THE REFERENCE MATERIALS SYSTEM -
A FRAMEWORK FOR SUBSTITUTION ANALYSIS*

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Abstract - A comprehensive systems approach to materials policy analysis, the Reference Materials System (RMS), has been developed and is described in this paper. The RMS provides a systematic approach to organizing diverse materials on all processes ranging from extraction of resources through their refinement, transportation, fabrication, installation, and maintenance at the point of end use, as well as recycling. This system can be used for the assessment of material technologies, substitutions and policies, and has been applied to assess the role of renewable materials as substitutes for energy intensive nonrenewables.

The format employed for the RMS is similar to that of the Reference Energy System (RES) used for energy analysis. It provides an engineering process description of material flows and related efficiencies, environmental impacts, and costs. The utilization of materials in the economy may be shown by using the RMS in conjunction with interindustry models of the economy of the input/output variety. When used in continuation with such economic models the methodology allows for the analysis of materials policies and of the needs for renewable and nonrenewable materials to meet the demands of continued economic and social development in developed and less developed countries.

INTRODUCTION

The availability of materials for housing, durable goods, industrial construction, transportation systems, and energy is central to the life-style and prosperity of the United States (U.S.). The materials system is quite complex in view of the existence of a large number of natural sources of renewable and nonrenewable character, and the multitude of technical activities operating within a complex institutional framework. The technical activities include the exploration for a wide range of material resources, conversion of these resources into useful products, operation and maintenance of these products over their life span, and finally recovery or recycling of these products back into the resource stream. Although the materials system is a vital element of the nation's economy, this system has many other attributes involving its effect on employment, energy needs, capital requirements and environment. Technical and policy options designed to deal with specific issues may alter the trade-offs between these conflicting characteristics.

While energy problems have occupied much of the national attention lately and have led to the formation of the Department of Energy, there is no focal point for the formulation and coordination of materials policies. In the U.S. supply, demand, and allocations within the materials system are largely determined by independent forces working through the market. The problems arising from growing environmental concern and changing patterns in international supply and demand generally induce changes in resource markets that are outside the scope of the decision-making capacity of the private sector. Government support for research and development in materials system is increasing but is still quite fragmented. Government policies as well as private sector decisions must be based on improved up-to-date knowledge of the technical, economic, and environmental parameters of the materials system. This kind of information is also useful to scientists and engineers who need technical data on materials properties and processes, and business needing information on materials supply and demand.

A large number of formal and informal materials information systems has been devised, both in private and public sectors. Unfortunately these systems, in addition to being quite

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disparate and incompatible, are generally deficient in that they consider only isolated aspects of the materials system. The need to address the broad technical and policy questions in both the public and private sectors points toward the requirement for a framework within which economic, environmental, and technical factors involved in the supply and utilization of materials may be simultaneously considered for analysis of the materials system. The objective of this paper is to outline such a comprehensive framework, the Reference Materials System (RMS), that may be used to assess the broad impacts of materials policies. The RMS represents the supply and demand balance in the materials system and the technologies employed to produce and utilize materials.

REFERENCE MATERIALS SYSTEM

Many studies have been performed on the energy and environmental aspects of materials production. Berry(1) and Midwest Research Institute(2) have published information on the energy inputs to the production of glass, aluminum, and plastic container materials and Ayres(3) has analyzed environmental impacts associated with materials production. Hannon(4) has considered the direct and indirect energy inputs to materials using input/output modeling in the analysis of recycling policies. The Reference Materials System format provides a comprehensive and standard format in which the results of such process analysis of specific materials and production steps may be displayed. The methodology is similar to the Reference Energy System which has been coupled to interindustry models of the economy(5) and can be used in a similar manner to provide a generalized coupled process and economic model for use in technology and policy analysis. The Reference Materials System concept has been employed as the central systems analysis approach by the Committee on Renewable Resources for Industrial Materials of the National Research Council (NRC). The thrust of the NRC study was to identify the most promising areas for substituting nonrenewables by renewables which in turn would highlight the Research and Development (R&D) programs needed to overcome the barriers to production and use of renewable resources. The RMS approach has also been adopted for a study(6) in Ireland concerned with the use of biomass as a source of energy. Although the specific emphasis on the various policy objectives will vary from country to country depending upon its stage of development, mineral base, etc., the RMS, because of its general nature, can be applied as a policy and planning tool in any national situation. For example, minimizing the labor requirement at the expense of capital expenditure by choosing a particular technology in an industrialized country may not be the desired objective of a developing country where the opposite is generally true. Such policy objectives are exogenous to the RMS and are formulated independently.

The nation's materials system can be thought of as consisting of an integrated set of technical activities such as exploration, refinement, conversion, transportation, fabrication of material resources into useful products, and finally, the maintenance and recycling of these products. The RMS is a network representation of the physical flow of materials through all of the production and utilization steps that a resource must go through to be used for a specific purpose in the economy. The scope of the RMS is outlined in Fig. 1. At the left-hand side is a listing of resources both renewable and nonrenewable, while the products and end uses, defined at the functional level, are listed on the right side. The definition of the use of materials for specific functions and purposes is central to the RMS concept. Only at this level can conservation and substitution opportunities be analyzed with any technical reliability. Engineering properties such as strength to weight ratios, corrosion resistance, and durability must be considered.

The completed RMS involving a network representation of the flow of materials from the resource side through all of the "activities" listed along the top to a specific end use such as building and construction is shown in Fig. 2. This figure is quantified in terms of the mass of material flowing annually through each activity. The network can also be quantified in terms of energy use, cost, labor, and environmental effects. A path from a specific resource to a specific end use is called a "trajectory." Each "activity" in the trajectory represents a technical process or production step that is characterized by both a material flow element (and material losses) and the data elements listed, e.g., energy requirements, other material inputs, labor and capital needs, and environmental effects. The activity category involving "installation, erection and maintenance," not relevant in the energy system, is of special importance in the case of a materials system for evaluating life-cycle usage characteristics of materials. Opportunities for recycling of materials are identified in terms of activities characterized by material flows and data elements. Imports and exports of resources and products can be indicated by flow vectors from and into the appropriate nodes.

The RMS illustrated in Fig. 2 is simplified and aggregated for presentation purposes only. Additional detail is provided in versions of this system that have been developed for policy studies. An example of additional information that is needed is alloying materials such as chromium, molybdenum, and cobalt that provide desired strength and corrosion resistant properties for certain applications.

It is feared by many that resource scarcity will limit future economic and social development. Analysis of the role of materials in our society requires the extension of the Reference Materials System to a general economic framework. The conventional Input/Output framework provides a detailed picture of the structure of the economy and of interindustry flows. While normally quantified in monetary units, Input/Output Tables have also been quantified in physical terms (mass flows, energy flows, etc.) The Reference Materials System provides the basis for estimating the technological coefficients and material substitutions represented in the Input/Output Tables. Fig. 3 shows the format of a modified Input/Output Table. The flow of materials resources through the materials conversion processes into the other non-material industry sectors and the final demand sectors is represented by coefficients representing the mass of specific materials required per dollar or physical unit of output in the industry sectors. The summation of total outputs in dollar terms represents the Gross National Product (GNP) of the nation. This framework then provides the analytical link between GNP (which when exhibited in terms of individual sector elements is representative of a life-style pattern) and the requirement for specific materials. When presented at this level of detail, engineering analysis may be represented. This step of introducing the physical representation of a technical system in an economic framework has been accomplished for the energy system but not as yet for the materials system.

The logic of incorporating a physical representation of a technical system in an economic framework along with consideration of resource, labor, capital, and environmental factors is illustrated in Fig. 4. Starting at the bottom, resources are employed in technological systems to produce goods and services in the economy. Environmental effects are also produced that must be balanced against benefits of production. Policy actions or decisions taken at any level can affect the need for and use of materials and technology.

RMS projections of the material flows, compatible with the economic forecasts for the future years, say 1985 and 2000, can be prepared assuming a natural evolution of technologies and no new federal policy initiatives. This projected system can then be used as a base case for the substitution analysis and technology assessment as discussed in the following sections.

ANALYSIS OF MATERIAL UTILIZATION AND SUBSTITUTION

The RMS and the associated data can be used for the analysis of materials utilization and substitution. This is done by using the perturbation technique in which incremental effects of the substitution are analyzed with respect to the material flows and attendant energy, economic, and environmental implications indicated on the RMS diagram and backup data sheets.

The technique of perturbation analysis involves the following basic steps:

1. Analysis of the specific end use involved in a utilization or substitution problem.
2. Definition of any new processes to be used in the affected trajectory from the resource to the specific end use (definition of losses, energy, labor and capital requirements, and environmental effects).
3. Revision of flows through the affected trajectories in the RMS to reflect the revised utilization or substitution of materials and/or new processes.
4. Accumulation and tabulation of resource, energy, labor, capital, and environmental consequences of the utilization or substitution.

In analyzing the specific nature of the substitution, it is necessary to address the specific application. The mass ratio of substitution, e.g., kg of paper that would replace a kg of plastic, depends on the specific application and the nature of the material. Thus, one would have to focus, for example, on paper bags as a substitute for polyethylene bags. The determination of these substitution ratios must be done exogenously to the RMS and the results reflected in the revised or perturbed RMS. In certain instances, material preferences and substitution may be constrained or influenced by such factors as esthetics and codes or standards.

The parameters of the technical characteristics of new processes must also be obtained exogenously to the RMS by people with a process background. The intent of the RMS format is to capture those characteristics of the technology that are important to materials policy formulation because it is not available in a consistent and comprehensive format.

Following these steps, the perturbation of the appropriate trajectories and the accumulation of information on detailed consequences is straightforward using the RMS. In the case of an analysis of the substitution of paper bags for polyethylene bags for example, the flows through the wood to paper trajectory would increase by the appropriate amount while the flow of crude oil and natural gas through the petrochemical trajectory would be decreased. The full materials system implications may then be traced all the way back to the forest and the

source of the oil, imported or domestic. The results of the analysis may then be used as a basis of support or revision of the original utilization or substitution measure.

When used in this fashion, the RMS can be a useful technique for the analysis of materials policy. It must be recognized that the technique focuses on the physical structure of the system and its requirements. Thus, although substitution analysis may be performed in a rather direct manner, in cases of more general policy analysis the effects of a policy action on the supply or demand for materials use and on the physical structure of the system must be developed or estimated prior to use of the RMS.

A case study to evaluate the energy implications of substitution of plastics by paper products for certain kinds of packaging and containers has been included in the appendix.

EVALUATION OF NEW MATERIAL TECHNOLOGIES

The research and development policy area is of great importance to the future development of the nation's materials system. Only through the development of new technologies can the diversity and flexibility be realized to allow the materials system to adapt to the changes in the resource availability and environmental concerns that will occur over time.

The major thrust of the problem in this case lies in estimating the parameters of the new and as yet undeveloped technology. Having done this, the perturbation technique, as in the case of substitution analysis, can be used to compute the incremental effects with respect to resource consumption and attendant energy, economic, and environmental effects. The uncertainties in estimating the parameters of new technology are recognized but, by using the perturbation technique, the sensitivity of policy comparisons to errors in the forecast is reduced.

Following is the list of pertinent data on the technology under consideration that should be assembled prior to the actual technology assessment.

1. Date or dates of implementation,
2. Degree of implementation at the date, e.g., fraction of the total end use demand met by the use of this technology,
3. Primary material input,
4. Economic data: capital cost, plant life, operating and maintenance cost, etc.,
5. Environmental effects.

The place of the technology should now be appropriately noted on the RMS for the time-frame of interest. The technological area being replaced should also be noted and the resource allocations should be checked for consistency. Knowing the level of implementation, the technology is inserted in the RMS. The next step is to sum up the resource, energy, capital, and environmental consequences of the perturbed system and compare them with the base case to arrive at the incremental benefits (or losses).

It is clear that the system under discussion is static in time and that the replacement does not occur instantaneously. If the purpose of the assessments is just to ascertain the technological effect of the future system change, the lack of dynamic response is not critical. However, if the assessment is to be used for research and development planning, it is important that the cost of the research and development program be compared with the discounted present worth of the ultimate benefits of implementing the technology over the entire planning horizon. These benefits may be estimated with the static system by applying it at several points and calculating the present worth of that stream of annual benefits. With this information, a cost benefit ratio can be computed for technologies under consideration and the corresponding research and development areas can be ranked accordingly. Due account must also be taken of several other factors, e.g., uncertainties involved in any critical research areas, safety aspects, international questions, institutional factors, etc. before developing final research and development strategies. Finally, increased sophistication in the treatment of environmental impacts may be incorporated as an improvement in the above analysis. Regional definition of the materials system is important in some applications but is of extreme importance with respect to environmental effects as they cannot be addressed adequately in systems representing a national average situation.

APPENDIX

Case Study Of Material Substitution In Containers And Packaging Sector

Packaging is used for three major classes of goods: durables, nondurables, and foodstuffs. The overwhelming fraction of durable goods is packaged in corrugated cardboard. Corrugated cardboard is also most commonly used as a packing material in case of durables. Nondurables

consist of clothing, textiles, and chemicals and require a variety of packaging characteristics. Foodstuffs, the third major area for packaging, represent about 15% of the production activity of the U.S. economy and account for 60% of the total shipment value of the entire range of goods that are packaged. This sector involves the widest variety and largest amount of packaging materials, apart from corrugated cardboard, produced from renewable resources. In the following discussion, specific examples have been chosen for which both nonrenewables and renewables can be interchangeably used to meet certain packaging requirements. Such examples are: sanitary food containers used for milk, butter, margarine, frozen foods, ice cream shortening, etc.; trays for packaging meats, eggs, and produce; and flexible containers, e.g., bags and sacks.

Although labor requirements and capital costs are also important considerations in the comparison of alternative materials, attention is focused exclusively on energy implications in this case study of materials for containers and packaging.

In connection with sanitary food containers, two RMS trajectories are shown in Fig. 6. These correspond to the special case of half-gallon containers made of plastic and of paper. Mass flows and energy values shown in the figure under each activity link refer to requirements for manufacture of one container of each type. Energy data are in terms of the "gross" value of energy requirement. Summing all the energy components along the two trajectories, one can see that a plastic bottle weighing 54 grams needs about 8.4×10^6 joules, whereas an equivalent paper carton weighing 64 grams needs 6.4×10^6 joules. Also, the plastic bottle requires 22 grams and 55 grams of natural gas and crude oil, respectively, as chemical feedstock, while an equivalent paper carton needs 130 grams of groundwood. Adding the energy content of raw materials, the total energy inputs to a plastic bottle and an equivalent paper carton work out to 11.9×10^6 and 7.9×10^6 joules, respectively. In Fig. 5 two trajectories for the manufacture of size 6 meat trays from styrofoam and from molded wood pulp are shown. The energy requirements in the two cases add up to about the same value, 0.9×10^6 joules each. Here again, taking into account that 2.3 grams of natural gas and 7.2 grams of crude oil are needed as chemical feedstocks in the case of the polystyrene tray and 30 grams of groundwood is needed as raw material for one pulp tray, the total energy values increase to 1.3×10^6 joules remaining same in both cases. In the case of flexible containers, polyethylene is used for plastic bags and Kraft paper for paper bags. The energy cost of Kraft paper(1) is $= 48 \times 10^6$ joules/kg, and that of polyethylene, $= 160 \times 10^6$ joules/kg or 3.3 times as much. But, because medium-weight polyethylene bags weigh only half as much as an equivalent paper bag, the ratio of energy consumption of plastic and paper bags is $= 1.65:1$.

The above comparison is not entirely fair to plastics if there is the possibility of reusing the plastic containers. As an example, to make and fill a half-gallon plastic milk container a single time requires about 8.4×10^6 joules of energy. If it were reused, and the washing and filling costs remained the same with each use ($= 3.2 \times 10^6$ joules), then the cost would drop to 5.8×10^6 joules with one reuse, to 4.9×10^6 joules with two reuses, and to 4.5×10^6 joules with three reuses. Similarly, although a single use of plastic bags requires more energy than paper bags, the two become comparable if more durable polyethylene bags are reused once. These results are summarized in Table I. Using this information in conjunction with RMS with sufficient disaggregation in the Containers and Packaging Sector, the perturbation technique can be applied in rather straightforward manner to assess the full materials system implications in terms of energy and resource requirements arising from the substitution measures considered here.

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TABLE I

ENERGY REQUIREMENT FOR TYPICAL CONTAINERS AND PACKAGING

Container/packaging (product) type	Raw material requirements Per unit product				Energy of manufacture per unit product		Energy content of raw materials	Total Energy
	Unit weight (grams)	Natural gas (grams)	Crude oil (grams)	Wood (grams)	(10 ⁶ Joules)	10 ⁶ Joules/ Kg. of Product	per unit product (10 ⁶ Joules)	per unit product (10 ⁶ Joules)
<u>Half-gallon Milk Container</u>								
Polyethylene plastic	54	22	55	----	8.4 5.2*	155.0 96.0*	3.5	11.9
Paper	64	----	----	130	6.4 3.0*	100.0 47.0*	1.5	7.9
<u>Size 6 Meat Tray</u>								
Polystyrene plastic	6.7	2.3	7.2	----	0.9	127.0	0.4	1.30
Wood pulp	20	----	----	30	0.94	47.0	0.36	1.30
<u>Flexible Container (bag or sack)</u>								
Polyethylene	18	6	16	----	2.9	160.0	1.0	3.9
Kraft paper	36	----	----	70	1.7	48.0	0.8	2.5

* These values exclude the energy required for filling the containers.

Scope of Reference Material System and Associated Data Elements

<u>Resource base</u>	<u>Production (growing)</u>	<u>Harvesting or extraction</u>	<u>Processing</u>	<u>Transportation (aggregate)</u>	<u>Fabrication and recycling</u>	<u>Product Identification</u>	<u>Additional Fabrication (e.g., Erection) & Maintenance</u>	<u>End use and recycling</u>
<u>Renewables</u>								
Forest resources		<div> Land use Energy Fertilizer and chemicals Labor Environmental - solid waste Capital Cost Operating Cost Institutional and organization problems </div>	<div> Data Elements to be identified for each resource/activity combination </div>			Lumber		Commercial and
Grazing and rearing						Plywood		industrial
land resources						Paper		structures
-birds						Particle board		Housing
-cattle						and fiberboard		Transportation
-sheep						Chemicals		Furniture and
Crop land resources						Fibers and woven		upholstery
-cotton						fabrics		Energy
-cereal and sugar						Nonwoven fabrics		-fuel
cane						Elastomers		-power
-others						Fuels		Books and pub-
Other forest resources						Plastics		lications
-coconuts						Aluminum mill		Producer goods
-citrus peel						products		Textiles
-gum						Steel mill		-clothing
Marine resources including						products		-soft goods
agricultural types						Concrete		(footware)
-algae								-packaging
-menhaden etc.								Communication
<u>Nonrenewables</u>								
Aluminum								Disposable
Iron and steel								products
Cement and concrete								-packaging
Oil and gas								-other
Coal								Recreation
								(competes for
								use of land)

Figure 1

MATERIAL UTILIZATION IN THE ECONOMY: DATA FORMAT

INPUT TO SECTORS

Figure 3

SOCIO-TECHNICAL SYSTEM HIERARCHY

POLICY AREAS

- NATIONAL GOALS
- STANDARDS
- REGULATION
- REGULATION
- R&D
- TAX & SUBSIDY
- STANDARDS
- R&D
- STANDARDS
- TAX AND SUBSIDY
- REGULATION
- STANDARDS

SOCIO-TECHNICAL SYSTEM HIERARCHY

Figure 4

REFERENCE MATERIALS TRAJECTORIES

Half Gallon Milk Container (Plastic Bottle vs. Paper Carton)

Note: Numbers in the parentheses below the activity links refer to mass flow in grams and energy requirement in million joules, respectively, for the corresponding steps in the manufacture of one-half gallon milk containers.

* Energy content of resource.

Figure 5

REFERENCE MATERIALS TRAJECTORY
Size 6 Meat Tray (Polystyrene vs. Molded Pulp)

Note: Numbers in the parentheses below the activity links refer to mass flow in grams and energy requirement in million joules, respectively, for the corresponding steps in the manufacture of one Size 6 meat tray.

* Energy content of resource.

Figure 6