Incorporating prices into Life Cycle Analysis

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Outline

- Motivation
  - Usefulness of Life Cycle Analysis (LCA)
  - Limitations of current LCA for policy
- Incorporating price effects in LCA
  - Illustration using a 2 X 2 setting
  - Generic framework
- Future research
- Summary

Search for alternative transportation fuels

- **Phase I (1970's)**
  - as a response to artificial scarcity (OPEC embargo) and energy security, policy support was short-lived
  - environmental benefits were not the main driver
- **Phase II 1st Generation (2000-2006)**
  - as a response to real scarcity and concern for carbon emissions
  - ethanol and biodiesel from edible plant matter
  - LCA was used as a tool justify the environmental benefits
- **Phase II 2nd Generation (2007 onwards)**
  - recognition of problems with 1st generation biofuels
  - search for better biofuels
  - LCA is again used to show the relative advantage of potential 2nd generation fuels over 1st generation

LCA for policy

- As environmental concerns have grown so has the role of LCA in energy and environmental policy

- LCA is used extensively to compare the net environmental emissions of GHG, air pollutants and toxics arising from competing processes or products

The LCA technique:
an energy & material balance

Two types of LCA approach

- ***Economic input output*** (EIOLCA)
  - Based on IO model of the economy
  - Each industry has fixed proportion technology and uses produced and primary inputs to meet demand
- ***Process LCA***
  - Distinguishes between processes (irrigation with sprinkler vs furrow)
  - Detailed model of each process in the life cycle
  - Suitable for modeling new processes and products
  - But not easy to aggregate

Typical conclusion from LCA

- A typical LCA study comes to the conclusion that each liter or each megajoule of Fuel A on average results in x% less or more carbon emissions than Fuel B
  - Tilman et al. *Science* 2007
  - Farrell et al. *Science* 2006
  - Patzek and Pimentel *Natural Resources Research* 2005

- However such conclusions say little about future performance, say, when production expands and
  - Marginal agricultural expansion happens by clear-cutting forests
  - Marginal gasoline production comes from tar sands
  - Fertilizer production shifts towards coal from natural gas

Illustration - GHG impact of fuel switching by biorefineries (based on Farrel et al)

Switching to pure coal based biorefining reduces GHG benefits by 50%, while switching to pure gas based biorefining increases GHG benefits by 130% compared to average case

net GHG displacement based on source of energy used in biorefining of corn in US	**kg CO2e/liter of ethanol**	**% change compared to average plant**
Average plant which uses both coal and gas today (Farrell et al. *Science* 2006)	0.18	-
Coal only	0.09	-50%
Gas only	0.42	133%

Illustration - GHG impact of fuel switching in fertilizer production

Switching to pure coal based nitrogen fertilizer reduces GHG benefits by 63% compared to average case

net GHG displacement based on source of fuel used in producing N-fertilizer	**kg CO2e/liter of ethanol**	**% change compared to average plant**
Average fertilizer production (90% Gas +10% coal) (Farrell et al. *Science* 2006)	0.18	-
Coal only	0.07	-61%

Illustration – Combined effect

There is a net increase in GHG emissions and so there corn ethanol is worse than gasoline

net GHG displacement based on source of fuel used in producing N-fertilizer	**kg CO2e/liter of ethanol**	**% change compared to average plant**
Average fertilizer production (90% Gas +10% coal) (Farrell et al. *Science* 2006)	0.18	-
Coal only	-0.01	-106%

A greater than 100% reduction in net GHG displacement implies overall increase in emissions compared to baseline

Limitations of LCA

- Fixed proportions i.e, no possibility of input substitution
- Fixed technology
- Constant returns to scale
  – Agriculture may have decreasing returns to scale because of land quality distribution
- No capacity constraints
- Homogeneity

LCA ignores behavior

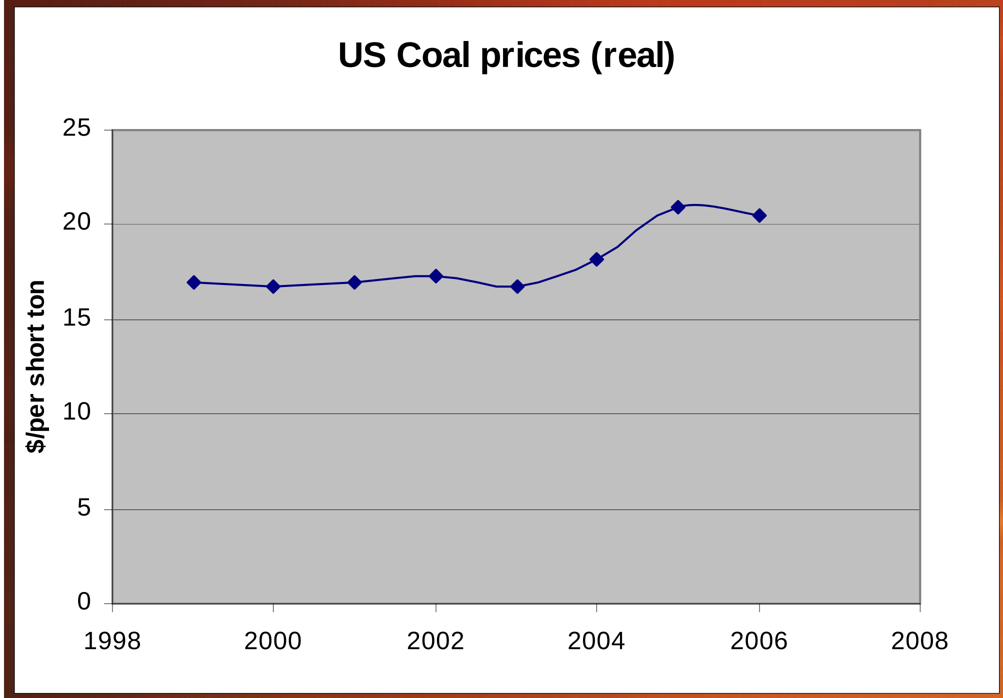
- No induce innovation
- Minimal attention to heterogeneity
- No input substitution in response to price changes
- No learning by doing
- No capacity to deal with impacts of policies

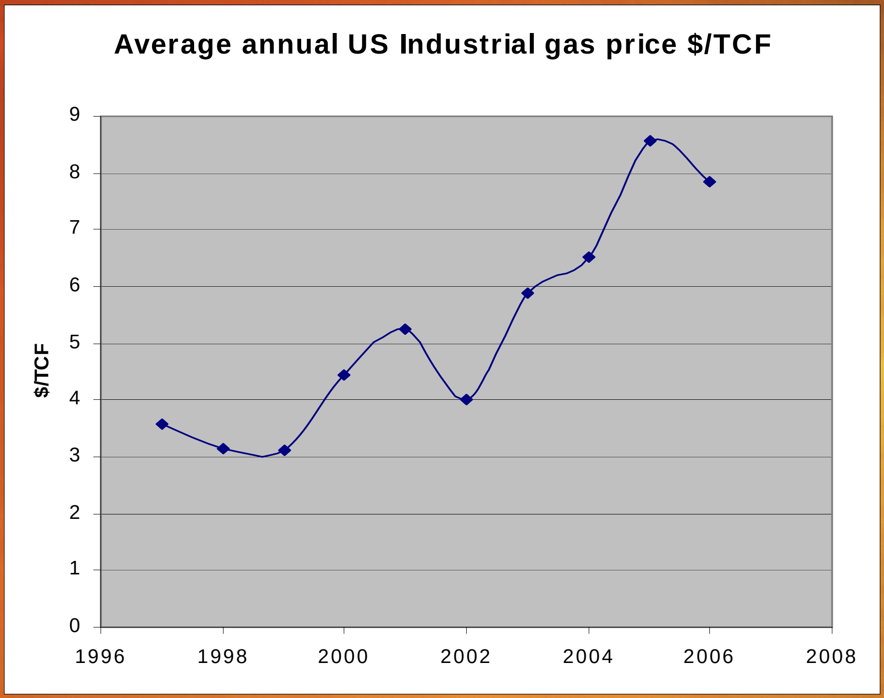
Why incorporate prices into LCA?

- Producers will *switch fuel*, *alter input mix, technology* etc. in response to a change in relative price of inputs
- So life cycle emissions will change
- Therefore we need a life cycle model that respond to change in economic factors

Relative fuel prices are changing

Gas has become relatively more expensive and hence producers are beginning to shift to coal which is cheaper but dirtier





Previous work

- Ayres and Kneese *AER* 1969
  - A general equilibrium model that attempts to compute the total externality arising from all economic activities
  - Relates the generation of residuals or pollutants to factor prices
- Limitations of this model
  - It is not a life cycle model of a single commodity
  - Fixed proportions and no joint production

Production economics and LCA

- The neoclassical production theory
  - Input use changes to prices- so LCA producing **a function- not a number**
  - So if price of polluting energy increases

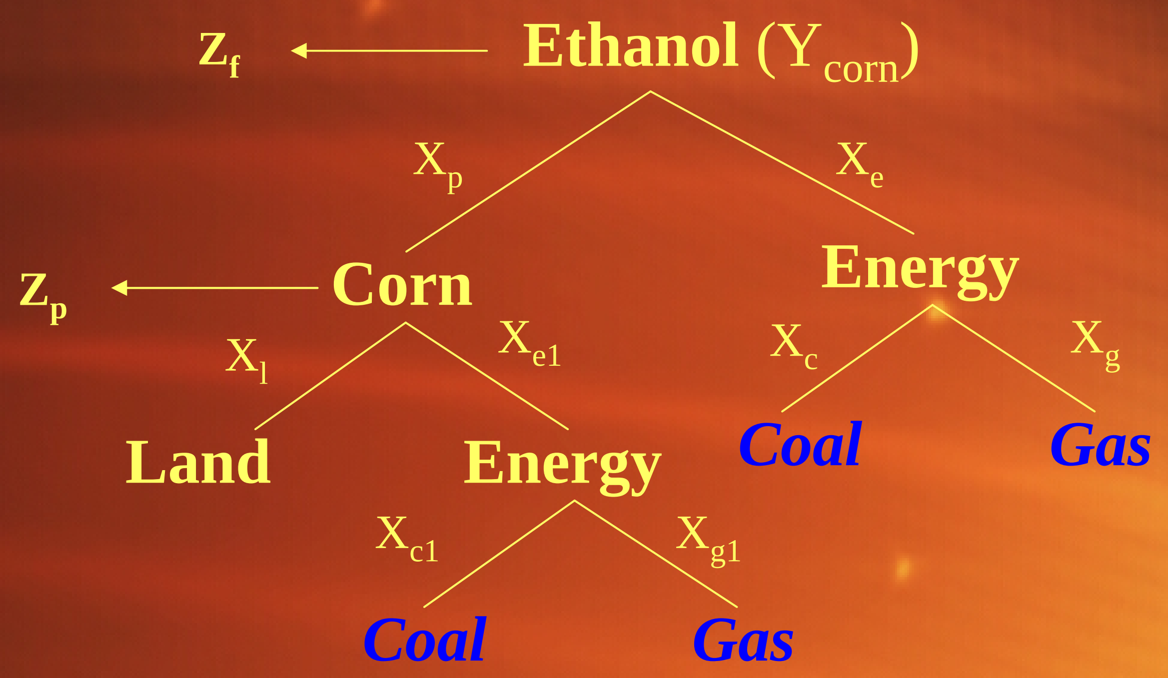
Innovation models

- Assume that changes in prices lead to creation and adoption of new technologies

A simple life cycle model of ethanol

- Consider just two stages in life cycle
  1. Conversion of corn to ethanol
  2. Production of corn
- Energy is an input into each stage
- Assume energy can be derived from one of two sources -
  - coal (dirtier) or gas (cleaner)

A simple life cycle model of ethanol



Y_f - biofuel
Z_p - pollution from farming
Z_f - pollution from conversion of plant matter of biofuel
X_c, X_g - quantity of coal and gas required to produce the energy
X_l - quantity of land to produce the required quantity of corn
X_e - quantity of energy required to convert corn to ethanol

Mathematical model - *production*

Let the production relationships be given by

$$Y_f = F_f(X_p, X_e)$$
$$X_p = F_p(X_1, X_{e1})$$
$$X_e = F_e(X_c, X_g) \text{ and } X_{e1} = F_e(X_{c1}, X_{g1})$$

If we assume cobb douglas functions, then

$$Y_f = A X_p^{\alpha_p} X_e^{\alpha_e}$$
$$X_e = B X_c^{\alpha_a} X_g^{\alpha_b}$$

$$\Rightarrow Y_f = C X_p^{\alpha_p} X_c^{\alpha_c} X_g^{\alpha_g} \qquad \textbf{(1)}$$

Mathematical model - *production*

Assuming profit maximization and perfect competition the cost minimizing factor demands are given by

$$x_i^* = x_i^*(\vec{p}_i, P, Y) = \frac{\alpha_i PY}{p_i} \quad \textbf{(2)}$$

where,
x_i^* - optimal level of input use
$\vec{p}_i$ - vector of price of inputs
Y_f - quantity of biofuel
P_f - output price of biofuel

Differentiating with respect to p_i

$$\frac{dx_j^*}{dp_i} = \alpha_i \frac{x_j^*}{p_i} \text{ if } i \neq j \;\&\; \frac{dx_i^*}{dp_i} = -(1-\alpha_i)\frac{x_i^*}{p_i} \quad \textbf{(3)}$$

Mathematical model - *pollution*

If the pollution function Z_f is linear then

$$Z_f = G_f(X_c, X_g) = b_c * X_c + b_g * X_g \qquad \textbf{(4)}$$

Differentiating with respect to p_c, the price of coal

$$\frac{dZ_f}{dp_c} = b_c \frac{dX_c}{dp_c} + b_g \frac{dX_g}{dp_c} \qquad \textbf{(5)}$$

Substituting for $\frac{dX_c}{dp_c}$ and $\frac{dX_g}{dp_c}$ using (4) into (5)

$$\frac{dZ_f}{dp_c} = -b_c(1-\alpha_c)\frac{X_c^*}{p_c} + b_g \alpha_c \frac{X_g^*}{p_c} \qquad \textbf{(6)}$$

Mathematical model - *pollution*

Substituting for X_c^* and X_g^* using (2) into (6)

$$\frac{dZ_f}{dp_c} = \alpha_c[\alpha_g \frac{b_g}{p_g} - (1-\alpha_c)\frac{b_c}{p_c}]\frac{P_f Y_f}{p_c} \qquad \textbf{(6)}$$

We can similarly derive an expression for Z_p

The life cycle pollution can be written as

$$\boxed{\Gamma_f = Z_f + Z_p} \qquad \textbf{(7)}$$

Mathematical model - *pollution*

If a fraction a_{pf} of the total corn production is used for ethanol and if Γ_p is the total pollution from corn production then

$$\Gamma_f = Z_f + a_{pf}\Gamma_p \tag{8}$$

$$\Rightarrow \quad \frac{d\Gamma_f}{dp_c} = \frac{dZ_f}{dp_c} + \frac{d}{dp_c}(a_{pf}\Gamma_p) \tag{9}$$

Thus the change in life cycle emission with a change in price of coal can be estimated as

$$\frac{d\Gamma_f}{dp_c} = \alpha_c \frac{1}{p_c}[\alpha_g \frac{b_g}{p_g} - (1-\alpha_c)\frac{b_c}{p_c}](P_f Y_f + a_{pf} P_p X_p)$$

Illustration for corn production

Let the agricultural production function be denoted as follows

$$Y_{corn} = f(X_L, X_f, X_I, X_l) = AX_L^{\alpha_L} X_F^{\alpha_F} X_I^{\alpha_I} X_l^{\alpha_l}$$

where, L-land, F-fertilizer, I-irrigation, l-labor

Assuming fertilizers are produced from natural gas while irrigation is using coal-based electricity and let the pollution function be denoted as

$$Z = b_F * X_F + b_I * X_I$$

Then assuming profit maximization and perfect competition we can determine the % change in pollution as function of % change in fertilizer price for a given α_F

Input price effect on total emissions

We show the % change in GHG benefits for 100% increase in natural gas price for three different levels of output elasticity (the exponent in the cobb-douglas function)

Exponent for fertilizer in farm prodn.	0.1	0.2	0.35
Exponent for gas fuel in biorefinery	0.1	0.2	0.35
If price of natural gas increases by 100%			
% increase in fertilizer emissions	9%	17%	26%
% increase in biorefinery emissions	9%	17%	26%
% decrease in net GHG benefits	**-44%**	**-78%**	**-122%**

In this model when exponent is 0.35 there is a net increase in GHG emission as shown by a decrease of more than 100% in benefits

Other useful experiments

- Impact of a carbon tax on net emissions
- Implications of decreasing returns to scale
- Joint production

Modeling the effect of a carbon tax

Carbon tax increases the relative price of coal leading substitution by gas and thereby increases net GHG benefits

Exponent for fertilizer	0.1		
Exponent for gas in biorefining	0.1		
Carbon tax ($/ ton C)	5	10	15
% increase in relative coal price	17%	35%	57%
% increase in GHG benefits compared to baseline	**117%**	**228%**	**383%**

Decreasing returns to scale (DRS)

- Where there is DRS then as production expands emission intensity will increase leading to lower net benefit

    - For example, in agriculture when land quality declines and there are emission associated with land use, expanding biofuel production may will increase the emission intensity of biofuel

Decreasing returns to scale (DRS)

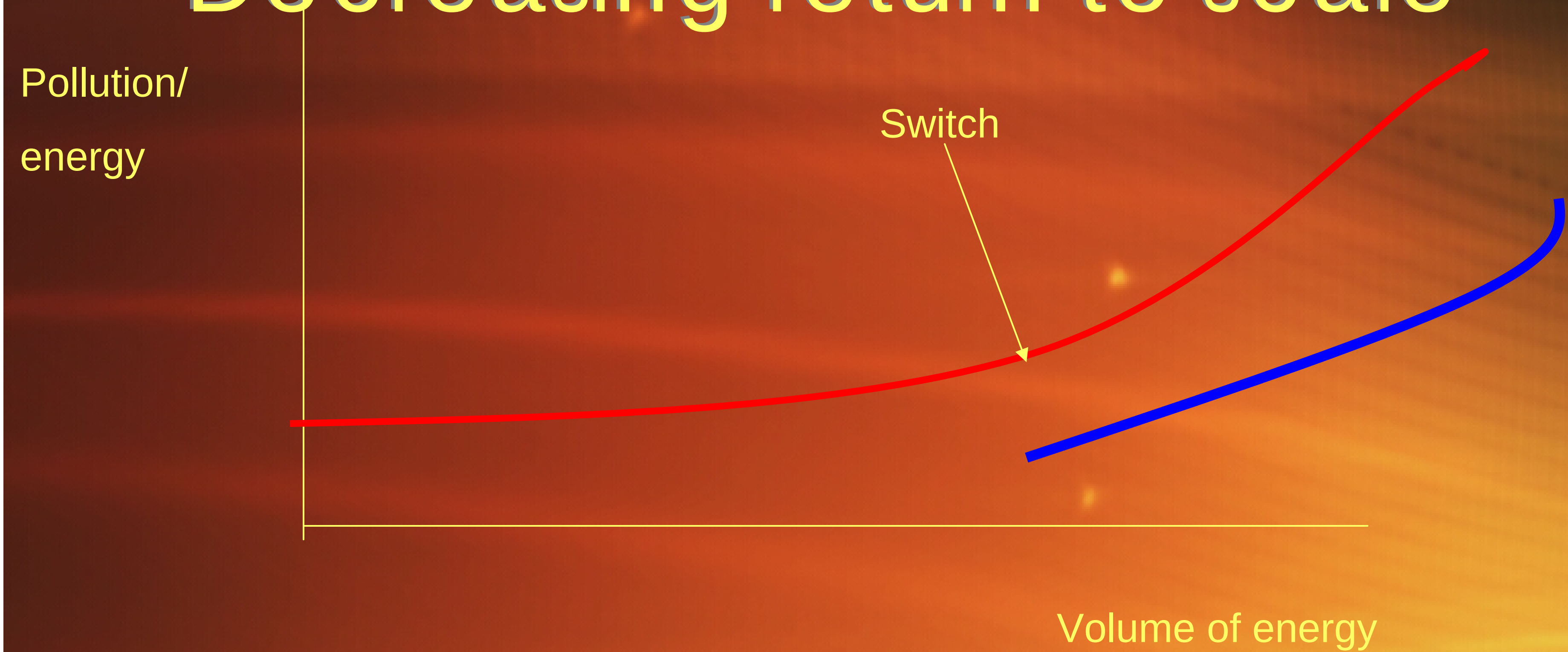
When there is DRS then $f(\lambda\vec{x}) \leq \lambda f(\vec{x}),\ \lambda \geq 1$

If the pollution function is $Z = \sum_{i=1}^{n} b_i x_i^*$ then

It can be shown that $$\frac{Z(\lambda y, \vec{p})}{\lambda y} > \frac{Z(y, \vec{p})}{y}$$

i.e., when there is DRS average emissions per unit output increase as total output increases

Decreasing return to scale



Higher volume may make it economical to adopt cleaner refining technology
Resulting in **a discontinuous downward reduction in pollution**

Extending to a general setting

The total emission associated with the k^{th} ir

$$\Gamma_k = Z_k + a_{1k} \times \Gamma_1 + .. + a_{1k} \times \Gamma_1 = Z_k + \sum_{i=1}^{n} a_{ik} \times \Gamma_i \;\; \forall k \in 1..n$$

Rearranging in matrix form

$$\Rightarrow \Gamma = (I - A)^{-1} Z$$

$$\frac{\partial \Gamma_k}{\partial p_i} = \frac{\partial Z_k}{\partial p_i} + \sum_{j=1}^{n} \frac{\partial (a_{jk} \times \Gamma_j)}{\partial p_i}$$

General expression for change in life cycle emissions

- Differentiating the expression for *Γ*, we get an expression for change in life cycle emissions with a change in one of the input prices

$$\boxed{\frac{\partial \Gamma}{\partial p_i} = (I - A)^{-1} B \frac{d\vec{X}_k}{dp_i}}$$

where,

$$B = [b_{jk}] \text{ with } b_{jk} = \sum_{j=1}^{n} \left(\frac{\partial g_k}{\partial X_{jk}} + \frac{\Gamma_j}{X_j} \right)$$

$$\frac{\partial \Gamma}{\partial p_i} = \left[\frac{\partial \Gamma_k}{\partial p_1} .. \frac{\partial \Gamma_k}{\partial p_n} \right]^T$$

$$\frac{\partial \vec{X}_k}{\partial p_i} = \left[\frac{\partial X_{1k}}{\partial p_i}, .. \frac{\partial X_{jk}}{\partial p_i}, .. \frac{\partial X_{nk}}{\partial p_i} \right]^T$$

Inputs to our model

1. Production (or cost) functions for every process included within the system boundary
2. A pollution function corresponding to each production process
3. The total industry output for each intermediate and final product
4. Prices of all commodities included within the model

Sources of data for model inputs

1. Economic estimates of production functions, energy demand and and pollution supply elasticities
2. Estimated parameters of adoption studies
3. Engineering data on new technologies and their

We will need more studies

- Refining methodologies
- Estimating LCAs as function of policies and prices

Future research

- Incorporate risk and uncertainty
- Non-competitive behavior
- Incorporate demand and extend to a general equilibrium setting
- Empirical testing of the model

New direction for LCA studies and use

- Traditional LCAs assume an homogenous Static economy ignore the dynamic divers economy we have
- Could provide assessment of the past while we design the future
- Ignored the responsiveness of firms and farms to incentives and regulations and are of limited value in policy design
- New approach and a multidisciplinary dialogue to establish it are needed

A new approach

- Integrates micro-economic theory with an engineering life cycle model
- An LCA model that is sensitive to change in economic conditions
- Allows for substitution, joint production and heterogeneity, technological change, risk and uncertainty
- Well suited for conducting policy experiments like the impact of a tax etc.