coproducts, by making assumptions about what products (and hence production emissions) the coproducts will substitute for. This so-called displacement method is on the right track, because it recognizes that coproducts effect emissions in other markets. (In its widely referenced international standards for lifecycle assessment [ISO 14041], the International Standards Organization recommends "expanding the product system to include the additional functions related to the coproducts" instead of "allocation". See B. P. Weidema, "Avoiding co-product allocation in life-cycle assessment," Journal of Industrial Ecology 4 (3): 11-33, 2001, for a good discussion.) The best extension of this "displacement" or "system-expansion" method estimates the effects in other markets as a function of changes in prices. This is what I propose here.

<u>i) A description of the method.</u> The ultimate objective is to estimate changes in emissions in the markets (e.g., for electricity) affected by changes in the production of the coproducts of alternative-fuel production processes. Changes in emissions in these markets are related to changes in production and consumption of the original products in the market. (The "original" products are those that are produced and consumed prior to or in the absence of the change in production of the coproducts. For example, electricity produced by coal-fired plants in the absence of electricity from cellulosic ethanol plants is an original product. In this example, we are interested in changes in emissions from coal-fired power plants as a result of the availability of electricity from ethanol plants.) Changes in production and consumption are related to changes in market price, which in turn are determined by the demand curve and by the supply curve before and after the change in production of coproducts.

As regards changes in the production and consumption of the original products due to the change in the production of coproducts, there are three general outcomes.

a) *All new coproducts are sold and simply displace original products in the market*. If coproducts are preferred to original products on some basis of price and quality, *and* if demand is completely inelastic (so that quantity demanded remains the same even if coproducts cause a reduction in price) or the supply curve is completely horizontal (so that there is no change in the supply curve in the relevant regions and price and quantity remain unchanged by the availability of coproducts), then all new coproducts will be sold and will displace higher-cost or lower-quality original products, and total quantity in the market will remain the same. In this case, the decrease in production of original products in the market (from which the decrease in emissions is to be estimated) will be equal to the change in the output of coproducts.

This actually is a special case of the more general outcome *c* below, because it obtains only under the limiting conditions of completely inelastic demand or completely horizontal supply. I discuss it separately, rather than as part of the more general case, because some (most?) of the lifecycle models that use a "displacement" method for estimating the emissions impacts of co-products do assume that all of the new coproducts simply displace original products, with no other effect. The conclusion here is that the simple-displacement assumptions in these models are correct only under the limiting conditions of completely inelastic demand or completely horizontal supply.

For the purpose of developing an estimation method in this report, this can be treated as a special case under *c* below.

b) *Some (but not all) new coproducts are sold and simply displace original products.* If the new coproducts are more or less of the same quality and price as original products, then price and total quantity demanded in the market will not change, and the choice between coproducts and original products will be random. Some new coproducts will be selected at random and will displace original products, but some will not.

Although this is possible, it is unlikely because revenue from the sale of all coproducts usually will be required to make the entire fuel-production operation profitable. Thus, unless fuel production is mandated or subsidized, it is not likely to occur under market conditions in which some new coproducts will not be sold. We reasonably can assume that this outcome is not likely.

Obviously, the most extreme form of this case -- all new co-products are clearly inferior to original products on the basis of price and quality, and as a result no new coproducts are sold (and production and emissions in the pertinent markets do not change) – is even less likely.

In outcomes *a* and *b* the net result of the change in the production of coproducts is a one-for-one displacement of original products. This, as mentioned above, is what some lifecycle models using the displacement method assume. However, outcome *a* is a limiting condition of the more general case discussed here, and outcome *b* can be dismissed as unlikely. Thus, in order to estimate changes in emissions in the markets affected by changes in the production of the coproducts, we must model the general case in which new coproducts are sold and can affect market prices and quantities.

c) *All new coproducts are sold and the market expands.* The most likely outcome is that all of the new coproducts are sold at or below prevailing prices. This can be represented by an outward shift in the market supply curve: at prices less than original market price, the supply made available to the market will increase by the amount of new coproducts available. For our purposes, this will have two pertinent effects: all new coproduct sales will displace production of higher-cost original products, and total consumption will expand. Thus, in this general case, the net reduction in production of original products (which is the basis for estimating the emissions changes) is equal to the displacement by the production of new coproducts *less* the expansion of consumption. This is the outcome which we should model[8].

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[8]The alternative of actually modeling the selling price of coproducts is too difficult to undertake here. Estimating willingness-to-sell (WTS) functions for coproducts is difficult because we cannot estimate WTS solely on the basis of long-run marginal cost, because coproducts in economic terms are “joint” products to which the assignment of long-run marginal costs is arbitrary. To get WTS for one joint product we must estimate long-run marginal cost for the entire production process and WTS for *all* products (i.e., the primary fuel products as well as the

Figure 2 shows the situation graphically. The availability of coproducts will shift the supply curve out, from S* to S: at any given price, the amount of product supplied will increase by the amount of new coproduct marketed. But in general, the equilibrium quantity of products consumed will not increase by the amount of new coproduct made available to the market, because the equilibrium price of products will decline. Hence, some portion of the marketed new coproducts will displace original high-cost supply, and some will satisfy additional demand stimulated by the lower price.

The balance between displacement and additional supply depends on the slope of the supply and demand curves. Consider again the extreme or boundary conditions. If demand is completely inelastic, there will be no change in consumption, and all of the marketed new coproducts will displace original higher-cost products. On the other hand, if demand is completely elastic, there will be no change in price, and all of the new coproducts will be additional consumption – there will be no displacement of original products at all, and hence no change in emissions[9]. Note that the extreme case of inelastic demand – which is what some models at least implicitly assume -- results in the maximum possible emissions "credit" to new coproduct production, whereas the

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coproducts), because the business requirement is that total revenue from the sale of all joint products covers total long-run production cost. Now, to estimate WTS for the primary fuel products, we must know the supply and demand curves for those products as well. Thus, in toto, we need to know supply and demand curves for all of the coproduct and primary fuel product markets, and the long-run marginal cost function for the entire production process. This is a lot of information. It is simpler and not unreasonable to assume that all coproducts will be sold at less than prevailing market prices.

[9] Similarly, if supply is completely horizontal, there will be no "outward" shift in supply and no change in price and quantity, and coproducts will simply displace higher cost original products. This can be understood intuitively as follows: if all original products are offered at one and only one price, then that will be the equilibrium market price as long as *any* original products are needed to meet demand, and some original products will be needed to meet demand as long as the total amount of lower priced coproducts offered is less than the market demand. And in this case, if the price does not decrease, quantity does not expand.

On the other hand, if supply is completely vertical, the increase in equilibrium market consumption will be equal to the amount of coproduct marketed (the outward shift in the vertical supply curve), and no original products will be displaced. This can be understood intuitively as follows: if the original supply is invariant with respect to price, then coproducts cannot displace original products, because the mechanism by which this displacement might be accomplished – price superiority – has no effect. In this case, the coproducts simply add to the fixed original supply.

extreme case of completely elastic demand -- which prima facie is at least as plausible as the extreme case of inelastic demand, yet which is not assumed by conventional lifecycle modelers – results in no emissions "credit" whatsoever.

Most likely, reality will lie between these two extremes, as indicated in Figure 2 . In Figure 2 , the amount of new coproduct marketed is equal to Q-Q'. As a result of the shift in the supply curve from S* to S, the price declines from P* to P, and the equilibrium quantity increases from Q* to Q. The difference between the total new coproduct quantity marketed, Q-Q', and the equilibrium increase in quantity, Q-Q*, is the amount of original higher cost product displaced, Q*-Q'.

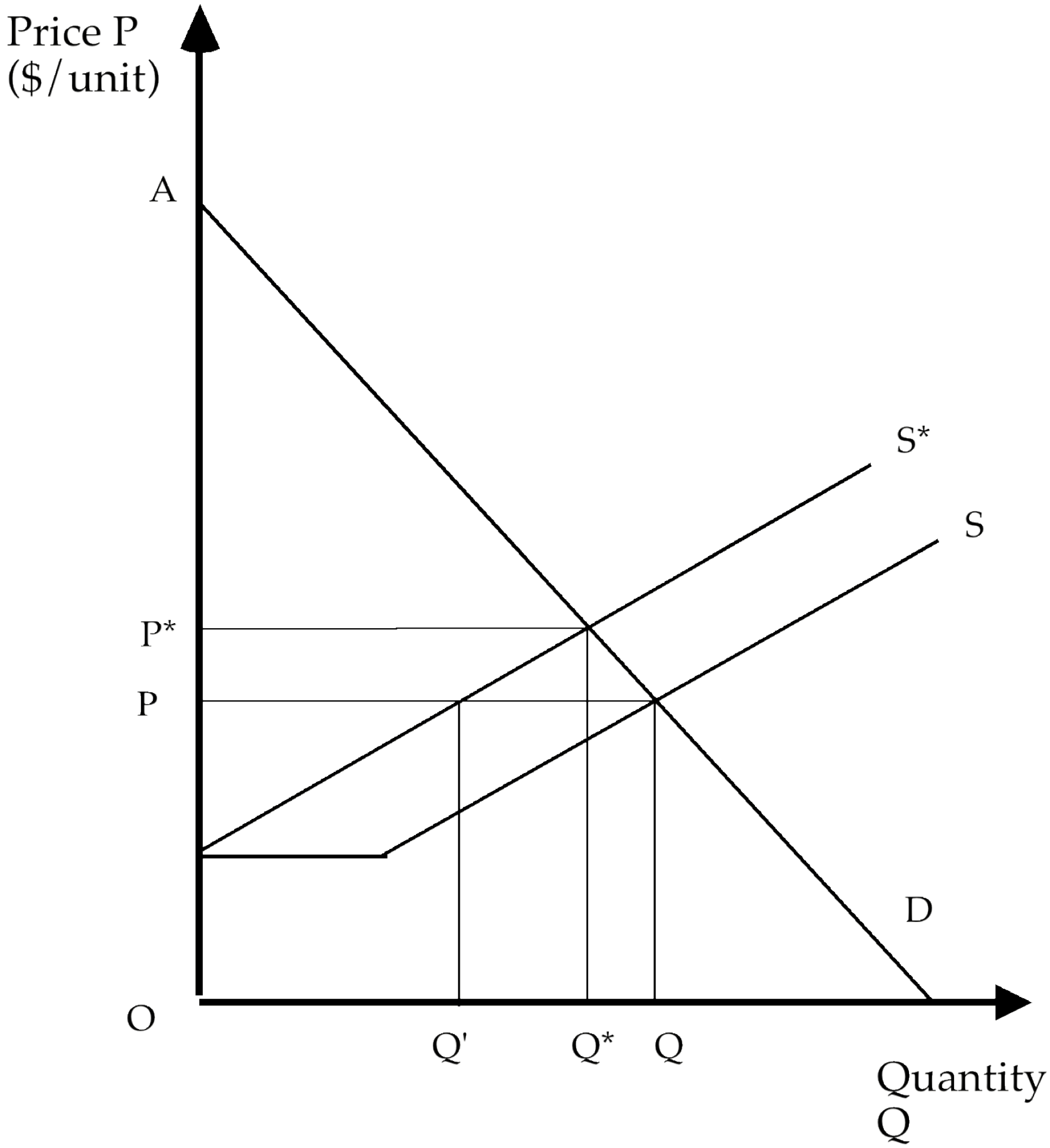

FIGURE 2. THE MARKET DISPLACEMENT EFFECT OF COPRODUCTS

ii) The method formally. To model Figure 2, we need to know the slope of the demand curve and the slope of the supply curve. With this information, we can estimate the change in price and the change in production of original products per unit of new coproduct marketed. With the net change in production of original products, we can estimate the change in emissions. With the change in price we can estimate the change in consumption of substitutes and the associated change in emissions in substitute markets.

Formally, let:

$$P^*-P = \Delta P \quad \text{(change in price)}$$
$$Q^*-Q' = b \quad \text{(displacement of original products)}$$
$$Q-Q^* = c \quad \text{(equilibrium increase in consumption)}$$
$$Q-Q' = \Delta Q = b+c \quad \text{(amount of new coproduct marketed)}$$
$$\text{Slope of demand curve} \equiv D$$
$$\text{Slope of supply curve} \equiv S$$

First, we wish to estimate the ratio of displaced production to marketed coproducts, $b/\Delta Q$, given the slope of the demand and supply curves. The slopes are given by:

$$D = -\Delta P/c$$
$$S = \Delta P/b$$

We can derive a relationship for $b/\Delta Q$ as follows:

$$b/c = -D/S$$
$$b/\Delta Q = -D/S * c/\Delta Q$$

Since $b/\Delta Q + c/\Delta Q = 1$, we have:

$$b/\Delta Q = -D/S * (1-b/\Delta Q)$$
$$b/\Delta Q * (1-D/S) = - D/S$$
$$b/\Delta Q = (-D/S)/(1-D/S)$$

We can use this relationship to estimate the amount of production displaced per unit of new coproduct marketed.

Next, we wish to estimate the change in price per unit of new coproduct marketed, $\Delta P/\Delta Q$, given the slope of the demand and supply curves. From above:

$$\Delta P/\Delta Q/(b/(\Delta Q) = a/b = S$$
$$\Delta P/\Delta Q = S * b/\Delta Q$$
$$\Delta P/\Delta Q = -D/(1-D/S)$$

With this change-in-price relationship, and with estimates of the cross-price elasticity of demand for substitutes, the baseline price of the coproducts, and the baseline consumption of substitutes, we can estimate the change in consumption of substitutes per unit of coproduct. With the change in consumption of substitutes and an estimate of the appropriate lifecycle emission factor, we can estimate the associated change in emissions, per unit of new coproduct marketed.

To arrive at an estimate of emissions changes per unit of production of the commodity of interest (e.g., gasoline or ethanol), rather than per unit of new coproduct, we will need to know the relationship between changes in the production of the commodity of interest and changes in the production of coproducts. This relationship is not necessarily one of fixed proportionality, but may be a function of cost and demand variables. In fact, in some cases a change in production of the commodity of interest will not result in a change in production of coproducts -- which means, technically, that in this case the "coproducts" really are not coproducts, but rather independently producible products. For example, it may be possible to vary the yields from a barrel of crude oil such that a change in gasoline production does not cause any change in residual-fuel production. In this case, there is no coproduct emissions impact to estimate.

In any event, with an estimate of the relationship between a change in the production of the commodity of interest and the change in the production of coproducts, and the estimate derived above of the change in emissions per unit of new coproduct, we can estimate the change in emissions per unit of production of the commodity of interest, due to the economic effects of coproducts.

<u>iii) Compatibility with method for estimating the price effects of inputs to AFLs.</u>
See section xi) of "General discussion 1."

<u>iv) Note: the DSM and the SSM estimate the impacts of changing one fuel option at a time; they do not estimate the impacts of changing several fuel options at once.</u> In the DSM, a shift in demand for an input commodity in an AFL has attached to it a PRLEF that represents the input's effect on the consumption of the commodity in generic emission sectors. However, neither the attached PRLEF nor anything else in the calculation of lifecycle emissions for the AFL in question actually *changes* the use of inputs explicitly represented in other AFLs in the LEM. In this sense, the proposed methods do not estimate the impact of one ALF on another, and as a result the fuelcycle g/mi estimates

must be interpreted as obtaining for implementing each fuelcycle change one at a time.

An example will help clarify this. A shift in the demand curve for natural gas due to new demand by natural-gas vehicles (NGVs) will increase the price of natural gas and reduce the consumption of natural gas by petroleum refineries that make gasoline. The DSM accounts for this effect in the lifecycle of NGVs by attaching to the new demand for natural gas by NGVs a PRLEF that accounts for the emissions effects of changes in natural-gas consumption in other sectors, *including* petroleum refining. However, the PRLEF, which is added to the natural-gas vehicle lifecycle, does not actually change the mix of fuels used by petroleum refineries *in the modeled gasoline lifecycle* in the LEM. (Put another way, the PRLEF calls on but does not change parameters related to natural-gas use by petroleum refineries.) Hence, we cannot interpret the lifecycle results for gasoline and the lifecycle results for NGVs as obtaining simultaneously, because the effect of natural gas on the gasoline lifecycle in not actually implemented within the model.

GENERAL DISCUSSION 3: AN ALTERNATIVE: ADDING EMISSION FACTORS TO A GENERAL EQUILIBRIUM MODEL

An alternative to adding price effects to a lifecycle emissions model is to add emissions to a general equilibrium model. This in fact has been done. Economists at U. C. Berkeley have developed for the California Air Resources Board (CARB) a computable general equilibrium model of the California economy with pollutant emission data for the industrial sectors. The model has 77 sectors, including 30 industrial sectors, 7 household sectors, and 36 government sectors. It solves for the prices of goods, services, and factors of production that equilibrate supply and demand. Goods and money are conserved. Industrial intermediate requirements are based on I-O tables (1992 I-O data), and demand is estimated from the Consumer Expenditure Survey for the West.

The model originally was developed for the California Department of Finance (DOF) to perform dynamic revenue analysis of state legislation. CARB approached UCB to expand the model to have more detail about industrial sectors (particularly petroleum) and to incorporate pollutant emissions, in order for CARB to analyze the economic and environmental impacts of energy strategies. The model developer (Peter Berck, Ag. Econ. Dept. at UCB) told me that emission factors were obtained by dividing CARB's estimates of total emissions from each sector by the I-O output of each sector.

The model is written in GAMS, and complete documentation is available from the internet.

For two obvious reasons, this particular model cannot do what ideally we would want to do -- namely analyze the lifecycle emissions impacts of alternative-fuel pathways in a general-equilibrium framework. First, the model represents the California economy, whereas we would want to represent the national or even global economy. Second, and more importantly, the model does not have sufficient sectoral/technological detail to represent alternative fuel production pathways.

However, we might be able to use the CARB/UCB/DOF model as a guide for either expanding a more suitable existing model or (less plausibly) building from scratch our own simplified general-equilibrium model with appropriate technological and emissions detail. We should investigate further whether there are publicly available general-equilibrium models that could be expanded to include sufficient sectoral detail and emissions data to enable the analysis of lifecycle environmental impacts of AF pathways within a general-equilibrium framework.

DISCUSSION OF PARAMETERS IN THE LEM

Now I turn to discussing price effects and major parameters in the LEM. As mentioned above, the discussion from here forward is organized by the table of contents to the LEM documentation.

The table of contents here is abridged, showing only those sections that I need to talk about. The abridged table of contents headings below are in bold. Following each pertinent heading is a short discussion of the importance of the parameter, the extent to which it is dependent on prices (or other economic variables), and whether and how we might want to represent this dependency.

INPUT AND OUTPUT

Projections of energy use and emissions

The LEM projects many major energy and emissions parameters out to the year 2050. These include oil imports by country, electricity generation mixes, petroleum refinery input-output, vehicle emission factors, fuel characteristics, and many more.

In principle, the trajectory of energy use over time is a function of energy prices and other economic variables. Although price is not a parameter in any of the LEM energy-use projection functions, many of the projections are extrapolations of published EIA projections from the National Energy Modeling System (NEMS), which of course does include energy prices and the effects of changes in energy prices.

We should attempt to incorporate into the LEM a simplified version of the NEMS price-dependent energy-use projections *only* if we wish to be able to represent the effect in year T+N of some change in an AFL in year T. Presently, the LEM calculates results for one user-specified target year T; it does *not* calculate emissions over time. More precisely: the user specifies a single analysis year between 1990 and 2050, and then any parameters that are a function of the analysis year are evaluated for that year. The lifecycle emissions are calculated given the parameters evaluated for the analysis year. Because the only time parameter is the analysis (target) year T, it is not possible to model the emissions over time, or emissions in one year given a change in a different year.

It would be a major and in my view not terribly important revision to make the LEM estimate emissions over time as a function of changing prices. Certainly, it would be too much to do this *in addition* to incorporating the kinds of price effects I outline in the DSM and SSM. Also, it is not clear to me how much the results of such a dynamic model would differ from those of the present “snapshot” model, although I suppose this ignorance also can be cited as a reason for further research.

Of course, the sort of expansion represented by the DSM discussed above does change “projected” energy use or emissions as a function of price -- but only in the year of analysis. The question here is whether these changes should be propagated over time, and I believe the answer for now is “no”.

CO2 EQUIVALENCY (CEF) CALCULATIONS

A CO2-equivalency factor (CEF) equates the effect of a gas other than CO2 to the effect of a gram of CO2. The equating can be on the basis of some measure of climatic effect (e.g., integrated temperature change over time) or some measure of the consequences of climate change, such as economic damage. The CEF is used to come up with a single measure of greenhouse-gas emissions; namely, CO2-equivalent GHG emissions. This is the sum of the mass emissions of each gas multiplied by its CEF (which is 1.0 in the case of CO2, the reference gas). The LEM does simple calculations of CEFs on the basis of sophisticated analyses done by others.

For two reasons, I think it is reasonable to ignore any price effects in the calculation of CEFs. First, the influence of energy prices on the value of CEFs is indirect and weak. The indirect linkage is as follows. Energy prices affect the quantity and mix of energy sources and major commodities, which in turn affect the quantity and mix of emissions of GHGs. Now, the marginal impact of any particular gas on climate -- which is precisely what the CEF is supposed to represent -- depends to some extent on the mix of other gases being emitted, which as just noted is a function of prices. CEFs depend on the mix of gases emitted because some gases have overlapping electro-magnetic absorptive capacities, and so "compete" for the same part of the solar spectrum. Two competing gases will have less of a total climatic effect, and hence less of an effect apportioned to each gas, then will two non-competing gases. Thus, there is some theoretical linkage between prices and the value of CEFs. However, I am reasonably sure that if one were to develop an integrated long-run economic/emissions/climate-change model that calculated CEFs for individual GHGs under different long-run economic scenarios, change in CEFs as a function of the change in major economic variables (perhaps represented by price) would be relatively minor. And, needless to say, developing such a model of CEFs would be quite difficult.

Second, my limited experience is that any plausible range of changes in CEFs is not likely to have a major effect on relative lifecycle CO2-equivalent emissions across alternatives.

Putting points one and two together, it seems to me that any effort to build a price/energy-use/climate-change model into the calculation of CEFs is not likely to significantly change the CO2-equivalent emissions results, and hence probably is not worth doing.

An economic damage index as an alternative to the GWP index

An EDI equates GHG emissions on the basis of the present value of damages from climate change, rather than on the basis of the integrated temperature change over time. Because of this, an EDI probably is more sensitive to price changes than is a GWP. Nonetheless, I feel that the reasoning from the previous section still applies, and that it is not worthwhile to incorporate price into the calculation of EDI-CEFs.

FUELS

The LEM specifies the carbon content, sulfur content, heating value, and in some cases other characteristics of a wide range of fuels. In many cases, fuel characteristics are projected out to the year 2050. Although fuel characteristics technically are a function of the prices of inputs to the fuel manufacturing process and of the demand for and price of finished fuels and fuel-products, the influence here of prices on fuel qualities and ultimately CO_2-equivalent emissions probably is too small (and too complex) to be worth modeling. In any event this effect is addressed much more easily by parametric analyses around fuel characteristics. For example, rather than model the use of MTBE and ETBE as a function of prices and other factors, it is simpler to estimate complete GHG results for gasoline with MTBE and for gasoline with ETBE.

MOTOR VEHICLES: ENERGY USE, FUEL STORAGE, AND WEIGHT

Motor-vehicle fuel economy is a function of fuel and technology prices, and is an important determinant of total CO_2-equivalent GHG emissions. However, because it is such an important parameter, I believe that it should be a user input parameter (which is what it is now in the LEM) rather than a modeled parameter, so that analysts can test its effects directly.

Nevertheless, it might be interesting to incorporate in the LEM a side calculation of fuel economy as a function of fuel prices, technology prices, and other factors, and then let the user specify whether the modeled fuel economy or some directly specified fuel economy is active in the model. If such a side model is relatively easy to construct and specify, it might be worth doing. This, though, would not be a price-emissions feedback loop of the sort I have proposed, but just a side calculation of fuel economy not integrated with any energy use and emissions calculations in the model.

Vehicle weight

In the LEM, the weight of an alternative-fuel vehicle (AFV) is calculated as the weight of the baseline light-duty gasoline vehicle (LDGV) or heavy-duty diesel vehicle (HDDV) plus weight differences between the AFV and the baseline in the powertrain, fuel-storage system, body, and structural support. The weight differences are input by the user or calculated from other simple user input parameters, such as lbs of tankage per lb of fuel carried.

The energy use of an AFV relative to that of the baseline vehicle is calculated as a function of the energy use of the baseline vehicle, the weight difference between the vehicles, and the aerodynamic drag. The relationship between weight and energy use and between aerodynamic drag and energy use are estimated on the basis of results from a detailed drive-cycle model (separate from the LEM). All of these relationships reasonably can be considered to be independent of price and other economic variables.

MOTOR VEHICLES: EMISSIONS

The LEM estimates g/mi emissions of CO, NMOC, NOx, PM, N2O, and CH4 as a function of a zero-mile emission rate, the user-specified model year of the vehicle, and a deterioration rate. In the case of CO, NMOC, NOx, and (for HDVs) PM, the zero-mile emission rate and the deterioration rate are specified on the basis of data from emission tests, emission-factor models such as MOBILE5 and PART5, and EPA's national emissions regulations. In the case of N2O, CH4, and LDV- PM, which are not regulated, the parameters are specified on the basis of emissions tests.

Emissions of SO2 are estimated on the basis of the sulfur content of the fuel and the rate of fuel use, and emissions of CO2 are estimated on the basis of the carbon content of the fuel, the rate of fuel use, and other parameters.

Given this background, what kinds of relationships between economic variables and emissions might we wish to model? There are at least three kinds: i) relatively direct relationships between emissions and general transportation-economic variables such as fuel cost, vehicle costs, or road tolls; ii) relationships between economic variables and the emissions regulations that affect the actual emission rates; and iii) relationships between emissions and emission taxes.

i) Economic variables and emissions. There is in reality no direct relationship between economic variables such as fuel or vehicle price and zero-mile emissions and emissions deterioration. There is however an indirect effect: factors such as the price of fuel can influence how and when vehicles are driven, which, to the extent that emissions are a function of driving patterns, can affect emissions. However, this relationship is weak and difficult to model and therefore in my view not worth further consideration.

ii) Economic variables and regulations. I believe that it is not possible to model the development of emissions regulations – and hence be able to predict motor-vehicle emissions – as a function of prices and other economic parameters. In the first place, the regulations of motor-vehicle emissions are themselves shaped by major environmental legislation, such as the Clean Air Act, and I do not believe it is possible to model law making, because it is so political. The same can be said about the actual development and implementation of regulations (such as emission standards) given governing legislation, unless the implementation of the regulations literally is formulaic, which it almost never is. So long as legislative and regulatory processes are political and non-formulaic, they are not easily modeled formally.

iii) Emission taxes. However, it might be interesting to incorporate into the LEM the ability to model the affect of policies that tax emissions. If emissions themselves were priced directly, say via Pigovian externality taxes, then emission rates and total emissions would be affected by the tax. Specifically, such a tax would affect emissions in three ways: a) to the extent that the total tax payment was related to the distance driven, the tax would tend to decrease driving and hence total emissions; b) the tax would tend to make consumers select lower-emitting vehicles from the existing mix of models; and c) the higher cost of emissions in principle would make consumers willing to pay more for emission control (or fuel economy), which in principle would make manufacturers invest more in emission control (or fuel economy) on all models.

The first effect, which is on total emissions rather than the per-mile emission rate, could be modeled as a function of the relationship between the cost of the tax and the perceived total cost of driving, the relationship between the perceived total cost of driving and the amount of driving, and the relationship between the amount of driving and emissions. To do be able to represent this effect, the LEM first would have to be expanded to estimate total emissions from a vehicle fleet (or from a vehicle over its life) rather than just emissions per mile. The second effect would require something like a vehicle choice model, and the third effect would require representations of manufacturer costs of emission control. Let us look at these three effects more closely.

a) The effect on total emissions. Although it would be interesting to expand the LEM to include models of vehicle production, fleet turnover, and total travel, for two reasons I would not rank this as a top priority. First, this sort of expansion would be a stand-alone add on to the LEM, or even a completely independent model, because it would not feedback to anything within the LEM. That is, this new model would take as input the output of the LEM, and would not produce anything that would affect the emissions-per-mile calculations within the LEM. I would prefer first to incorporate economic effects that necessarily would be "internal" to the LEM; i.e., that would feedback to emissions-per-mile calculations within the LEM. Second, Lew Fulton's Champagne model already does some of these things (I believe it can calculate the VMT and the vehicle mix-effects of a CO2 tax, for example), and has been used along with my model in work for the Canadians. (According to Lew, Peter Reilly Roe and NRCan still maintain Champagne, and Phil Patterson of the USDOE still may be maintaining a US version.)

b) and c) The effect on consumer choice and manufacturer production of vehicles. Again, although this sort of addition to the LEM would be interesting, it would be a stand-alone addition or independent model, and therefore is not in my view as high a priority as is making changes that feedback to emissions-per-mile calculations within the LEM. (These consumer and producer responses do not affect the per-mile emissions of any particular vehicle – which is what the LEM estimates – but rather affect the kinds of vehicles manufactured or chosen. The LEM does not model manufacturer production or consumer choice.) And, once again, this sort of work already has been done. In work sponsored by the USDOE, Train et al. (*Effects of Feebates on Vehicle Fuel Economy, Carbon Dioxide Emissions, and Consumer Surplus,* DOE/PO-0031, U. S. Department of Energy, Office of Policy, Washington, D. C., February, 1995) used a discrete choice model to estimate the impacts of emission fees and rebates on the short-run sales mix (consumer choice) and the long-run product mix (manufacturer production). They found that shifts in the product mix result in much larger improvements in fuel economy and reductions in emissions than does the shift in the sales mix.

<u>iv) Conclusion</u>. There are no important "internal" modifications to be made to the LEM as regards relationships between economic variables and motor-vehicle

emissions. Relationships between emission taxes and emissions are potentially pertinent and important, but can be (and have been) handled outside of the LEM.

PETROLEUM REFINING

BTUs of refinery energy per BTU of each major refinery product

Projections of the mix of refinery fuels

Allocation of refinery energy to specific products

Because petroleum refineries are the second-largest source of GHG emissions (after vehicles themselves) in the lifecycle of a petroleum vehicle, it is important to consider the representation of refinery energy use and emissions closely.

The LEM calculates emissions attributable to each petroleum product by multiplying BTUs of refinery energy per BTU of each product by a vector that breakdowns BTUs of refinery energy to individual fuels, and then by a vector of emission factors for each fuel. Thus, as regards emissions from the use of process fuels at refineries, there are three kinds of parameters to consider: BTU-process-energy/BTU-refinery-product, the mix of refinery fuels, and the emission factors.

<u>i) The BTU-energy/BTU-product parameter.</u> Presently, this parameter is input directly to the LEM for each petroleum product, on the basis of my analysis of studies of refinery operations. In some of the studies reviewed, the BTU/BTU parameter is estimated on the basis of linear-programming models of optimized refinery operations. It might be possible to do this optimization internally in the LEM, perhaps by making refinery energy use a function of the demand for and characteristics of various products and the energy requirements of specific process areas. Then, instead of estimating the BTU-energy/BTU-product parameter itself, the model would estimate the total change in refinery energy given a change in the demand for any one product, and assign that change to the one product. This would give a more accurate estimate of the "marginal" energy requirements of each product.

<u>ii) The mix of refinery fuels.</u> The LEM takes as inputs the mix of fuels used by refineries every year, as projected by the EIA's *Annual Energy Outlook* detailed

tables. (The same mix is used for every petroleum product.) Presumably, the EIA projects the quantity and mix of refinery fuels on the basis of both the energy requirements of producing a particular product slate and the costs of refinery fuels. In principle, I could reproduce something like the EIA projections within the LEM. This would be different from, and hence in addition to, the changes proposed with the DSM.

Referring first to the discussion of the DSM, note that refinery fuels would be both commodities to which PRLEFs are attached, and PACUs included in PRLEFs.

a). As commodities to which PRLEFs are attached, refinery fuels would be treated as follows. In the section of the LEM where g/BTU emissions from refinery-fuel use are calculated, g/BTU PRLEFs would be attached to the use of each refinery fuel. That is, in the refinery-fuel-use section, there would be additional terms (PRLEFs) that show lifecycle CO2 equivalent emissions of GHGs in all of the PACUs (see Table 2), due to changes in the price of fuel brought about by the use of a BTU of fuel (i.e., a one-BTU shift in the fuel demand curve) by refineries.

b). As a PACU, refineries would be treated as follows. Emission factors for refinery fuel use (in g/BTU) would be used in the calculation of PRLEFs that would attach to the use of fuel in AFLs. With reference to the discussion of the DSM, lifecycle emissions from the use of fuels by refineries would be one of the lifecycle emission factors mentioned in iv-g under "general discussion 1".

(See the discussion of the DSM above for more details on the proposed calculation method.)

Now, note that neither a) nor b) involve changing the mix of refinery fuels in (say) the gasoline lifecycle on the basis of the price of the fuels and other economic factors. It would be valuable to do this (that is, represent the refinery fuel mix as a function of the price of fuel, where the price of fuel is determined in part by the use of the fuel in other parts of the LEM) *if* we wished to be able to estimate how fuel use in one lifecycle affected fuel use in another lifecycle implemented at the same time. (As discussed in the "general discussion 2," section iv, the DSM and the SSM do not estimate the effect of one lifecycle on another.) However, there are a multiplicity of such interactions between lifecycles, and I believe that it is too complicated and of too little additional value to attempt to model these interactions. It is simpler just to interpret the results of the LEM as applying to implementing one lifecycle at a time, as discussed in "general discussion 2," section iv.

iii) Emission factors: For general background, see the discussion of emissions under "motor-vehicle emissions." In that section, I consider three kinds of relationships between economic variables and emissions: i) relatively direct relationships between emissions and general economic variables such as energy cost; ii) relationships between economic variables and the emissions regulations that affect the actual emission rates; and iii) relationships between emissions and emission taxes. I conclude in that section that the first kind of relationship is not significant, the second kind is not possible to model, and the third kind is potentially important and interesting but – because it does not affect the calculated per-mile emission rate -- can be done in a separate model, with no feedback into the LEM. These conclusions regarding the first two kinds of relationships apply here to the case of refinery emissions and economic variables. However, the third conclusion, regarding emission taxes, does not apply here, because a tax on refinery emissions, unlike a tax on motor-vehicle emissions, *would* affect the calculated lifecycle CO2-equivalent emission rate *per mile* (because refinery emissions are a part of the calculation of lifecycle emissions per mile).

It therefore may be interesting and important to incorporate within the LEM the effect of emissions taxes on refinery fuel use and ultimately on fuelcycle CO2 equivalent emissions. In this respect, it is useful to distinguish between taxes on CO2 and taxes on urban air pollutants.

a) Tax on CO2. A producer can respond to a CO2 tax in three ways: use less fuel, switch to fuels with less carbon, or capture and dispose of CO2 before it is emitted to the atmosphere. Now, as regards the first two responses, a tax on fuel carbon has the same effect as a tax on CO2, and so a tax on CO2 can be represented in the model by an increase in the price of fuel, using the variation of the DSM discussed in section ix) of "general discussion 1". To model the third response, one would need information on the cost of capturing and disposing of CO2. However, I am not that interested in the possibility of capturing and disposing of CO2, and so do not accord high priority to developing a model of CO2 capture and disposal as a function of CO2 taxes (or CO2 emission limits)[10].

b) Taxes on urban air pollutants. For three reasons, I assign relatively low priority to modeling the effect of a tax on urban air pollutants. First, I do not think it likely that emissions other than CO2 ever will be taxed. Second, changes in emissions of urban-air pollutants usually have a relatively minor effect on fuelcycle CO2-equivalent emissions (although they obviously can have a

[10] The LEM does have CO2 capture and disposal as a user-specifiable option in certain fuelcycles (via "on" or "off" switches) with no consideration of prices or emissions limits.

relatively large effect on fuelcycle emissions of urban air pollutants). Finally, it would be relatively difficult to model this sort of effect.

<u>iv) Coproducts of refinery operation.</u> A shift in demand for and consequent change in refinery production of one petroleum product, such as gasoline, may change the refinery output of other petroleum products, such as residual fuel oil. The change in the output of the other petroleum products will change the price and consumption of the other products. The change in consumption will affect emissions, and the change in price will affect the consumption of substitutes. The change in the consumption of substitutes also will affect emissions. This is of course is the “coproduct” effect discussed in “general discussion 2”, and addressed by the SSM developed in that section.

Thus, to represent this in the LEM, we would proceed generally as outlined for the SSM, in “general discussion 2”:

a) estimate the relationship between the production of the commodity of interest (say, gasoline) and the production of the coproduct (say, residual fuel oil);

b) estimate the slope of the supply curve in the coproduct market;

c) estimate the slope of the demand curve in the coproduct market;

d) with the estimates of b) and c), use the SSM to estimate the displacement of original products by the coproducts per unit of coproduct marketed;

e) with the estimates of b) and c), use the SSM to estimate the change in price in the coproduct market per unit of coproduct marketed;

f) with the estimates of a) and d), calculate the displacement of original products per unit of the primary commodity of interest;

g) with the estimates of a) and e), estimate the change in price in the coproduct market per unit of the primary commodity of interest;

h) estimate cross-price elasticities of demands for substitutes for the coproducts, the baseline price of the coproducts, and the baseline consumption of the substitutes;

i) with the change in price from g) and the estimates from h), estimate the change in consumption of substitutes for petroleum products.

j) estimate the resultant changes in emissions per unit of primary commodity of interest, following the method of the DSM (e.g., iv-g to iv-i).

Note that in some cases the first step (a) may be complicated, requiring knowledge of the cost of and markets for coproducts.

Emissions of pollutants from refinery process areas

CO2 emissions from the control of CO and NMOC emissions from process units

Emissions from refineries are estimated by individual process area or boiler, with specific emission factors and emission-control factors for each area or boiler. See the discussion above of emissions factors for the use of refinery fuels.

ELECTRICITY GENERATION

Efficiency of electricity generation

National average mix of fuels used to generate electricity

The efficiency of electricity generation and the mix of fuels used to generate electricity are important determinants of emissions in fuelcycles that use significant amounts of electricity. In principle these are a function of the cost of fuels and the cost of efficiency-enhancing technology.

The LEM projects the efficiency and quantity of generation by fuel type on the basis of EIA's projections of fuel use by electricity generators. The EIA projections presumably consider fuel costs and capital costs. I believe that it is not worth attempting to reproduce a simplified version of the EIA projections in the LEM for the purpose of estimating the efficiency of electricity generation as a function of prices and other economic variables. (For a bit more discussion, see "input and output, projections of energy use and emissions," above).

However, electricity use and the inputs to power generation should be *both* commodities to which PRLEFs are attached, *and* PACUs included in PRLEFs (see the discussion of the DSM, above). Considering electricity use separately from power generation, and considering the attachment of PRLEFs to the electricity lifecycle separately from the estimation of PRLEFs for electricity as an emission source, we have four combinations to treat.

<u>i) Attaching PRLEFs to the calculation of emissions from power generation.</u>
As commodities to which PRLEFs are attached, the inputs to power generation would be treated as follows. In the section of the LEM where g/BTU emissions from power generation are calculated, g/BTU PRLEFs would be attached to the use of each fuel input. For example, in the calculation of emissions from coal-

based generation, there would be an additional term that shows lifecycle CO2 equivalent emissions of GHG (per BTU of coal) in all coal PACUs, due to changes in the price of coal brought about by the use of a BTU of coal (i.e., a one-unit shift in demand for coal) for power generation.

ii) Attaching PRLEFs to the calculation of emissions from electricity use. As a commodity to which a PRLEF is attached, electricity use would be treated as follows. In the section of the LEM where g/kWh emissions from electricity use are calculated, g/kWh PRLEFs would be attached. For example, in the calculation of emissions from the use of the national-average electricity mix, there would be an additional term that shows lifecycle CO2 equivalent emissions of GHG (per kWh) in all electricity PACUs, due to changes in the price of electricity brought about by the use of a kWh of electricity (i.e., a one-unit shift in demand for electricity).

Note that one would have to be careful here to avoid double-estimating some effects. For example, the PRLEF attached to electricity use should *not* include the emissions effects of changes in the prices of inputs to power generation, because those effects will be included already in the g/kWh emission factor for electricity use, via the PRLEFs attached to the inputs to power generation discussed in section i just above.

iii) Electricity generation as a PACU included in PRLEFs. Emission factors for electricity generation (say from the use of coal) (in g/BTU) would be used in the calculation of PRLEFs that would attach to the use of coal in AFLs. With reference to the discussion of the DSM, lifecycle emissions from the use of coal to generate electricity would be one of the lifecycle emission factors mentioned in iv-g under "general discussion 1".

iv) Electricity use as a PACU included in PRLEFs. Similarly, emission factors for, say, generic or national-average electricity use (in g/kWh) would be one of the lifecycle emission factors used in the calculation of PRLEFs.

High-renewables generation scenario

The LEM has an electricity-generation scenario that has more renewable-fuel input than does the baseline based on the EIA's AEO. This high-renewables scenario is linked to fuelcycles that use a lot of renewable energy, on the assumption that a world in which more renewable fuels are used in transportation also is a world in which more renewable fuels are used in electricity generation.

One perhaps could model this sort of relationship (between the use of renewable fuels in transportation and the use of renewable fuels in other sectors such as electricity generation) rather than just make a relatively arbitrary assumption about it. For example, one could associate with renewable fuelcycles in transportation specific policies represented by changes in the price of supply curve for renewable fuels in general. The use of renewable fuels in non-transportation activities in the LEM (e.g., electricity generation) could be made a function of the price and quantity variables that represent the action that originally drives the use of renewables in transportation. This addition would be interesting, and perhaps of nontrivial importance if the policies and functions are such that it is possible to get large changes in the use of renewable fuels outside of transportation. It might be particularly important in modeling the emissions impacts of actions that stimulate the use of biofuels in transportation.

Uncontrolled emissions from utility boilers

Emission-reduction factor due to emission controls

Controlled emissions from electricity generation are estimated by multiplying uncontrolled emissions by an emission-reduction factor, for each generating technology and fuel. The emission reduction factor is estimated on the basis of the phasing in of emission controls. The actual input variables are uncontrolled emissions, the effectiveness of emission control technology, the fraction of output subject to emission control in a base year, and the rate of increase in output subject to control.

With one important qualification, the conclusion of the discussion of motor vehicle emissions applies here. The conclusion there is that the affect of economic variables on emissions via emission-control technologies is too indirect and complex to be worth modeling here. However, there is an important difference between the treatment of electricity and the treatment of transportation. Because transportation is the main focus of analysis in the LEM, results are reported for specific fuel/vehicle/emission control technologies, without -- and here is the key -- much need to aggregate across the technologies or determine the "marginal" vehicle/fuel combination. By contrast, because the output of the electricity sector is an input into many processes in the LEM, there is in principle a need to determine the characteristics of the actual power delivered "at the margin" to each of the electricity-using sectors. (Technically this does arise in transportation, too, because heavy-duty truck transportation is an input to a number of processes, but this can be considered a second-order effect reasonably well handled by assuming average truck transport characteristics for all processes.) This means that, in principle, the efficiency of generation, the mix of generation fuels, and the phase-in of emission controls (which as mentioned above is represented in the model) should be a function of fuel prices, electricity demand, and other factors, in each electricity market.

Presently the LEM does vary the mix of fuels used to deliver the power to several major end-use sectors, but this variation is input by the user and is fixed over time and not a function of economic variables. And as mentioned above, what is calculated is an average emission-control reduction for each fuel type in a given year, independent of economic variables.

It would be better, in principle, to specify fully controlled and uncontrolled emissions for each fuel type (for power plants), and then let the mix of controlled and uncontrolled generation over time be a function of electricity cost (different for controlled and uncontrolled generation) and sector-specific demand and regulatory variables. This is an important but potentially complicated revision to the LEM.

Greenhouse-gas emissions at hydropower facilities

The LEM estimates emissions of CH_4 and CO_2 from hydropower reservoirs. The LEM uses constant emission factors per kWh of hydropower, but in reality these emissions are a function of the surface area of reservoirs, which in turn is a function of the drawdown of the reservoir for hydropower generation, which in turn is a function of electricity demand and prices. However, I believe that any feedback effects of economic variables to emissions from hydropower reservoirs has too minor of an effect on LCGE to be worth modeling.

PRODUCTION OF ALTERNATIVE FUELS

In the lifecycle of an alternative fuel, the fuel production stage generally is one of the largest consumers of major commodities (such as natural gas) and one of the largest sources of emissions. The price/emissions effects of this use of major commodity inputs to the production of alternative fuels can be handled by the DSM, in which major inputs to the production of alternative fuels have PRLEFs attached to them. For more details, see the discussion of the DSM, and the discussions under “petroleum refining” item ii and “electricity generation” items i and ii.

Because there is relatively little production of alternative fuels today, there is no need to include alternative-fuel production as one of the PACUs included in PRLEFs. Similarly, because alternative fuels themselves generally are not inputs to other processes, there is no need to include alternative fuels themselves among the commodities to which PRLEFs are attached. (See the list of commodities to which PRLEFs would be attached and the list of PACUs, in the discussion of the DSM.) Thus, only the use of inputs to alternative fuel production need be incorporated into the price/emissions model discussed here.

Note that crops and biomass are inputs to some alternative-fuel production processes. PRLEFs attached to crop and biomass inputs would estimate the price/emission effects in the “agriculture: crop production” PACU.

Coproducts of the corn-to-ethanol conversion process: conceptual background

GHG emissions displaced by the DDGS coproduct of dry-mill ethanol plants

The co-product displacement credit for wet-mill plants

Assumptions about coproducts can have a significant impact on LCGE in the corn-to-ethanol lifecycle. In the present LEM the coproducts of corn-to-ethanol plants are assumed to displace production of alternative sources of animal feed. The inputs to the calculation of the emissions impact of these coproducts include: the amount of coproduct per unit of corn input; the amount of coproduct equivalent as feed to a unit of alternative soy or corn feed; and a “net displacement factor,” which is a direct estimate of the amount of original feed product displaced per unit of new coproduct marketed (the ratio of Q*-Q’ to Q-Q’ in Figure 2). The net displacement factor is assumed on the basis of an informal discussion of coproduct markets; it is not formally calculated according to the SSM outlined above.

Given the importance of coproducts in the analysis of lifecycle emissions for corn-to-ethanol, it might be worthwhile to simulate within the LEM the market for animal feed rather than just assume a net displacement factor. The simulation would be based on estimated slopes of supply and demand curves, according to the SSM outlined in “general discussion 2”. Because there are different kinds of animal feed (soy-based feed, corn-based feed, and the coproducts of the corn-to-ethanol process), one would have to identify a primary feed commodity for which direct displacement by coproducts was estimated (via the slope of the demand and supply curve), and substitute feed commodities for which indirect effects were estimated on the basis of cross-price elasticities.

Note that the emissions impacts of changes in the production of primary and substitute feed commodities displaced by corn-to-ethanol coproducts must incorporate the entire lifecycle of the displaced primary and substitute commodities. The LEM presently includes lifecycle emissions from the production and transport of corn as animal feed. Emissions from the lifecycle of other significant sources of animal feed potentially affected by coproducts of corn-to-ethanol should be added to the LEM.

A final consideration (albeit one not directly relevant to the discussion of incorporating price effects into the LEM) is that corn-to-ethanol coproduct animal feed has different characteristics (for example, as regards digestibility) from even its closest competitors. It has been argued that some of these differences can affect GHG emissions. For example, digestibility might effect emissions of methane, which is a GHG. This sort of effect should be investigated and if found to be significant should be added to the LEM.

Coproducts of wood-to-alcohol production

Electricity displaced by electricity exported from wood-to-ethanol and grass-to-ethanol plants

Bioethanol plants can be designed to export large amounts of electricity to the grid. This exported electricity can displace the generation of fossil-fired electricity and thereby have a significant impact on LCGE for bioethanol.

In the present version of the LEM the inputs to the calculation of the emissions impact of exported electricity include: the amount of electricity generated per unit of ethanol produced; the net displacement factor, which is a direct estimate of the amount of original electricity displaced per unit of new electricity generated by bioethanol plants; and the mix of generating fuels displaced by the exported electricity. The net displacement factor is assumed on the basis of an informal discussion of demand for electricity and substitutes for electricity; it is not formally calculated according to the SSM outlined above.

Given the importance of electricity exports to the calculation of lifecycle GHG emissions for bioethanol, it would be worthwhile to apply the SSM framework discussed in "general discussion 2", rather than just assume a net displacement factor. As explained above, the heart of the SSM is the estimation of the slopes of supply and demand curves and the estimation of cross-price elasticities for substitutes for electricity (e.g., natural gas instead of electricity for cooking). In this case, we would want to estimate electricity supply and demand curves (and substitution possibilities) for the regional markets where the exported coproduct electricity would be sold. However, in order to estimate changes in emissions (which is our ultimate objective), we would have to translate shift in electricity demand curves into changes in generation by fuel type, because emissions depend on the type of fuel used for power generation. To do this, we would have to have something akin to a dispatch order for the regional electricity supply being modeled.

The amount of electricity generated per unit of ethanol produced actually can be quite variable, depending on the balance between biomass converted to ethanol and biomass left over for power generation. This balance depends on the cost of ethanol conversion, the cost of power generation, the revenues from ethanol sales, and the revenues from electricity sales. Although it might be possible within the LEM to model these costs and revenues, and hence determine an "optimal" plant design, I believe that it is better to leave this optimization to others, and perform scenario analyses within the LEM of the emissions impacts of different plant designs regarding ethanol production vs. electricity production.

Coproducts of the soy biodiesel production process

This should be handled in the same way as proposed for the coproducts of corn-to-ethanol. See also the discussion of the SSM, above.

Emission factors for plants that produce ethanol or methanol

Emission factors for plants that produce hydrogen from natural gas

Emission factors for wood-waste combustion in boilers

See the discussion of emission factors under “motor vehicles: emissions,” “petroleum refining,” and “electricity generation.” Note, though, that the treatment of emissions from alternative-fuel production processes could be simpler than the treatment of emissions from electricity generation, because we could assume that most if not all AF production plants would use state-of-the art emission control systems. Hence, there would be no need to determine whether the "marginal" alternative-fuel production will come from controlled or uncontrolled plants; presumably it would all come from controlled plants.

PRODUCTION OF CORN, SOYBEANS, TREES, AND GRASSES

This section of the LEM documentation discusses the energy, chemical, and land inputs to the production of crops and cellulosic biomass. In the LEM this use is represented in simple input-output terms; for example, X gallons of diesel fuel, Y lbs of nitrogen, and Z acres of land produce one bushel of corn. Emissions from the use of energy for cultivation and from the manufacture of fertilizers generally are at least 15% (and in some cases a much greater percentage) of lifecycle CO2-equivalent emissions.

The price/emissions impacts of using energy, fertilizer, and land in the production of crops and cellulosic biomass can be estimated by the DSM, in which the land, fertilizer, and energy inputs have PRLEFs attached to them. The PRLEFs attached to energy inputs to agriculture will represent the price/emissions effects in the energy PACUs of Table 2; the PRLEFs attached to fertilizer inputs will represent the price/emissions effects in the “agriculture: fertilizer use” PACU; and the PRLEFs attached to land inputs will represent the price/emissions effects in the “agriculture: land use” PACU. (It may be desirable to disaggregate the “agriculture: fertilizer use” PACU into several different crop categories.) Note that the estimation of PRLEFs for fertilizer use will require information on the price elasticity of demand for fertilizer use.

Finally, note that as a PACU included in PRLEFs, energy use in agriculture is subsumed under “offroad, energy use”.

Where will the marginal corn come from?
This question will be addressed in the section on “greenhouse-gas emissions related to cultivation and fertilizer use”.

Note on the impacts of conservation tillage
Conservation tillage, in which some crop residue is left on the soil, can reduce erosion and improve soil properties, but also can require greater use of pesticides and fertilizer. As a result, its impact on GHG emissions is unclear. Although it might be interesting to attempt to model the adoption of conservation tillage as a function of economic and other variables, I feel that it would be too difficult and probably ultimately of too little emissions impact to be accorded high priority.

Collection, grinding, baling, and transport of corn residue
Corn residue can be left on the field to enhance the soil, used as a fuel in the conversion of corn to ethanol, or itself converted to ethanol. Each of these routes has considerably different lifecycle GHG emissions. I believe that each of these routes should be represented in the LEM as independent scenarios, rather than modeled (or weighted) as a function of economic and other variables.

ENERGY USED TO MANUFACTURE AGRICULTURAL CHEMICALS

The LEM has a detailed representation of the lifecycle of fertilizers and pesticides used in agriculture. Emissions from the manufacturing of agricultural chemicals can be significant absolutely (1,000 to 10,000 grams of CO2 equivalent per million BTU of fuel), and in some cases are a large fraction of LCGE for biofuels.

The discussion of price/emissions impacts here is similar to that for “electricity generation”. PRLEFs would be attached to the major inputs to agricultural chemical manufacturing, in the calculation of emissions for that lifecycle. Because agricultural chemicals also are inputs to other processes, PRLEFs would be attached to agricultural-chemical products wherever they are inputs to other lifecycles (see for example “production of corn, soybeans, trees, and grasses”). The PRLEFs attached to agricultural chemicals as inputs to other processes would estimate the price/emissions impacts in the “agriculture: fertilizer use” PACU of Table 2. The calculation of emissions impacts in this PACU would use emission factors for the *entire* lifecycle of agricultural chemicals (i.e., would include emissions related to the application and use as well as the manufacture of agricultural chemicals) in one or more general applications. Future work should determine precisely how the “agriculture: fertilizer use” PACU should be represented (i.e., determine which combination of uses or average uses lifecycle emissions should be calculated for).

As discussed above in section ix) of “general discussion 1: a way of expanding the LEM to include price effects of commodity use (inputs) in AFLs”, it would be useful to represent the effect of policies that change commodity prices directly (e.g., a carbon tax on natural gas, which is a input to the manufacture of agricultural chemicals). See that section for further discussion. It also might be possible to explicitly project major commodity prices over time, but I would accord this relatively low priority. (In this last regard, see the discussion under “input and output, projections of energy use and emissions”.)

GREENHOUSE-GAS EMISSIONS RELATED TO CULTIVATION AND FERTILIZER USE

Nitrogen input in energy crop system E

N2O from nitrogen input (GHGN2OFE)

N2O emissions related to cultivation of organic soils (GHGN2OSE)

NOx and NH3 related to use of synthetic nitrogen fertilizer and animal manure (GHGNO2FE)

Nitrogen used in the production of biomass can via several different pathways affect emissions of greenhouse gases such as N2O. In the production of corn and soybeans, greenhouse-gas emissions related to nitrogen use are a significant fraction of total LCGE.

In the LEM a series of parameters or simple equations represent the physical conversion of nitrogen to GHG emissions. These physical processes – for example, the rate at which soybeans fix nitrogen, or the fraction of fixed nitrogen that is converted to N2O -- may reasonably be assumed to be independent of economic parameters.

However, the *use* of nitrogen in biomass production – for example, the amount of synthetic nitrogen fertilizer applied to corn – in principle is a function of economic parameters such as the price of fertilizer, the marginal yield per unit of fertilizer, and the marginal value of the corn product. Because the use of nitrogen can be an important determinant of LCGE, it might be worthwhile to model the economics of nitrogen use. However, I do not here propose a method for doing this in the LEM.

Of course, GHG emissions related to fertilizer use would be incorporated in the DSM discussed above, as follows. PRLEFs would be attached to the use of crops, fertilizer, biomass, and land wherever they are inputs to other lifecycles (see for example “production of corn, soybeans, trees, and grasses”). The PRLEFs attached to these would estimate the price/emissions impacts in the “agriculture: fertilizer use,” “agriculture: crop use,” “agriculture: biomass use,” and “agriculture: land use” PACUs of Table 2. The calculation of emissions impacts in these PACUs would use emission factors for the entire lifecycle of agricultural chemicals, including emissions related to cultivation and fertilizer use.

CH4 and CO2 emissions from soil (parameters GHGMFE, GHGMSE, and CO2SFE)

Nitrogen fertilization and carbon storage off-site (parameter CO2NFE)

Changes in carbon in soil and biomass, due to changes in land use (parameter CO2CE)

The discussion here is similar to the discussion in the previous section regarding emissions from fertilizer use.

In the LEM a series of parameters or simple equations represent changes in carbon storage and carbon-related emissions due to cultivation of land. These physical processes may reasonably be assumed to be independent of economic parameters. However, the use of land for cultivation in principle is a function of economic parameters such as the price of land, the productivity of land, and the value of the product. Nonetheless, I do not here propose a method for modeling the use of land as a function of economic and other parameters.

GHG emissions related to changes in land use would be incorporated in the DSM as follows. PRLEFs would be attached to the use of crops, biomass, and land wherever they are inputs to other lifecycles (see for example “production of corn, soybeans, trees, and grasses”). The PRLEFs attached to these would estimate the price/emissions impacts in the “agriculture: crop use,” "agriculture: biomass use," and "agriculture: land use" PACUs of Table 2. The calculation of emissions impacts in these PACUs would use emission factors for the use of crops, biomass, or land, including emissions related to changes in carbon storage and carbon emissions.

PRODUCTION OF OIL, GAS, AND COAL

Representation of international trade in crude oil, petroleum products, coal, and natural gas

In the calculation of energy use and emissions from the international transport of fuel commodities, the LEM uses the EIA's AEO projections of imports and exports of fuels by country. I believe that there is little reason to attempt to reproduce a simplified version of the AEO projections within the LEM, especially because typical changes in international trade flows have a very small effect on LCGE.

Venting and flaring of associated gas

Emissions of methane from coal mining

Emissions of methane and natural gas contribute nontrivially to LCGE in coal, oil, and natural-gas fuelcycles. In the LEM these emissions are calculated from detailed historical data and are not a function of economic variables.

In principle, methane emissions are a function of the design and operation of the fuel systems, and these in turn are a function of fuel price, system costs, and other economic variables. Although it might be interesting to model emissions as a function of economic variables, it would be difficult and uncertain and in my view of limited value. In this case, I believe it is adequate to continue to use price-independent emission factors in the LEM.

ENERGY USED IN MINING (FEEDSTOCK RECOVERY)

The inputs to the recovery of oil, gas, and coal account for only a small fraction of LCGE from the use of these fuels. If the number of inputs to which PRLEFs can be attached must be limited in order to allow the model to solve, then PRLEFs should *not* be attached to inputs – such as those in the production of oil, coal, and gas -- that have a minor effect on LCGE. Thus, only if there are no constraints on the number of PRLEFs in the LEM would the inputs to the recovery of oil, gas, and coal have PRLEFs attached to them.

The recovery of oil, gas, and coal is not a separate PACU included in PRLEFs, but rather is a part of "energy use: other industrial processes".

NATURAL GAS TRANSMISSION AND DISTRIBUTION

Energy intensity of natural gas transmission

See the preceding discussion "energy used in mining".

Leaks of natural gas

See the discussion of "venting and flaring of associated gas" and "emissions from coal mining".

SHIPMENT OF FEEDSTOCKS, FUELS AND VEHICLES

In the LEM, emissions from the shipment of feedstocks, fuels, and vehicles are calculated for a particular shipping mode (e.g., rail) as the product of the length of haul, the energy use per ton-mile, and the fraction of total ton-miles shipped by the particular mode. These emissions typically are a minor fraction of LCGE.

In principle, all of three of these parameters – haul length, energy intensity, and mode choice – can be modeled as a function of various economic parameters. Indeed, the EIA's NEMS does model some of these as a function of fuel costs and other cost and performance parameters. If sufficient resources are available to us, it might be worthwhile to attempt to do this sort of economic modeling within the LEM, although in consideration of the minor contribution of this stage to LCGE I would suggest that such modeling be given low priority.

See also the discussion under "representation of international trade in crude oil, petroleum products, coal, and natural gas".

FUEL MARKETING AND DISPENSING

Energy required to compress or liquefy gases

The LEM estimates emissions from the evaporation or leakage of fuels and from the use of energy to dispense and if necessary compress fuels during the marketing stage. With the exception of methane leakage, evaporative and leakage losses generally have only a minor impact on LCGE[11]. (Also,.)

Fuel evaporation and leakage is a function of the design, operation, and emission-control technology of fuel marketing systems. Although all of these parameters are a function of fuel demand, capital costs, operating costs, and other economic variables, I believe that it would be too difficult and of too little impact to actually model evaporative and leakage losses as a function of economic variables. In this case, I believe it is adequate to continue to assume fixed emission factors in the LEM.

However, the use of energy to compress gaseous fuels is a different matter. It takes a lot of energy to compress natural gas or hydrogen, and it would be straightforward to incorporate this use of energy into the PE framework proposed here. The use of electricity at service stations, for compression and dispensing, should have attached to it a PRLEF which would account for the price and emissions effect on energy PACUs due to using energy for fuel compression or dispensing. See the discussion of the DSM for more details.

I do not believe that energy use at gasoline service stations is significant enough to warrant it being a separate PACU for which PRLEFs are estimated (see the discussion of the DSM).

EMISSION FACTORS FOR INDUSTRIAL BOILERS AND OTHER STATONARY SOURCES

See the discussions of emissions under “motor vehicles: emissions,” “petroleum refining,” and “electricity generation”.

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[11] Evaporative emissions of hydrocarbons can be significant compared to tailpipe emissions of hydrocarbons

EMISSION AND ENERGY-USE PARAMETERS FOR NONROAD ENGINES

The LEM includes a variety of nonroad engines, such as tractors and forklifts. There is a relatively detailed treatment of the emissions and energy use of large non-road engines such as forklifts: emission factors and fuel use are estimated by model year, on the basis of actual and planned emissions regulations.

Emissions from nonroad engines. As regards direct relationships between prices and emissions from nonroad engines, see the discussion under "motor vehicles: emissions" and "petroleum refining".

Nonroad fuel use as a commodity of interest to which PRLEFs might be attached. In the discussion of the DSM, I propose that petroleum products – which include diesel fuel, the primary fuel used by offroad engines – be one of the commodities to which PRLEFs are attached. However, I have not identified every use of every petroleum product to which PRLEFs should be attached. (I propose doing this detailed identification during the actual development of the expanded model.) The use of diesel fuel by nonroad engines thus may or may not have a PRLEF attached to it.

Nonroad fuel use as a PACU in the calculation of PRLEFs. In "general discussion 1", I propose that offroad fuel use be one of the PACUs in the estimation of PRLEFs. This means that the lifecycle CO2-equivalent emission factor calculated for offroad engines (g/BTU-fuel use) may be used in the calculation of PRLEFs in the manner delineated in the discussion of the DSM. (See "general discussion 1" above.)

If nonroad fuel use is both a PACU in the calculation of PRLEFs *and* a commodity to which PRLEFs are attached, the resultant circularity will further tax the solution capability of the LEM. Too many additional such circularities may overtax the model.

FUELCYCLE EMISSIONS FROM THE USE OF NATURAL GAS, ELECTRICITY, FUEL OIL, AND LPG FOR HEATING AND COOKING

Applying the model to estimate fuelcycle emissions for space heating and water heating

Up to the point of end use, the lifecycle of fuel used for, say, home heating is virtually the same as the lifecycle of that fuel used in transportation. Hence, all of the previous discussion of the lifecycle of fuels -- at times nominally in the context of transportation -- applies to fuels for space heating.

End-use emission factors for residential and commercial heating

End-use efficiency

In the LEM emission factors and end-use efficiency for heating are specified directly, on the basis of studies of efficiency and emissions for particular fuels and technologies. The LEM does not project the mix of fuels or technologies used in home heating, but instead simply reports emissions results for each fuel type given the assumed efficiency and emission factors (corresponding to a general, unspecified technology type).

Efficiency and emissions. I do not believe that it is worthwhile to model efficiency and emission factors for heating as a function of technology costs, fuel prices, and demand. Efficiency and emissions are technical characteristics, and it is beyond the reasonable scope of this effort to model technology choice as a function of fuel price, technology costs, and other economic factors. See also the discussions of emissions and efficiency under "motor vehicles: emissions" and "electricity generation, efficiency of electricity generation".

Heating fuel use as a commodity of interest to which PRLEFs are be attached. However, it probably would be worthwhile to model fuel consumption and emissions in the heating sector as a function of changes in fuel demand and prices. In the discussion of the DSM, I propose that natural gas and fuel oil -- the primary fuels used for heating – be commodities to which PRLEFs are attached. Although I have not positively identified every specific use of these fuels to which PRLEFs should be attached (I propose doing this detailed identification during the actual development of the expanded model), the use of these fuels for heating probably should have PRLEFs attached, because the LEM already calculates lifecycle emissions for heating and because heating-fuel use is proposed to be a PACU in the DSM See the discussion of the DSM and PRLEFs for more details.

Heating as a PACU in the calculation of PRLEFs. I propose that the DSM have "heating" as one of the generic PACUs that could be affected, via price changes, by the use of fuel commodities in AFLs. This means that the lifecycle CO2-equivalent emission factor calculated for heating (g/BTU-fuel use) may be used in the calculation of PRLEFs in the manner delineated in the discussion of the DSM. (See "general discussion 1" above.)

“OWN-USE” OF FUEL

"Own use" refers to the methodological treatment of the use of fuel F in the production-and-use lifecycle of fuel F; for example, the use of diesel fuel by trucks in the lifecycle of producing diesel fuel from crude oil. This "loop" is fully accounted for in the LEM. Price is not a factor, even in theory, in the functional representation of this feedback loop. (Price is a factor in the choice of fuel, but it is not a factor in the representation of fuel-cycle loops and feedbacks given particular fuel choices. I discuss the effect of price on fuel choice elsewhere in this report.)

RESULTS FROM THE REVISED GHG EMISSIONS MODEL

I do not expect that there would be much use in incorporating estimates of LCGE per mile into the sort of PE framework discussed here, mainly because the lifecycle emissions themselves are an analytical result and not a policy-relevant quantity. For example, although it is possible to tax CO2 emissions from motor vehicles, and thus perhaps sensible to incorporate the effect of such a tax on fuel use, vehicle travel, fleet average emissions, and energy use in non-transportation sectors (this is discussed above, in the section “motor-vehicles: emissions”), it is not likely that there ever will be a tax on a fuelcycle total as such (as opposed to taxes on the individual sources in the fuelcycle). If this is so, there is no need to incorporate the lifecycle g/mi results themselves into the PE framework.