J. ENVIRONMENTAL SYSTEMS, Vol. 20(4) 287-301, 1990-91

CALCULATING THE NET GREENHOUSE WARMING EFFECT OF RENEWABLE ENERGY RESOURCES: METHANOL FROM BIOMASS*

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ABSTRACT

We present a quantitative method that accounts for all greenhouse gases (GHGs) emitted from technical systems (not just their primary processes) for their full life-cycle plus after effects to give an unambiguous basis for comparing the total greenhouse warming "forcing" of alternative projects or plans. A systems perspective is used to include the entire supporting infrastructure. The life-cycle-plus perspective includes the GHGs emitted during the system's construction, operating life, and salvage periods plus final decay of residual GHGs. It captures all system emissions, including activities separated in location or time, to characterize the technical or policy trade-offs available to decision makers. The fundamental soundness of the method is demonstrated by assessing the total greenhouse warming effect of a biomass energy system.

As debate continues about an international agreement for stabilizing and/or reducing greenhouse gas (GHG) emissions, concern has been raised about the imperative for the more developed and industrialized nations to acknowledge the need for developing nations to use cleaner fuels, such as renewable resources, in the most efficient manner [1, 2]. Should flexibility for meeting agreed upon criteria be built into a global market for GHG emissions trades, for example, compliance

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* This research was supported by a grant from the Sarkeys Energy Center, University of Oklahoma.

doi: 10.2190/22FP-J4BR-NXQF-91EB
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among nations and development sectors could be subject to a variety of constraints including the availability, cost, and feasibility of adopting appropriate technologies [3, 4]. Under these circumstances, decision making within individual nations, which is likely to follow a "bottom-up" pattern of policy change, may benefit from the active transfer of proven climate-benign advanced technologies from industrialized nations [5, 6]. Yet, for such an international effort to succeed, clear agreement will have to be reached on a verifiable method for calculating the net global warming effect of alternative technical systems, particularly energy and energy-dependent systems.

Concurrently, new initiatives within the United States to improve urban air quality and reduce CO_2 and other GHG emissions have focused attention on the need to design and utilize energy systems and fuels that can meet new air and climate quality standards. The national energy strategy in tandem with the 1990 Clean Air Act Amendments seeks to reduce the risk of global warming chiefly through gains in energy efficiency and the regulation/reduction of specific GHGs such as chloroflurocarbons and sulfur dioxide [7]. In addition, states such as California are developing plans to reduce their overall global warming contribution through a variety of regulatory and nonregulatory means [8]. Technological innovations that result from such programs are typically more environmentally benign than conventional technologies and hold appeal as candidates for transfer elsewhere including overseas [9].

Since industrial and agricultural activities release GHG emissions in a continuous manner which varies in quantity over the lifetime of their operation, strategies developed to aid planning and decision making must take these characteristics into account. Various measures developed for this purpose which relate the warming potential of all GHGs to an equivalent gas, usually carbon dioxide, exhibit one or more critical flaws in failing to account explicitly for continuous releases of GHGs [10-13]. They may fail to account completely for the entire suite of GHGs released as a result of project construction, operation, and decommissioning activities; oversimplify the absorption traits of specific trace gases to calculate greenhouse forcing equivalency to CO_2; or assume single-pulse outputs. In view of the pressing need to develop a common framework for comparing the effectiveness of alternative global warming mitigation actions, the adoption of imprecise or misleading global warming potential measures for use both in technology assessment and transfer could create unforseen problems.

We have developed a quantitative method for accounting for all GHGs emitted from technical systems for the full life of each activity to give decision makers an unambiguous basis for comparing the total greenhouse warming forcing of alternative projects or plans [14, 15]. This method can capture all source emissions of GHGs from activities that may be separated in location and/or time more fully than current methods, and thus characterize more completely the technical or policy trade-offs available to decision makers who may seek to maximize other goals such as energy efficiency or reduction of total costs while minimizing risks associated with global warming. As an illustration, the net global warming effect of a biomass-based methanol fuel production system is summarized in this article. The example is timely as it affords an opportunity for defining more accurately the key criteria necessary to make informed decisions at national and international levels.

ENTIRE EFFECT OF ANY PATH

A single defect which characterizes many of the approaches to mitigating GHG effects is the factor of incompleteness. Evaluations of fuels which concentrate on end-of-pipe emissions often ignore all previous steps in the production chain, which could change the evaluation markedly. Industrial process evaluations often focus primarily on point-source emissions and ignore distributed emissions in other sectors with which they may be connected. In a like manner, discussions of agricultural systems often ignore the many fossil fuel subsidies existing through direct energy uses and chemical inputs. These are all parts of the correct definition of the basic problem [16]. A second area in which some analyses are found wanting pertains to the documentation of all GHG emissions associated with a system, particularly from sources imbedded in subsidiary processes and operations. Third, a fault of some analytic methods is that timesaving shortcuts are attempted, such as expressing the behavior of other GHGs as equivalent CO_2 [10-12, 17]. Accumulating evidence suggests that the warming effect of each GHG should be calculated by itself, and the effects added to get the total warming forcing [18]. Fourth, some methods try to characterize the total effect of a system by use of response relationships which are based on the injection of single pulses of GHGs into the atmosphere [19]. In truth, important systems will inject GHGs into the atmosphere for many years, often at varying rates. Also, effects will continue to persist years after the systems are shut down. Thus, a complete analysis must include the whole system lifetime plus after effects.

We argue first that a systems perspective is a more powerful way to achieve completeness than most current methods by using it to include, in the analysis, the entire supporting infrastructure of a primary process, not just its own costs, emissions, etc. Second, we argue that a life-cycle perspective must be used to include the complete effects of each element from birth to well after its demise. For comparison of alternative systems, analysis of each should include all GHGs emitted during the construction of the entire system (invested emissions) and those released throughout its operating life and salvage period (direct emissions) plus final decay of residual GHGs, i.e., its full life-cycle. Third, we seek to demonstrate the fundamental soundness of systems and life-cycle analyses by presenting a practical approach for assessing directly the total greenhouse warming effect of a system via the Warming Forcing Factor. This approach utilizes the absorption effectiveness and atmospheric lifetime of each and every GHG emitted by a system, with all the rigor available for describing each.

Systems Concept

The systems concept is used widely in engineering and scientific analysis. When a system includes a process or operation of interest, which has global impact and elements that may be at different locations around the globe, it must be identified completely and carefully to prevent oversights and errors. With each primary process, industrial or agricultural, there is a supporting infrastructure which sustains it. Conversely, without the primary process, there would be no need for each infrastructure element or a pro rata share of that element to exist. This combination of elements constitutes the GHG-emitting system: every operation from raw material production to final waste treatment, through all intermediate steps including transportation, should be accounted for whether or not any of the operations are separated in time or location from the primary process.

The approach is especially helpful when considering replacement of, for instance, fossil fuel systems with biomass systems (Figure 1). Growing wood for combustion to replace coal is often cited as having zero net CO_2 generation, i.e., photosynthesis fixes an amount of carbon equal to that burned and respired [20, 21]. However, the labor and energy used to plant and raise seedlings and the labor, fuel, and other energy expended in chemicals, logging, transport, and processing result in GHG emissions. Much of this support represents a fossil fuel subsidy that would necessitate planting substantially more trees than were burned to attain a zero sum balance. A systems viewpoint discloses fully that many apparently benign energy sources can, in fact, have hidden GHG emissions associated with raw material mining and processing, construction and operation. In general, the more complex the system, the more opportunities there are for energy consumption and GHG emissions.

The next requirement imposed for method development is to include any and all GHGs that might be released from the system to the atmosphere. Further, the method should provide a measure of the total warming effect of the system throughout its entire life and any post-operation decay of the GHGs it emitted. This approach requires that the instantaneous radiation absorption efficiency of each GHG must be considered as well as its total lifetime in the atmosphere. This method differs from the authors' Emissions Index in which the integrations were calculated over the lifetimes of the species [10]. It also differs from the IPCC Global Warming Potential measure, which is the instantaneous radiative forcing times concentration in the atmosphere integrated over an unspecified time divided by the corresponding values for carbon dioxide [11]. Both have been criticized for their dependence on linearity assumptions and neither ties directly to use in life-cycle, phased analysis.

System Life-Cycle

A strong feature of the recommended method of analysis is the inclusion of all the emissions of a system through its entire life-cycle and any residual thereafter.

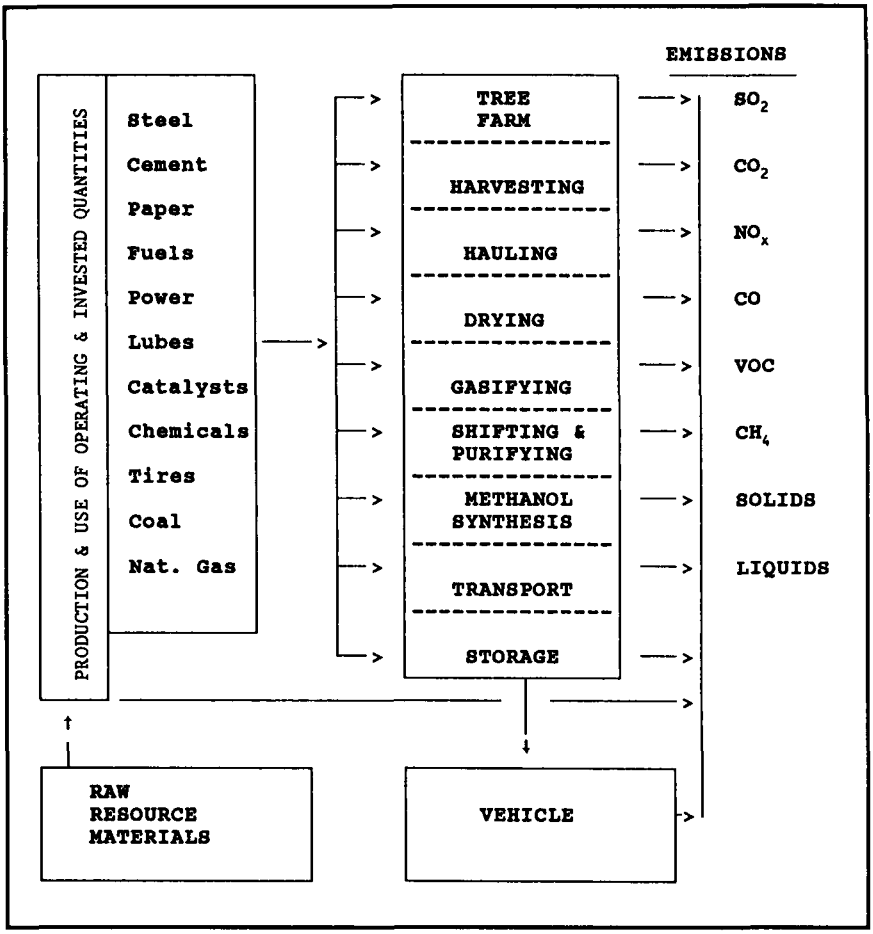

Figure 1. System definition for methanol from woody biomass.

Therefore, the method requires definition of the system life-cycle and identification of the GHG emissions for each period in that life. It is convenient to divide the total time under consideration into four periods:

Period 1. Everything associated with bringing the system into being, i.e., research, development, testing, engineering, detailed design, procurement of materials and construction operations (termed development/construction).

Period 2. The entire operating life of the system from startup to final shutdown.

Period 3. All cleanup work, including teardown, salvage, perhaps entombment of elements, and all final waste disposal.

Period 4. All final effects of the system after the end of Period 3, covering the decay of GHGs and other waste streams.

With these concepts in place, the quantitative development is straight-forward. The first part uses information on the GHGs discharged by a system to determine the amounts actually in the atmosphere at various times through system life and after it ceases operation. As defined, the first time period covers the initial warming effect due to the invested emissions from the preoperations interval of the system beginning at $t = t_1$ and ending at $t = t_2$. The second time period, operations, begins at $t = t_2$ and ends at $t = t_3$, and the third covers post-operation cleanup or system decommissioning from $t = t_3$ to $t = t_4$. The fourth or final period is one during which all the GHGs remaining in the atmosphere from the previous phases decay and vanish, i.e., from $t = t_4$ to t_∞ or the end of the GHG lifetime.

The mathematical development for quantitative analysis is carried out for each period and then the relationships are added to cover the entire life-cycle-plus time effect of the system. A simple material balance is written for a given period, i.e.,

$$\frac{dN(t)}{dt} = P(t) - \lambda\,(t)\,N(t), \tag{1}$$

where N(t) is the number of moles of the GHG emitted by the system existing in the atmosphere at any time, t, P(t) is the rate of the GHG emission by the system as a function of time, and $\lambda\,(t)$ is the rate of decay of any mole of the GHG in the atmosphere. Thus, while the GHG is being injected into the atmosphere, part of that released earlier in the period has been removed by one or several processes. Integration of this equation with the proper relationship for $P(t)$ and $\lambda\,(t)$ gives the number of moles which are present in the atmosphere at any time, with rigor limited only by the information on $P(t)$ and $\lambda\,(t)$.

For purposes of illustration and preliminary analyses, we made several simplifying assumptions: 1) the rate of injection, P, is constant at an average value for each period, as shown in Figure 2; and 2) the rate of decay for each GHG is constant, suggesting that simple first-order decay occurs. Thus, a simplified material balance can be written as follows, where P is the rate of injection, moles/unit time, and λ is the

$$\frac{dN(t)}{dt} = P - \lambda N(t) \tag{1a}$$

rate of decay, in moles per unit time per mole present. Dickinson and Cicerone applied this balance to constant emissions of CFC's [22]. Integration for real values of λ yields

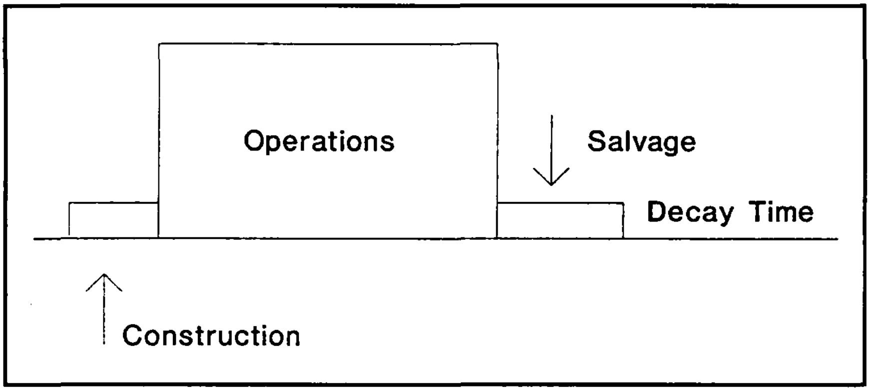

Figure 2. Simplified profiles for system periods.

$$N(t) = \frac{P}{\lambda}(1 - e^{-\lambda t}) + N(t_0)e^{-\lambda t}. \tag{2}$$

In the approach discussed here, the total greenhouse warming forcing is calculated for the system for each active gas alone, as a function of the concentration at any instant, times its absorption efficiency, integrated over the duration of the period of the lifetime of the GHG for the decay phase. The concentration value is the ambient atmosphere value plus the emission of the system. Similarly, the absorption efficiency value is for that portion of the response curve applicable at the time. Then, the total system warming forcing is calculated by summing the effects of the individual gases.

Finally, the total warming forcing can be related to the total lifetime useful output of the system (e.g., kwh) to yield an index of performance: the Greenhouse Warming Effect Index. As noted, essentially all the data needed for calculations should be available from careful material and energy balances normally carried out for each block of the technical flowsheets needed to describe the system. As a footnote to the procedure, GHGs which decay into GHGs, such as methane and carbon monoxide, can also be treated by slight modification of the material balance equation [15]. Only simple integrations are needed to convert GHG emissions and lifetimes of gases to warming effects for spreadsheet presentation. These are easily carried out by table or on personal computers.

WOOD BIOMASS TO METHANOL CASE STUDY

This case study was executed in full conformance with the method outlined above, so the following steps were involved.

1. Individual process flowsheets were prepared for every block, or subblock if required, of the operations from beginning to end shown in Figure 1, for

making detailed energy and material balances. Standard flowsheets were augmented by inclusion of all mobile and fuel-driven equipment estimated for operation of that block. All flowsheet blocks were scaled from the gasifier so the flowsheets are in material balance.

- For example, this required estimation of all the operating and service vehicles used for the tree farm, the engine capacity of each, and horsepower-hours of operation per cycle. Then, based on fuel use per horsepower hour, total direct fuel consumptions were developed. To these consumptions were added the consumptions in the fuel chain to prepare each gallon of fuel going into an engine, i.e., indirect consumptions. These represented a fossil fuel subsidy often overlooked for energy use and emissions analysis.
- The flowsheets were also detailed to show consumables such as fertilizers, pesticides, herbicides, water, building heating fuel, and electric power. Both direct and indirect energy consumptions were estimated for each.
- For transportation blocks, primary equipment needs were determined and consumptions estimated. Auxiliary vehicles were included. Other consumables such as lubrication oils, shop heat and power were estimated. Then both direct and indirect energy consumptions were estimated.
- For wood chip gasification and conversion to methanol, a contractor's study was selected and examined in detail [23]. Additions were made as necessary to cover auxiliary vehicles, and oversights as regards owner's costs not considered by the contractor. Add-on direct and indirect fuel energy and chemical consumptions were estimated.

2. Detailed lists of all equipment in every block were prepared which included all commodity materials used to bring every block of the operating flowsheet into being. This was done by disaggregating equipment, machinery, buildings, services, and civil installations into units of basic materials, such as steel, concrete, copper, aluminum, etc.
   - This listing was employed to sum up the total amount of each basic material invested in plant and machinery to bring the system into being. Then, information on the energy use and emissions of the system which produced the material, e.g., cement, was used to convert the amount of material installed into "invested" energy and emissions of a direct nature.
   - Secondary information on the system used to produce the commodity material was employed to estimate the invested energy and emissions due to commodities used to create this system, e.g., steel used to build the concrete plant. A reaction to this calculation might be that it deals

  with second-order infinitesimals. This may be true, but *a priori* rejection of these quantities is not warranted until several detailed analyses prove the case.
- Finally, to add to the operating component of invested energy and emissions, estimates must be made of human inputs to R&D, engineering, design, and construction. Also, fuel and power usage for construction and construction equipment are estimated to derive energy use and emissions.

3. The operating life of the system was set, along with the stream factor, turnaround and maintenance philosophy, to yield useful output per unit time. This defines the energy output, which can be compared with the total operating and invested energy inputs to yield energy efficiency.
4. Energy balances were prepared by use of the flowsheets and material balances. These quantities were aggregated to determine total operating inputs and invested inputs for calculation of simple ratios or efficiencies. The integrated lifetime useful output divided by the integrated operating inputs yields a simple operating efficiency. The integrated output divided by the total of the operating and invested inputs yields the total system energy efficiency.
5. Emission quantities were more difficult to determine and aggregate. Direct fuel usages were converted to emission quantities based on fuel composition and NO_x generation characteristics of engines, i.e., gasoline versus diesel. Similar summations were carried out for all other combustion processes. Finally, all emissions were aggregated, invested emissions for Period 1 and operating emissions for Period 2. For this first analysis, the salvage phase (Period 3) was ignored. Use of new information from the Electric Power Research Institute [24] regarding errors in nitrous oxide values obtained from grab samples markedly reduced the estimated nitrous oxide emissions from the anticipated values. Emissions were converted to average values for both the construction and operating phases and the relationships for constant-value releases were used for calculating the moles of each GHG in the air at any instant [14].
6. Greenhouse warming forcing calculations were carried out using the basic relationship for warming forcing [14]. This relationship uses the moles present times the instantaneous absorptivity of the GHG divided by the volume of the atmosphere. The expression is integrated over each period of project life, plus the additional time required for the residual concentration of the GHG to decay to zero.
7. Abbreviated results from the study are presented to provide a picture of end-to-end values for a complete system (all values are subject to slight revision in final calculation rechecks). An input of 310 tons of green wood per operating day yields 170 tons of dried wood and a product of 77 tons of

fuel grade methanol. An operating energy efficiency of 41 percent was calculated, including external energy subsidy. The primary GHG emission, of course, is carbon dioxide. Some 160 kg of CO_2 are emitted for every 10^9 J of methanol produced by the system (390 lb CO_2/million Btu) and another 69 kg of CO_2 are emitted for every 10^9 J of methanol burned in an engine. The profile of CO_2 existing in the atmosphere, above background, due to the system is shown in Figure 3.

IMPLICATIONS FOR GREENHOUSE POLICY

The method of analysis presented above is directly applicable to comparison of alternative technological paths to the same end use, i.e., kwh, vehicle miles, pounds of plastic, etc., even though the paths are markedly dissimilar. This result is obtained because the complete warming forcing effect of each path is calculated for a given system life. The associated warming forcing is then normalized by relating it to the total useful output of the system, i.e., kwh per unit warming or the reciprocal thereof. This approach provides a way to compare systems of markedly different components, for example biomass-to-methanol (agricultural plus industrial) with conventional petroleum-to-gasoline (industrial fossil fuel) for vehicular fuel. It would be greatly applicable to electric car systems.

For comparing different systems, the method facilitates identification and quantification of pollution conversions and intersectoral transfers. For example, if methanol from wood is substituted for gasoline, nominal improvement in urban smog may be obtained. However, in essence, that pollution is moved from the city and converted to a doubling of the CO_2 discharged to the atmosphere elsewhere. Identification of the intersectoral transfer enlarges the scope of the problem; should the rest of the nation have a voice in approving a local solution which will affect the nation and the world?

Information gathering, sharing and compilation are important elements in the Administration's global environmental change research program [25]. Our proposed method fits this effort like a glove. It should be clear that the same system definition can be used to calculate the economic cost, net energy use, and net global warming forcing. All three measures can be related to units of useful output to obtain a common basis. All can be developed with slight extension of the energy, material, and money balances normally carried out [26, 27]. Sensitivity analyses can be made in the normal manner. With cataloging of the data, on consistent bases and on generic systems, approaches with the same output can be rank-ordered in each category in regard to their desirability.

The federal administration appears to favor development of a market-based approach, as in the 1990 Clean Air Act Amendments, to attain compliance with possible atmospheric stabilization objectives. Thus, it is implied that a "bottom-up" approach resulting from aggregation of many individual voluntary decisions would be preferred to a small number of "top-down" mandates. In a practical

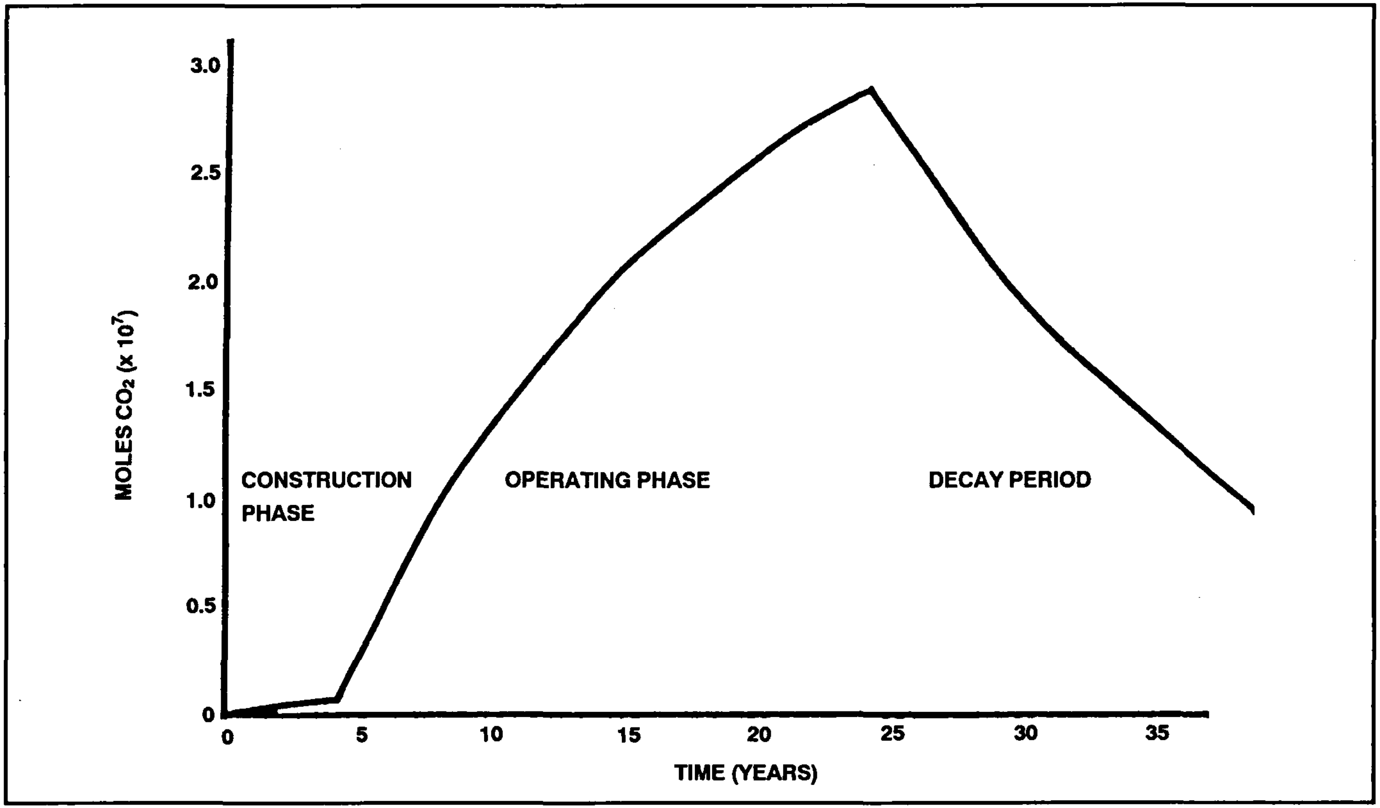

Figure 3. Moles CO$_2$ in atmosphere from project vs. time.

sense these decisions would be made by many smaller, decentralized groups based on prevailing conditions existing at the time.

Even with the possible adoption of national targets for GHG emissions reduction which could reorient entire industries, decisions would be made at the margins of existing conditions. Thus, individual companies or groups of investors would be faced with questions of the type outlined above; should a certain amount of crude oil production and refining be shut down and a matching amount of biomass-based methanol production be constructed to take its place to meet vehicular fuel needs? The proposed analytic method is easily applied here.

The "sunk cost" practice from economic analysis is a concept that has definite applicability to GHG warming forcing analyses [28]. A sunk cost is one that was incurred in the past and cannot be altered by present or future action. Economic decisions related to future action should not be permitted to be affected adversely by sunk costs [29]. The same rationale should be applied to decisions regarding GHG emissions and the warming forcing of individual systems; what happened in the past should not influence decisions regarding the future. A particularly important area is that of choosing between continued operation of an existing system and shutting it down and building and operating an alternative system.

The first analysis of all systems should be on the basis of "grassroots" start-from-scratch creation of the system. This is obviously correct for situations such as the wood-biomass-to-methanol system for auto fuel discussed herein. However, where the basic decision is a choice between building the biomass system, continue with gasoline, or await reformulated gasoline, comparison of these alternatives as grassroots systems would be inappropriate. The relevant warming forcing for the gasoline system, where adequate or over-capacity already exists, does not include construction of the system. Since it exists already, prior emissions have long since entered the ecosystem and cannot be recalled. Therefore, the warming forcing of the gasoline system will come from future operations, salvage, and decay, plus the use of the gasoline. For reformulated gasoline, the analysis should be based on the prorated effect of the current system, plus the prorated effect of constructing and operation, etc., of facilities to produce new blending agents (e.g., MTBE). Otherwise, the gasoline system is falsely burdened, except in those countries where the gasoline system does not exist. Applicability to this type of situation is a strong attribute of our method of analysis.

The method outlined is particularly applicable to assessment of basic technologies. Others have recognized the need to include more components in general economic analysis [30] and are gradually broadening the scope of analysis toward the system definition outlined above. Yet great difficulty exists in utilizing general, sectoral economic data from many different sources, with unknown gaps and assumptions, to continually include new sectors and increase the accuracy of the overall result. Careful studies of generic systems using the proposed method can provide benchmarks for adjusting major sectoral studies and rank ordering basic approaches. Further, with the responsibility the national laboratories have regarding technology transfer [31], they must be careful to make the correct technology available. This means that any of the three scenarios typified above could apply with respect to a given developing country. The transfer agent should be able to defend quantitatively the choice for any transfer. With our method, the analyses to do so are relatively simple.

CONCLUSIONS

In any program or agreement for controlling greenhouse warming forcing in which transfer of clean technologies to developing countries would be central, the entire effect of each candidate should be defined clearly. This requires a systems perspective, consideration of lifetime-plus effects, and determination of the effect of each GHG separately. A method of analysis which meets these requirements has been described. When applied to trade-offs such as biomass-based methanol fuel versus gasoline, effects such as the intersectoral transfer of pollution and increased greenhouse warming forcing become evident. We believe this method shows real promise and should be used as the basis for the collection and sharing of information between public and private agencies to provide detailed data for rank-ordering generic systems with respect to their respective greenhouse warming forcing, energy usage, and dollar cost.

ACKNOWLEDGMENTS

We thank Dawlat El-Sayed for her assistance with the analysis and Thomas James, Director, Science and Public Policy Program for his contributions. Lennet Bledsoe and Kathie Ewing helped prepare the manuscript.

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