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SYSTEMS FRAMEWORK FOR MATERIALS POLICY*

BY

Naresh Bhagat and Kenneth C. Hoffman**

National Center for Analysis of Energy Systems
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

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ABSTRACT

A comprehensive systems approach to materials policy analysis, the Reference Materials Systems (RMS), has been developed and is described in this paper. The RMS provides a systematic approach to organizing diverse information corresponding to various 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 as an evaluative tool, specifically, for the assesment of materials, technologies, and policy and has been applied to the analysis of renewable materials as substitutes for energy intensive nonrenewables. In addition, the definition of end uses on a functional level provides the basis for material substitution analysis.

The format employed for the RMS is similar to that of the Reference Energy System. As such it provides an engineering process description of material flows and related efficiencies, environmental impacts, and costs that may be used in conjunction with interindustry models of the economy of the input/output variety.

INTRODUCTION

The availability of materials for housing, durable goods, industrial construction, transportation systems, and energy is central to the lifestyle and prosperity of the United States. While energy problems receive much attention and have led to the formation of two major Federal Agencies to coordinate policies, and research and development, there are no similar focal points for materials. The material system is quite complex in view of the availability of many natural sources of renewable and nonrenewable character, and the multitude of technical activities operating within a complex private and governmental 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.

While the material system is central to the operation of a modern society, this system has many other attributes involving its effect on employment, energy needs, and capital requirements. Although the material system is a vital element of the nation's economy, it also involves environmental effects that adversely affect the quality of life. Technical and policy options designed to deal with specific issues may alter the trade-offs between these conflicting characteristics. The need to address these broad implications 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 the planning and analysis the materials system. The objective of this paper is to fulfill this need by developing a framework such that technical and policy options that will influence the future development of the nations material system, can be evaluated in a consistent and uniform manner.

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 imputs 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 imputs to materials using imput/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.

The nation's material system can be thought of as consisting of an integrated set of technical activities such as exploration, refinement, conversion, transportation, fabricaton of material resources into useful products, and finally, the maintenance and recycling of these products. The RMS is a network representaton 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 Figure 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.

A completed RMS presents a network representation of the flow of materials from the resource side through all of the "activities" listed along the top of figure 1, to a specific end use such as housing. 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 meterial flow element (and material losses) and thedata elements listed (e.g., energy requirements, other material imputs, labor and capital needs, and environmental effects.) The activity category involving "installation, erection and mainenance", not relevant in the energy system, is of special importance in the case of material system for evaluating life cycle usage characteristics of materials. In some instances, it will be necessary to develop data for several representative subactivities within an activity. This may be required to give detail on sequential or alternative processes, techniques, etc. within an activity. For example, under the processing activity in stell trajectory, pig iron production and steel making are to be considered sequentially while steel making by electric furnace, open hearth furnace and basic oxygen furnace etc. will have to be treated as alternative processes and represented by three parallel activity links on the RMS steel trajectory. Opportunities for recycling of materials are also identified in terms of activities characterized by material flows and data elements. Imports and exports of resources and products are indicated by flow vectors from and into the appropriate nodes.

An aggregate RMS with exhaustive list of renewables and most commonly used nonrenewables has been developed for the year 1972. The material flows and the corresponding energy requirements for the RMS are shown in figures 2a and 2b respectively. Similar systems with additional nonrenewables can be prepared that project the material flows, compatible with the economic forecasts, for the years 1985 and 2000 assuming a natural evolution of technology and no new federal policy initiatives. These projected systems 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., lbs. of paper that would replace a lb. 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. Frequently, such technical detail, or reality, is overlooked in 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 polyethlene 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 material 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 material system. Only through the development of new technologies can the diversity and flexibility be realized to allow the material 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 pertubation technique, same 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 recongnized 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 that date e.g., fraction of the total end use demand met by the use of this technology.
3. Primary material imput.
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 a 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 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 benifits. With this information, 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 above analysis. Regional definition of the material 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.

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 are 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 are given 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.

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 Figure 3. These correspond to the special case of half-gallon containers made of plastic and of paper. Mass flows [1] and energy values [1] 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 0.12 lb needs about 8495 Btu's, whereas an equivalent paper carton weighing 0.14 lb needs 6053 Btu's. Also, the plastic bottle requires 0.038 lb and 0.107 lb of natural gas and crude oil, respectively, as chemical feedstock, while an equivalent paper carton needs 0.28 lb 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 11,310 and 7453 Btu's respectively. In Figure 4 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, 875 Btu's each. Here again, taking into account that 0.0047 lb of natural gas and 0.013 lb of crude oil are needed as chemical feedstocks in the case of the polystyrene tray and 0.064 lb of groundwood is needed as raw material for one pulp tray, the total energy values increase to 1219 and 1195 Btu's respectively. 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 ~ 20,500 Btu/lb, and that of polyethylene, ~ 68,250 Btu/lb, 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 8500 Btu of energy. If it were reused, and the washing and filling costs remained the same with each use (~ 3070 Btu), then the cost would drop to 5785 Btu with one reuse, to 4880 with two reuses, and to 4427 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 1. Using this information in conjunction with RMS with sufficient disaggregation in Containers and Packaging sector, perturbation technique can be applied in rather straightforward manner to assess the full material system implications in terms of energy and resource requirements arising from the substitution measures considered here.

REFERENCES

1. Makino, H. and Berry, R.S., Illinois Institute for Environmental Quality: Consumer Goods - A Thermodynamic Analysis of Packaging, Transport, and Storage, June 1973

2. Hunt, R.G. and Welch, R.O., Midwest Research Institute, Kansas City, Missouri: Resource and Environmental Profile Analysis of Plastics and Non-Plastics Containers, MRI Project No. 3719-D, November 1974

3. Ayres, R.V. and Kneese, A.V.: Production, Consumption and Externalities, American Economic Review, 1969

4. Hannon, M.B., Center for Advanced Computation, University of Illinois, Urbana, Illinois: System Energy and Recycling - A Study of the Beverage Industry, January, 1972

5. Hoffman, K.C.: Methodology or Technology Analysis with Application to Energy Assessment, ASME Paper 75-Wa/TS-8, American Society of Mechanical Engineers, New York, 1975

Table 1

Energy Requirement for Typical Containers and Packaging

Container/packaging (product) type	Unit weight (lb)	Raw material requirements Per unit product: Natural gas (lb)	Crude oil (lb)	Wood (lb)	Energy of manufacture: per unit product (Btu)	(Btu/lb of product	Energy content of raw materials: per unit product (Btu)	Total Energy: per unit product (Btu)
1. Half-gallon Milk Container								
Polyethylene plastic	0.12	0.038	0.107	-----	8,495 5,445*	70,790 45,370*	2,814	11,310
Paper	0.14	-----	-----	0.28	6,053 2,840*	43,230 20,280*	1,400	7,453
2. Size 6 Meat Tray								
Polystryrene plastic	0.0148	0.0047	0.013	-----	875	59,120	344	1,219
Wood pulp	0.045	------	-----	0.064	875	19,440	320	1,195
3. Flexible Container (bag or sack)								
Polyethylene plastic	0.04	0.013	0.036	------	2,730	68,250	951	3,681
Kraft paper	0.08	-----	-----	0.16	1,640	20,500	800	2,440

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

Scope of Reference Material System and Associated Data Elements

Resource base	Production (growing)	Harvesting or extraction	Processing	Transportation (aggregate)	Fabrication and recycling	Froduct Identification	Additional Fabrication (e.g., Erection) & Maintenance	End use and recycling

Resource base

Renewables

Forest resources
Grazing and rearing land resources
- -birds
- -cattle
- -sheep

Crop land resources
- -cotton
- -cereal and sugar cane
- -others

Other forest resources
- -coconuts
- -citrus peel
- -gum

Marine resources including agricultural types
- -algae
- -menhaden etc.

Nonrenewables

Aluminum
Iron and steel
Cement and concrete
Oil and gas
Coal

[Bracketed list under Harvesting or extraction]

Land use
Energy
Fertilizer and chemicals
Labor
Environmental
- -solid waste

Capital Cost
Operating Cost
Institutional and organization problems

} Data Elements to be identified for each resource/activity combination

Product Identification

Lumber
Plywood
Paper
Particle board and fiberboard
Chemicals
Fibers and woven fabrics
Nonwoven fabrics
Elastomers
Fuels
Plastics
Aluminum mill products
Steel mill products
Concrete

End use and recycling

Commercial and industrial structures
Housing
Transportation
Furniture and upholstry
Energy
- -fuel
- -power

Books and publications
Producer goods
Textiles
- -clothing
- -soft goods (footware)
- -packaging

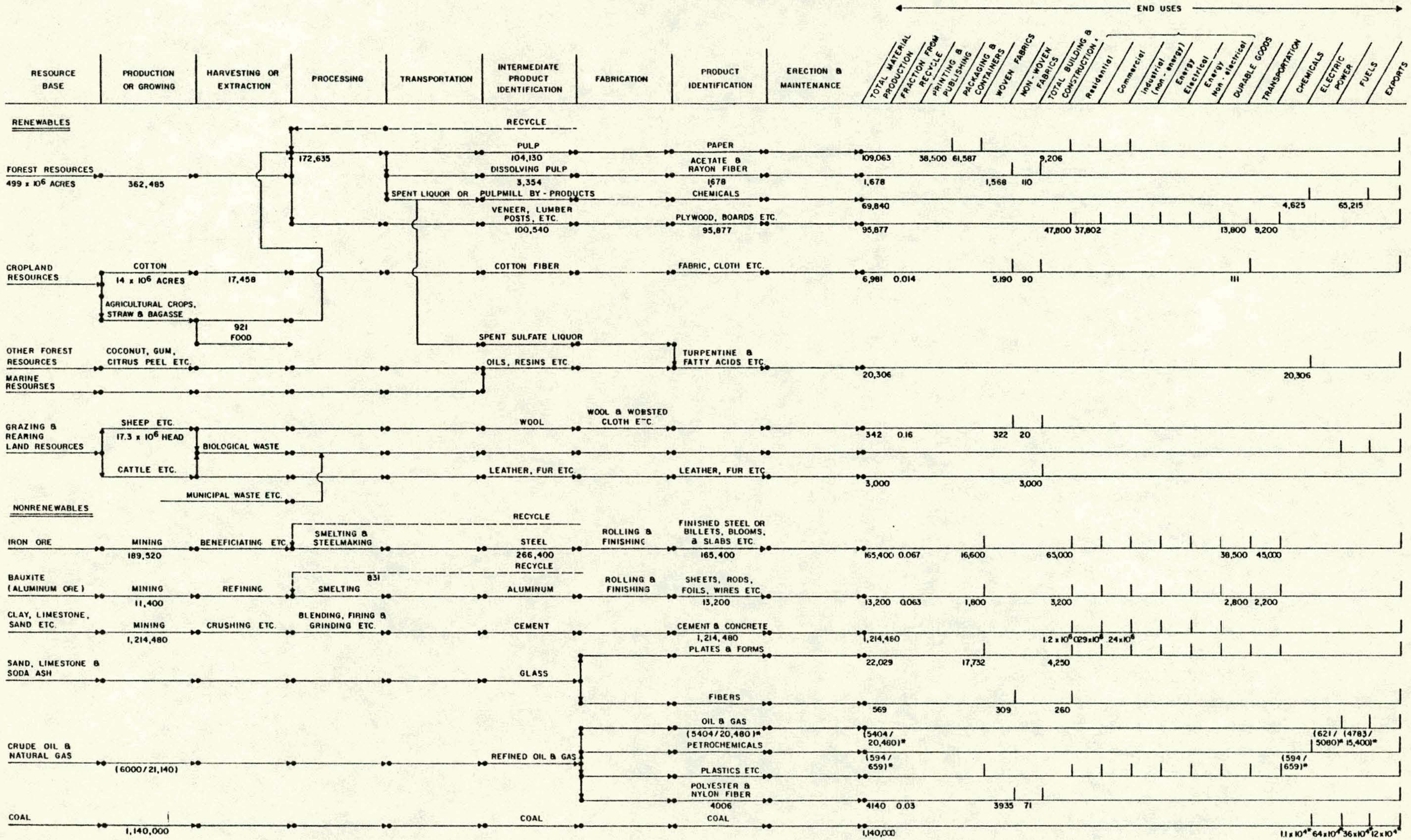
Communication
Disposable products
- -packaging
- -other

Recreation (competes for use of land)

Figure 1

AGGREGATE REFERENCE MATERIAL SYSTEM

MASS FLOW IN MILLION POUNDS (YEAR 1972)



NOTES:

(1) IN THE OIL & GAS TRAJECTORY, THE NUMBERS IN THE PARENTHESES, SEPARATED BY SLASH, ARE MILLION BARRELS OF OIL & BILLION FEET^3 OF GAS RESPECTIVELY.

(2) THE NUMBERS WITH ASTERISKS, CONFINED ONLY TO OIL & GAS AND COAL TRAJECTORIES, INDICATE FLOW IN TERMS OF PRIMARY RESOURCES INSTEAD OF PRODUCTS.

FIGURE 2a

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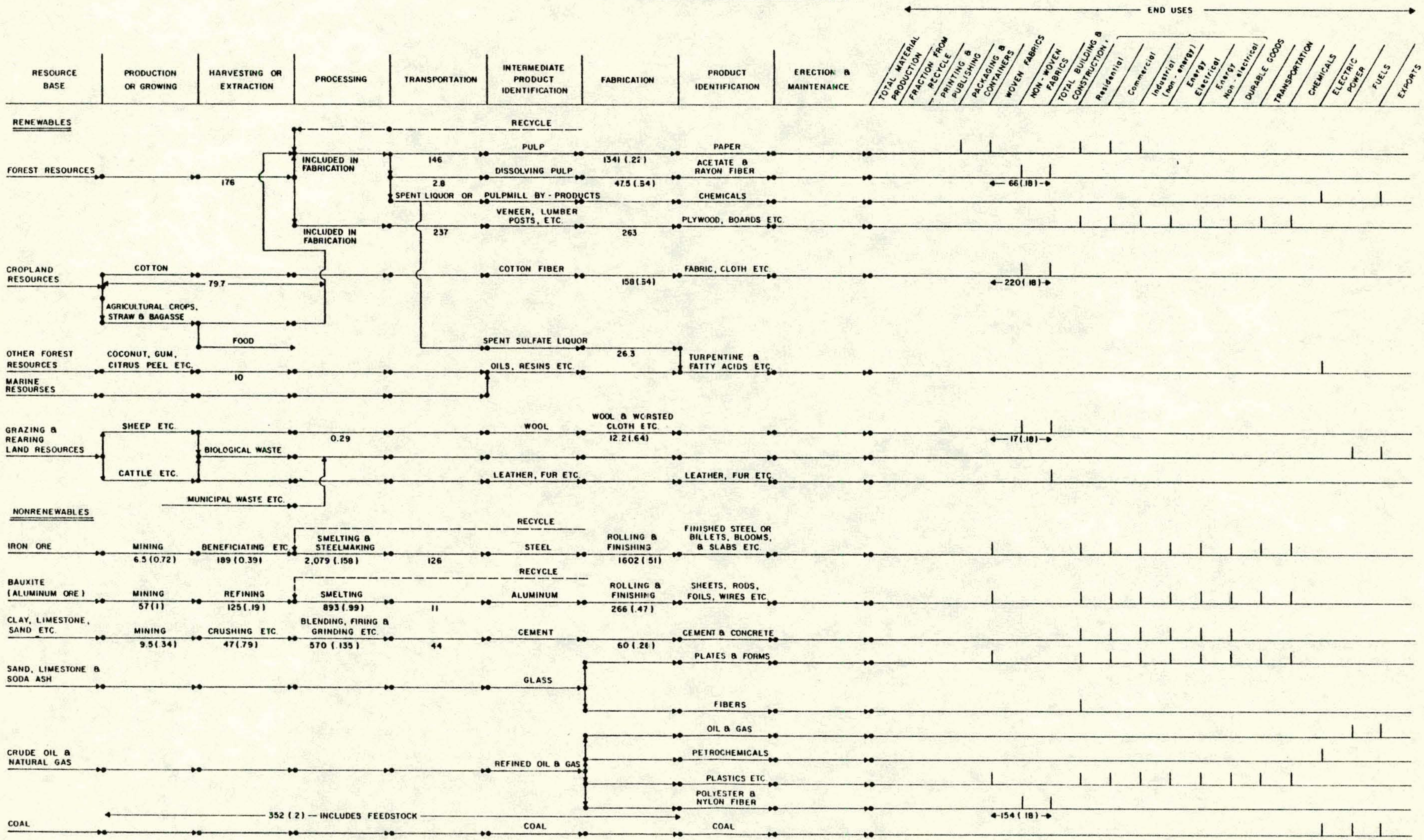
AGGREGATE REFERENCE MATERIAL SYSTEM

ENERGY REQUIREMENT IN 10^{12} BTU (YEAR 1972)



NOTE: NUMBERS IN PARENTHESES REFER TO FRACTION ELECTRICAL, AT A HEAT RATE OF 10,500 BTU PER KwH.

FIGURE 2b

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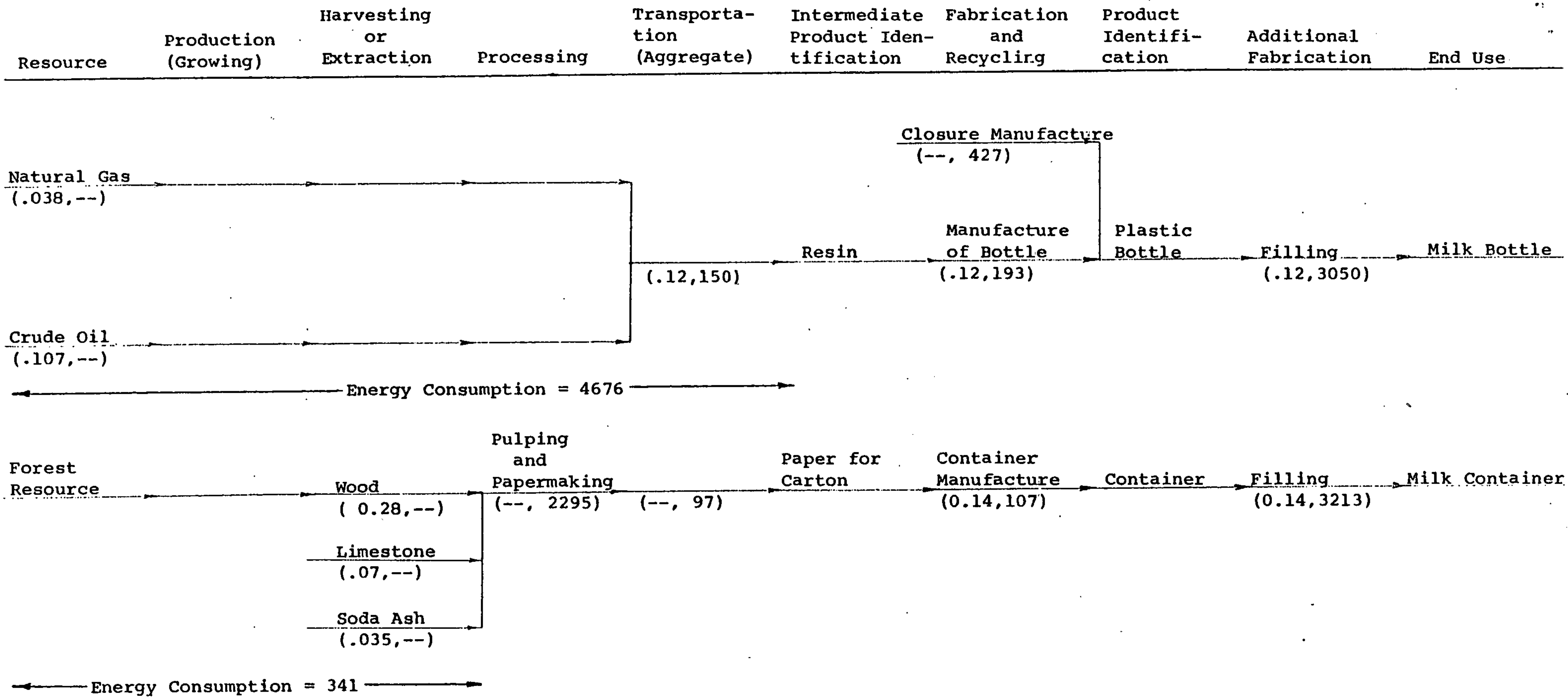
REFERENCE MATERIALS SYSTEM

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

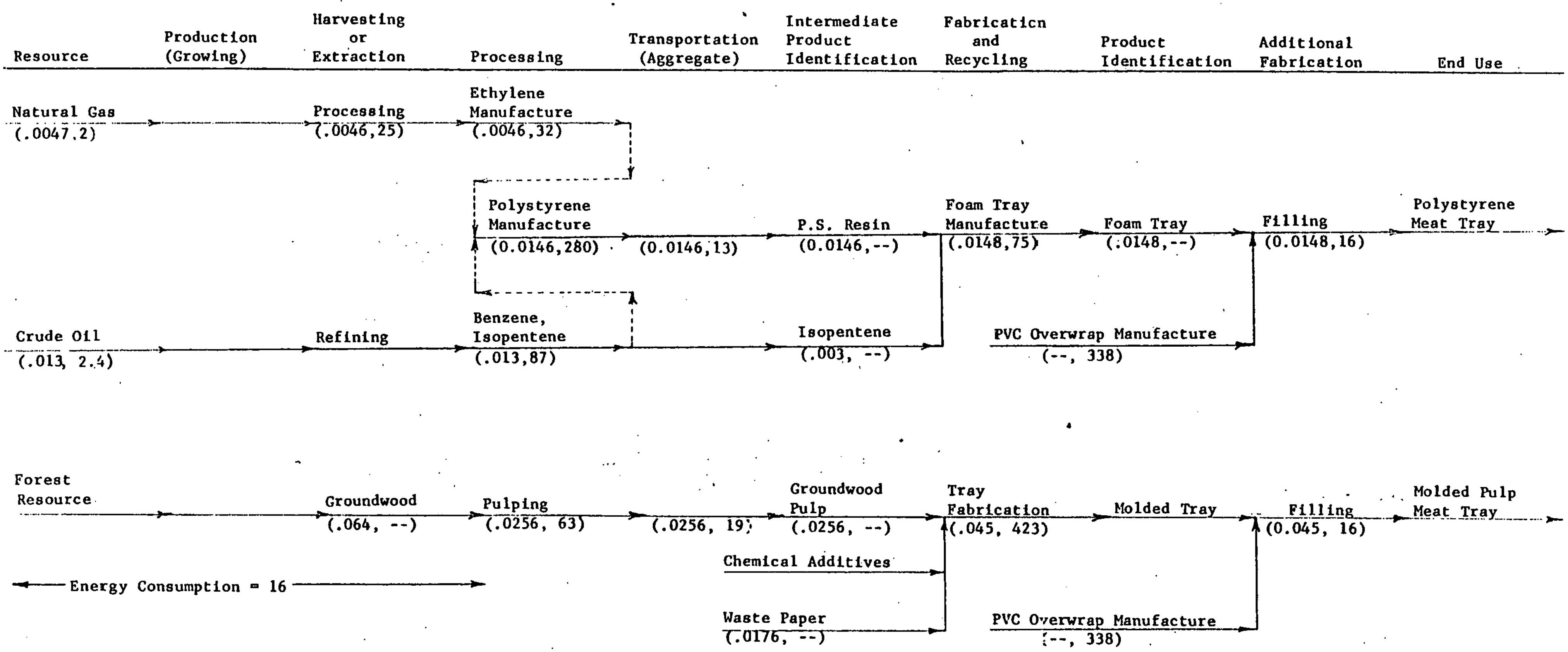


NOTE: Numbers in the parentheses below the activity links refer to mass flow in lb and energy requirement in Btu respectively for the corresponding steps in the manufacture of one half gallon milk containers.

Figure 3

REFERENCE MATERIALS SYSTEM

Size 6 Meat Tray (Polystyrene Vs. Molded Pulp)



NOTE: Numbers in the parentheses below the activity links refer to mass flow in lb. and energy requirement in Btu respectively for the corresponding steps in the manufacture of one Size 6 meat tray.

Figure 4