An Integrated Environmental and Economic Modeling Framework for Technological Transitions

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Abstract. There is an increasing demand for models that address both environment and economy, and that also estimate or forecast the impacts of introducing new and markedly different technologies from those already existing in the systems under study. Because most conventional models are calibrated to recent data characterizing current economic structure and conditions, their standard turn-key operation will need to be replaced by more comprehensive algorithms and procedures designed to explicitly accommodate shifts in technology and economic structure. This paper lays out one viable alternative for integrating environmental and economic modeling frameworks, and focuses specifically on one of the major challenges to this kind of modeling, that of dovetailing life cycle assessment and input-output modeling frameworks.

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Introduction

As the world focuses more sharply on the relationships among physical, economic, and social systems, models that integrate two or more of these systems grow in importance. At the national level, recent decades have seen evidence of the increasing emphasis on linked problem domains within federal agency programs and initiatives. In the U.S., the National Research Council established the Committee on Human Dimensions of Global Change in 1989 with support from other agencies,[1] and numerous related federal agency programs and initiatives have developed since, including the U.S. Department of Agriculture under its NIFA program, which Aims to improve economic, environmental, and social conditions in the United States and globally, and the National Science Foundation under the Science, Engineering, and Education for Sustainability (SEES) program intended "to advance science, engineering, and education to inform the societal actions needed for environmental and economic sustainability and human well-being."

The purpose of this paper is to describe an approach that has developed in response to the increasing need for models that span environmental and economic domains in the context of the adoption of new technology. The integrated modeling approach is being implemented for two on-going research NSF- and USDA-funded research projects. The approach is general enough to address two distinct problem domains but specific enough to provide a comprehensive assessment of each.

The NSF project centers on a comparative regional analysis of the state of West Virginia in the U.S. and Shanxi province in China. Both regions are rich in energy resources, and the two regions share similar economic challenges. Both regions have long and strong traditions in coal extraction, both have potential for increased development or expansion of shale gas extraction activities, and bot face uncertain futures as pressures mount for the adoption of cleaner, green technologies to replace coal as an energy source. The USDA project centers on the socioeconomic impact of developing woody biomass as an energy resource in a rural region. The research questions revolve primarily around the environmental and economic consequences of activities that range from harvesting through processing to use of woody biomass in the region.

The two projects differ in scale, differ in technological focus, and differ in terms of temporal and spatial character, but share the needs to develop or identify useful environmental data, to add to or replace existing technologies, and to assess the consequences of these technological transitions. The approach presented here begins with either life cycle assessment (LCA) or secondary sources of environmental and economic process data. The process data are used to modify and extend an input-output (IO) model of economic structure, which can then be used as the basis for spatial, and temporal comparative statics analyses, and which also become the data foundations for computable general equilibrium model (CGE) parameterization and calibration of the

[1] Supporting agencies included the National Science Foundation, the John D. and Catherine T. MacArthur Foundation, the National Research Council Fund, and the U.S. Geological Survey (NRC 1992).

respective economies before and after the relevant technological transitions. The CGE models can then be used to deepen understanding of the likely behavioral changes and additional economic consequences of adopting the new technologies.

Hence, LCA, IO and CGE analytical frameworks and procedures underlie both funded research projects. In the following pages, we present the approach generally, focusing in depth only on one aspect of the overall approach that receives very little explicit attention in the literature, namely the actual transition from LCA to IO framework and the resulting model representation of technologies in transition. We discuss data requirements where relevant, review modeling foundations leading to the construction of SAM/CGE frameworks used in the integrated models, highlighting the salient issues that enter into the various modeling procedures, but leave more comprehensive discussions of the kinds of CGE analyses that can be carried out to future reports.

Model Components

Environmental Data

Environmental data are generally linked to production levels by their relation to output volumes. For each industry, we will generally have estimates of emissions/$. While the use of monetary units subjects the analyses to the vagaries of time, it does at least provide a point of reference and can be useful for qualitative if not quantitative comparisons. The quantitative results will bear some inaccuracy, but rankings of policy alternatives are likely, though not guaranteed, to be more reliable.

Perhaps more important than tying environmental contributions to monetary units are issues of process and product mix within the aggregate industries that typically comprise the multi-sectoral models commonly used in these problem domains and contexts. Industry classifications for these multi-sectoral models almost always group a range of products that while related might be produced by very different methods and use differing sets of input materials or the same inputs but in differing amounts. Even a single-product industry can be heterogeneous in process, giving rise to both differing usage of environmental inputs and generation of environmental outputs.

These problems, however, plague virtually all system-level environmental analytical schemes. Data at the process level for all processes and products simply do not exist, so the convention has been one of accepting the error inherent in sectoral estimates of environment inputs and outputs as the price to be paid for the ability to conduct system-level impacts assessments at all. Widely accepted and widely used models of this type are common (see e.g., the EIO-LCA model at http://www.eiolca.net/).

It is possible, however, to at least eliminate some sources of error by working at the most disaggregated level at which data are available. In the NSF context of replacing aging brown with greener technologies, the availability of estimates of emissions by power generation fuel source (from secondary data) enables specific subsector-process weighting in the construction of an aggregate power generating sector – or potentially even maintaining full sub-sectoral detail in disaggregated format – with environmental input and output estimates that more accurately reflect the specific mix of fuel sources in use at a place and time.

Life Cycle Assessment[2]

When environmental data are not available from secondary sources, life cycle assessment (LCA) can be a viable alternative. According to Cooper, Jackson and Leigh (2013) "LCA is a protocol standardized by the International Standards Organization (ISO 2006a, ISO 2006b) to assess the life cycle impacts of energy and materials use and waste by an industrial system. LCA is most frequently used to quantify environmental impacts." A key phase of LCA is the *inventory analysis*, which involves "compiling an inventory of materials and energy use and waste as inputs and outputs of the industrial system."

"In LCA it is the life cycle inventory analysis that describes the interaction of industrial processes, ideally extending from materials and energy acquisition … through materials processing, construction/manufacturing, technology use and maintenance, and ultimately to reuse, remanufacturing, recycling, and/or disposal. The construction of a life cycle inventory typically starts with a single technology or a 'core' set of processes of interest, … adding the processes needed to produce materials and energy … in the core and beyond, and 'downstream', adding the processes that use or manage the materials and energy for the core and beyond. This concept of the 'core' set of processes is the foundation for the link to regional IO modeling.

An LCA *process model* is used to solve a life cycle inventory problem with a mechanism that parallels the solution of an economic input-output model. The primary difference lies in the definition of system boundaries. The system boundaries for an LCA process model are much more tightly constrained yet still overlap those of an IO model, which extend to the entire regional inter-industrial system. The key to establishing compatibility between the two is to further constrain the LCA process boundaries in such a way as to exclude direct and indirect linkages among industry sectors that are already accounted for in a standard IO model.

For a typical life cycle inventory solution, we follow Heijungs and Suh (2002) we define the system boundaries explicitly as the *technosphere* – the set of processes within the system boundary being assessed, and the *environment* – all others. The processes in the technosphere are typically formulated into a non-singular technology matrix, $\boldsymbol{A}$, which is inverted and then post-multiplied by a demand vector f, which represents what the entire system ultimately should deliver.

LCA: Mathematical Foundations

In LCA, $\mathbf{A}^{-1} f = s$ generates a *scaling vector*, s, that enumerates the levels of output from each process needed to meet the specified demand. Next, s is used to scale the environmental flows for each process, conventionally represented as matrix $\mathbf{B}$ with

[2] Readers interested in a comprehensive treatment of the LCA-IO linkage mechanisms are referred to Cooper, Jackson and Leigh (2013), upon which this section draws heavily.

columns corresponding to each process in **A** and rows representing inputs and outputs from the environment (e.g., crude oil and carbon dioxide emissions). The inventory result g, ($\mathbf{B}s = g$), summarizes the life cycle resource use and emissions.

Input-Output Models of Economic Systems

IO models have a variety of applications, founded on a database that identifies the buyers of each industry's outputs, the sources of each industry's inputs, the goods and services purchased by households, governments, investment activities (like the construction of new factories), and exports. The sources of goods and services include industries, households, governments, and imports. All of these sales and purchases are quantified in monetary units (e.g., $US).

These data can be arranged in tabular (matrix) format such that the rows correspond to sellers (i.e., industries, households, government and other institutions, capital) and columns correspond to buyers. The industry accounts are "double-entry" in the sense that the sum of industry purchases (inputs) equals the sum of industry sales (outputs) for each industry. Industry purchases include all payments by industry, including payments to capital (profits), so receipts (sum of sales) always equal expenditures (sum of purchases).

The IO accounts become a behavioral modeling framework when some behavioral assumptions are made, the most important of which is that each industries purchases are fixed proportions of output, so that percentage increases in output of will require increasing all purchases by the same percentage. With this assumption, we can solve the input-output system for the total requirements of all inputs that are needed to produce a given amount of output, e.g., for export. Since each industry requires inputs from other industries to produce output, each supplying industry will need to purchase more inputs from other industries, and so on. This set of interindustry relationships gives rise to the well-known multiplier effects that are often used to characterize economic structure, economic impacts, etc.

It is apparent, then, that if one industry's purchasing pattern – its production function – changes, the other industries will also be either directly or indirectly effected. Likewise, the region's overall economic structure will change. This link between economic structure and industry production function provides the first direct link to the two projects.

Input-output (IO) and Life Cycle Assessment (LCA) modeling share a strikingly similar mathematical foundation and formulation, yet melding the two frameworks is not completely straightforward. In particular, the boundaries of the two systems must be brought into alignment carefully, so as to avoid double counting. To comprehensively describe the procedure by which the two frameworks can be conjoined, the next section presents in brief the salient features of the input-output system and its mathematical foundations.

Input-Output Models: Mathematical Foundations

In input-output (IO) modeling, a technology matrix A represents the dollar amounts of row inputs needed to produce one dollar of column industry outputs. By convention, output is notated by $x_i \in X$, for industries i, and dollar flows of inputs between industries are denoted by $z_{ij} \in Z$, so technical coefficients are computed as shown below.

$$a_{ij} = z_{ij} / x_j \tag{1}$$

The amounts of output delivered to final consumers or exported from the region are called final demand, and represented by $y_i \in Y$. The output balance equations relating inputs and outputs from an IO system are given by:

$$X - Ax = Y \tag{2}$$

$$(I - A)^{-1} Y = X \tag{3}$$

Here, final demands are the remainder once intermediate inputs are subtracted from total output produced.

More recent data compilation and publication for input-output systems have as their own foundations a commodity-by-industry (CxI) framework comprising two sets of information. The first depicts the commodities used by industries and is called the Use table, U, and the second depicts the commodities produced (made and supplied) by industries called the Make (or Supply) table conventionally annotated by V. These two tables can be combined to create the equivalent of an interindustry IO table. The example below illustrates the mathematical foundation based on an industry technology assumption in which industry shares of commodity production are invariant.

By definition,

$$Ui + E \equiv q \tag{4}$$

Where E is commodity final demand and q is commodity output. Then

$$Vi = g \tag{5}$$

where g is industry output (denoted X in conventional industry-by-industry frameworks), and

$$V'i = q \tag{6}$$

By assumption,

$$B = U\hat{g}^{-1} \tag{7}$$

$$U = B\hat{g} \tag{8}$$

By substitution,

$$q = Bg + E \tag{9}$$

By assumption,

$$V = D\hat{q} \tag{10}$$

$$D = V\hat{q}^{-1} \rightarrow d_{ij} = v_{ij} / q_j \tag{11}$$

Post-multiplying both sides of equation (10) by q yields $Dq = V\hat{q}^{-1}q = Vi = g$. So

$$g = Dq \tag{12}$$

and matrix *D* serves as a transformation from commodity to industry space and its inverse transforms industry to commodity, so

$$Y = DE \tag{13}$$

Where *Y* is final demand in industry rather than commodity space. Substituting equation (12) into equation (9) yields

$$q = BDq + E \tag{14}$$

so

$$(I - BD)^{-1} E = q \tag{15}$$

$$E = (I - BD)D^{-1}g \tag{16}$$

$$D(I - BD)^{-1} E = g \tag{17}$$

From equation (16)

$$E = (D^{-1} - B)g \tag{18}$$

$$DE = (I - DB)g \tag{19}$$

$$(I - DB)^{-1} Y = g \tag{20}$$

Equation (20) is the commodity-by-industry equivalent of equation(3).

LCA and IO: Comparison and Contrast

In the IO framework, the elements of the technology matrix are non-negative by definition, since the inputs are taken from the economic system and there cannot be negative amounts of industry output. I.e., all inputs are physical products produced by other industries and absorbed by the consuming industries in their production processes.

By contrast, the LCA is designed to capture extractions from and contributions to the technosphere and its environment, so for that reason, the technology (process) matrix will have negative and positive values corresponding to these extractions and contributions. The LCA matrix will have a unit value (1.0) to represent the process output, where the process output is not explicitly a part of the IO technical matrix. Hence, in effect, the LCA technology matrix, A, is more closely aligned with the IO framework's $(I - A)$ matrix, called the Leontief matrix. These two matrices – the LCA A and IO Leontief matrix $(I - A)$ share nearly identical interpretations. Positive values in each are *contributions* to the technosphere and environment, and negative values are *extractions*.

To reformulate an LCA process matrix so that it can be used to represent a specific new activity without double-counting industry interaction among industries already captured in a traditional IO table, those industries are placed in their own partition and represented as an (appropriately dimensioned) identity matrix in the process matrix. The scaling vector generated using this modified process matrix is then converted from the physical units used in LCA to monetary units, at which time it corresponds directly to, and can be used to modify or create a Use-table type column for the core process. A simplified example of this procedure is presented in the following section.

Melding IO and LCA Frameworks

When a new process is added to an IO system, we can generate a corresponding new column of a Use matrix using a modified approach to LCA process table construction.[3] Begin by setting up a conventional LCA process matrix, but partition the process matrix into four quadrants according to New Activities and Conventional Industries (those already present in the IO matrix), as shown in Table 1 below:

Table 1. Hypothetical Biomass Process

	New Activities/Processes Associated with the New Technology							Existing Industries				
	BioMass Processing	Ancillary activity 1	Ancillary activity 2	Ancillary activity 3	Ancillary activity 4	Ancillary activity 5	Ancillary activity 6	Existing Industry 1	Existing Industry 2	Existing Industry 3	Existing Industry 4	
BioMass	1	0	0	0	0	0	0	0	0	0	0	1
New Activities /Processes	-0.7	1	0	0	0	0	0	0	0	0	0	2
	-0.3	0	1	0	0	0	0	0	0	0	0	3
	0	-1	-1	1	0	0	0	0	0	0	0	4
	0	0	0	-0.04125	1	0	0	0	0	0	0	5
	0	0	0	-0.01375	0	1	0	0	0	0	0	6
	0	0	0	-8.25	0	0	1	0	0	0	0	7
Existing Industries	0	0	0	-2.75	0	0	0	1	0	0	0	8
	0	-0.3	0	0	0	0	0	0	1	0	0	9
	0	0	-0.15	-0.05	-0.00042	-0.00007	-0.05	0	0	1	0	10
	0	0	0	-2	0	0	-2	0	0	0	1	11
	1	2	3	4	5	6	7	8	9	10	11	

Table 1 depicts an hypothetical woody biomass process matrix partitioned according to whether the activities and accompanying processes are new or are virtually identical to existing industries (this example corresponds to an IO table with only four industry sectors). The biomass process shown here used inputs from ancillary activities 1 and 2 (AA1 and AA2), both of which use inputs from AA3 and from existing industries. AA3 uses inputs from AA4, AA5, and AA6 along with existing industry inputs, and so on. For the purposes of creating a new column in the IO commodity-by-industry Use matrix, the fact that the only existing-industry column entries are unit values in the rows of the

[3] This procedure was introduced in Cooper, Jackson, and Leigh (2013).

existing industries indicates that additional rounds of exchange lie outside of this process description. Indirect and subsequent rounds of exchange will be captured once the new column has been inserted and the biomass activity becomes an additional industry in the IO matrix.

To complete the Use column construction, post-multiply the inverse of this matrix by a unit final demand vector. The existing-industry rows of the resulting vector will be the values that comprise the new Use table column corresponding to the biomass industry, as shown for the example process in Table 2.

Table 2. Process Inverse -- Unit Final Demand Product

BioMass	1
New Activities /Processes	0.7
	0.3
	1
	0.04125
	0.01375
	8.25
Existing Industry 1	2.75
Existing Industry 2	0.21
Existing Industry 3	0.507518
Existing Industry 4	18.5

To complete the IO accounts, a new industry row corresponding to the Biomass industry also needs to be added to the make table. Whereas the values in the use column correspond to commodities used by the Biomass industry, the values in the new make row correspond to the regional Biomass industry's production of commodities. If the new industry produces commodities that were previously produced by other industries in the IO system, they can simply be entered in this row in the columns corresponding to the pre-existing commodities. If new commodities are produced, new commodity columns corresponding to each new commodity would be added. If these new commodities substitute for inputs other industries use, the Use table would have to be edited to reflect these substitutions.

New Industry Impacts

A number of alternatives exist for impact model "drivers." The most straightforward alternative is simply to allow all new output to enter the production system as replacement for imports. This method reflects the consideration of *avoided* life cycles in LCA (e.g., new sources of these commodities preclude the need to import them from other economic regions). Post-adjustment output, employment and income levels can be compared to pre-adjustment levels to determine impacts. However, should total intra-regional demand for new commodity output be less than total produced, a final demand entry corresponding to exports will be required to balance the accounts, a concept that would be reflected in a well-developed, consequential LCA (Ekval and Andræ 2006). Likewise, other well-founded final demand estimates can be used, including export scenarios. Finally, more elaborate structural decomposition analyses can yield additional insights.

Research Application Contexts

The NSF Shanxi-WV project involves the comparison of two regions – first without any change, and then under policies or strategic programs that will alter the production functions of the energy sector. The energy sector production function will change as the two regions adopt new technologies (e.g., gas or renewables to replace coal). These changes will result in altered economic structures. The differences between new and old structures can be quantified and assessed for their implications on economy and environment. Note that the changes can be real and observed or hypothetical. Hypothetical scenarios allow the *ex ante* assessment of alternative energy policies and programs. Databases exist that can be used to parameterize the production functions and the environmental emissions of energy and other industry activity.

The NIFA project involves the introduction to an economy of new biomass energy production technologies and related industrial activity. The introduction of these activities will fundamentally change the economic structure of the region, which will again allow for the quantification and assessment of the consequences of these economic and environmental changes. LCA data will be used to modify and augment publicly available production and environmental data.

Downstream Analytical Modules

Structural Decomposition Analysis

SDA is a mathematical approach to the comparison of two economic structures that uses IO accounts as input data. SDA can facilitate a temporal analysis by comparing the economic structure of one region for two different time periods, or a cross-sectional analysis by comparing two different economies for the same time period.

Differing levels of economic output reveal economic structural changes or differences. These changes, for each industry, are decomposable into two parts: the change/difference that is attributed to changes/differences in final demand (i.e., increases or decreases in personal consumption, investment, government, exports), and the change/difference that is attributed to technology (i.e., production functions and interindustry relationships). Both types of changes will be expected for temporal analyses, and both can be relevant for cross-sectional comparisons depending on the nature of the policies and programs under study.

The Social Accounting Matrix (SAM)

SAM models are often viewed as extended IO models. The extensions typically include the provision of additional detail on institutions – particularly households – and the relationships among value added (income, profits, government receipts) and final demand (investment, government expenditures, etc.). The SAM completes the representation of the circular flow of income in an economy. An expanded but still concise description of SAMs can be found here.[4]

Since SAMs extend IO models, the information in IO models that differentiates economic structures will be embedded in the derived SAMs.

Computable General Equilibrium

CGE models are used to simulate economic behavior that extends beyond the kinds of behaviors that can be modeled using IO or SAM models. Much of the data used to parameterize a CGE model come from SAMs. For this reason, a CGE built upon one SAM will exhibit different behavior and generate different solutions to a CGE built upon another. This provides the opportunity to develop separate models, e.g., for southern WV with and without biomass production, or to develop a single model that includes a biomass production sector, then run the model with economic activity in that sector and again without economic activity in that sector and compare the model outcomes. Likewise, for the NSF project, we can develop a CGE model with representations of all technologies but different levels of operation in each simulation scenario. The generalized modeling process is shown in Figure 1, below.

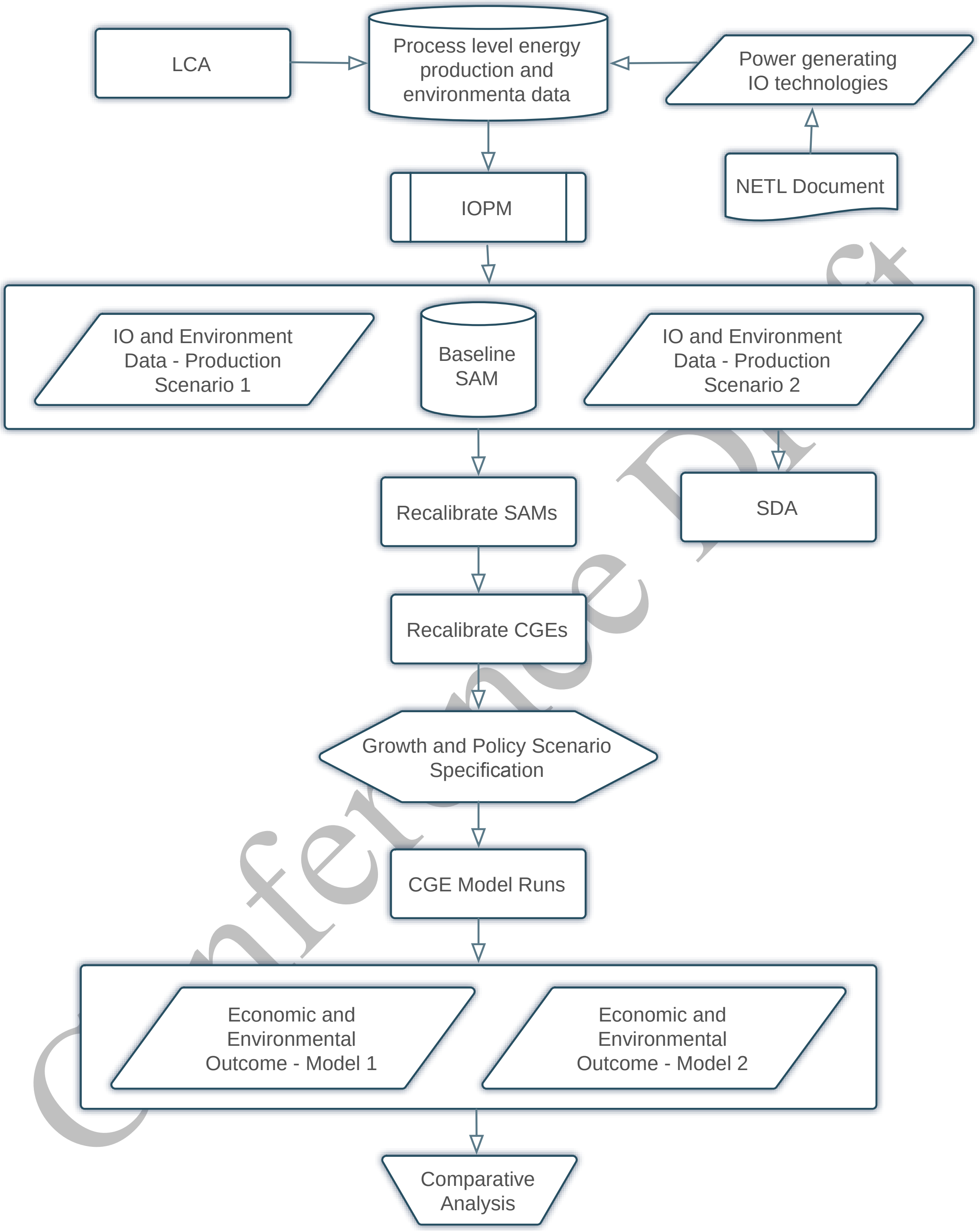
Note that the two projects that have driven this model formulation will not be identical but will be instances of this generalized approach. For example, the NIFA project will explicitly incorporate aspects of an LCA underway in the WVU Forestry department as a part of the project, whereas the NSF project we will make use of secondary data from LCA procedures implemented elsewhere and by others.

For the NSF project there will be two baseline SAMs, one for WV and one for Shanxi Province. Each will be modified according to the modeling scenarios to be evaluated. For the NIFA project, there will be one baseline IO and SAM that models the economy without having introduced woody biomass production, and that IO/SAM pair will be modified to generate the second IO/SAM/CGE model.

Both model databases will support SDA analyses. For NSF, the SDA will decompose the differences between the two regional economies (WV and Shanxi), while the NIFA SDA will be a before and after comparison of the same region.

[4] From "The impact of public Employment guarantee strategies on gender equality and pro-poor economic development. The Levy Economics Institute. Research Project 34. http://www.levyinstitute.org/pubs/rpr_01_08_IN.pdf

Figure 1 Generalized Modeling Process



Summary and Discussion

One of the greatest difficulties in modeling complex systems lies in adequately capturing changes in the structural relationships that define them. Few system-level models exist that can overcome this difficulty without departing from their classical application contexts. Econometric modelers are accustomed to parameterizing their models based on historical time series that culminate in the current system structure, from which forecasts of system activity depart. These models – at least conventionally constructed econometric models, implicitly assume that the economic system structure evolves gradually along a path established by the historical structural trends on which they are calibrated. They clearly cannot be expected to accurately reflect the kinds of dramatic systemic effects of the introduction of entirely new technologies. Likewise, classically formulated input-output, social accounting matrix, and CGE models all calibrated to a single system structure, cannot adequately reflect significant structural changes.

For these reasons, the conventional turnkey approaches to modeling systemic changes will likely have to be abandoned for assessing the impacts of the adoption of new technologies that change system structure enough to violate the assumptions upon which they are built.

References

Cooper J, RW Jackson and NG Leigh. (2013) Computational Structure for Linking Life Cycle Assessment and Input-Output Modeling: A Case Study on Urban Recycling and Remanufacturing. In Giarattani F, G Hewings and P McCann. (eds.) Handbook of Industry Studies and Economic Geography, Edward Elgar: Cheltenham.

Ekvall, T., A.S.G. Andræ (2006) Attributional and Consequential Environmental Assessment of the Shift to Lead-Free Solders, International Journal of Life Cycle Assessment, 11(5) 344-353

Heijungs, R., S. Suh (2002) The Computational Structure of Life Cycle Assessment, Kluwar Academic Publishers: Dordrecht, The Netherlands

International Standards Association (ISO), 2006, ISO 14040:2006 *Environmental management -- Life cycle assessment -- Principles and framework*

International Standards Association (ISO), 2006, ISO 14044:2006 *Environmental management -- Life cycle assessment -- Requirements and guidelines*

National Research Council (1992). Global Environmental Change: Understanding the Human Dimensions. Stern, Paul C., Oran R. Young, and Daniel Druckman Editors; Committee on the Human Dimensions of Global Change. National Academy Press: Washington, D.C. 1992