A Framework for Sustainable Materials Management

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Achieving global sustainability will require a decoupling of material consumption from economic value creation. While industrialized societies have achieved gains in resource efficiency and waste recycling, total material throughput continues to rise. Environmental pressures will only be exacerbated as the world's developing economies increase their consumption rates. This paper describes an integrated framework for sustainable materials management that will help to address these critical challenges from a systems perspective.

INTRODUCTION

Increasing material flows contribute to many of the world's environmental and social problems. In the near term, sustainable development is threatened not so much by the depletion of non-renewable resources such as minerals or fossil fuels, but rather by over-exploitation of renewable resources and the life cycle impacts or "externalities" associated with material extraction, transport, and utilization.[1] These externalities include potential climate change due to global warming emissions; degradation of air, water, land, and wildlife habitats in industrialized areas; and depletion of natural resources including fresh water, biomass, and topsoil. Hence, there is a need to explore the potential for achieving sustainable materials management (SMM).

As the global economy grows more highly connected, more materials are being consumed and transported over longer distances. A recent overview study of materials and waste streams in the European Union (E.U.) concluded that there is no absolute decline in the volume of the European Union's total resource requirements, and that a shift from domestic sources toward the use of imports is shifting environmental burdens to other regions of the world.[2] Improvements in resource efficiency alone cannot guarantee the sustainability of industrial societies, and material substitution and recycling strategies will only delay the ultimate depletion of non-renewable stocks since complete recycling of waste streams is impossible.[3] At the same time, a switch to large-scale energy generation based on renewable resources is likely to have unacceptable environmental impacts.

In response to these challenges, this article presents an integrated perspective on the relationship between materials flow and sustainability, the options for reducing material intensity in a diverse and growing global economy, and the available tools for assessing the impact of material flows on environmental, economic, and social well-being.

To understand material flows, it is helpful to adopt a conceptual framework that includes the sources of materials, their pathways through the natural and built environments, and their eventual sinks. Figure 1 presents a simplified systems view that partitions the physical world into three types of interconnected systems.

Ecological Systems

Ecological systems comprise the biosphere and provide products and services to industrial and societal systems. They contain four types of natural resource stocks. *Renewable resource* stocks (e.g., forests) are replenished over time provided that the rate of exploitation does not exhaust the existing stock. These are often described as natural capital. *Non-renewable resource* stocks (e.g., petroleum) can be exploited at any time, but once the finite stocks are exhausted they cannot be replenished and need to be replaced by other forms of capital. *Environmental media*, including air, water, and land, are finite and cannot be depleted, but their quality may be

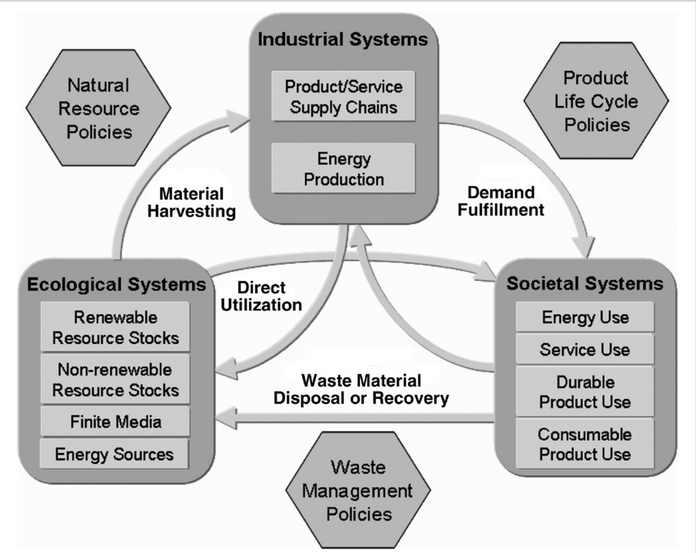

Figure 1. A systems view of material flow cycles and policy frameworks.

degraded. For example, land area may be left unexploited, used for agriculture, degraded due to soil erosion, or rendered "sterile" by commercial or industrial use. Last are *sources of energy*, including solar, geothermal, and tidal energy, which are effectively infinite but may be influenced by human activities.

Industrial Systems

Industrial systems utilize ecosystem services and extract or "harvest" materials, drawing upon the described types of ecological resource stocks in varying degrees. Industrial wastes that cannot be re-used are deposited back into the biosphere. There are two major categories of industrial systems.

Supply chain systems, actually networks, are sequences of supplier-customer links that begin with primary resource extraction and end with the delivery of a finished product or service to fulfill a societal demand. *Energy production* systems are similar to supply chain systems, except that the end product is energy utilized either within the industrial systems or to fulfill societal demands, including residential and transportation uses.

Societal Systems

Societal systems consume the products, services, and energy supplied by industrial systems, and generate waste that is either recycled into industrial systems or deposited back into the biosphere. Societal systems may also consume ecosystem services and resource stocks directly (e.g., through farming). Product use can be separated into two categories. *Durable* consumer goods (e.g., automobiles) are used repeatedly over an extended period, possibly requiring ongoing consumption of supplies and energy. At the end of their useful lives the products become waste, which is potentially recyclable. *Non-durable* consumer goods (e.g., food items) are used once and either wholly or partially consumed, with the remainder becoming potentially recyclable waste.

Mirroring these physical systems is an economic system that mediates most transactions involving flows of materials, goods, and services, although ecological flows are often ignored. Economic growth will typically correspond to increased "throughput" in terms of the total amount of materials flowing through the three systems, and may be a consequence of population growth or growth in material demand per capita.

DEFINING SUSTAINABLE MATERIALS MANAGEMENT

It is clear that negative environmental impacts (i.e., externalities) related to increasing material flows represent a threat to ecological sustainability. However, there is an opposite pressure from socio-economic systems: population growth and economic development tend to increase the demand for materials. A lack of adequate material goods, including food, water, and medicines, afflicts a large proportion of the world's population, which is growing at the rate of about 90 million people per year. According to the World Bank, roughly 2 billion people lack potable water and sanitation, leading to proliferation of both viral and bacterial infectious diseases.[4] Close to 3 billion people, more than half the developing world's population, live in extreme

UNDERSTANDING MATERIAL FLOW PATTERNS

As a baseline for sustainable materials management (SMM), one must understand the relative magnitude of material flows in the global economy. Material flow analysis (MFA) and the associated methods of material flow accounting are important tools for quantifying these flows.[13] Essentially a mass-balance approach, MFA calculates the mass of materials entering and leaving a defined system boundary (Figure A). A key indicator used in MFA is domestic material consumption (DMC), calculated by subtracting exports from direct material inputs. Domestic material consumption accounts for the direct trans-boundary flows of materials, but not for the indirect material flows associated with the product chains of imports or exports. A fraction of annual materials input is sequestered in capital stocks of durable assets, mainly buildings, while a fraction of these stocks enters the output stream as durable assets are retired.

Another useful indicator is total material requirements (TMR), which considers the "material rucksack" of indirect, hidden flows, including mining wastes and other discards, which are carried along with direct material inputs but generate no economic value and can disturb the natural environment. The size of the rucksack can be significant. For example, a diamond ring weighing 10 g has a rucksack of about 6,000 kg, while an average newspaper has a rucksack of 10 kg.[14] Since these hidden wastes do not enter the economic system, they represent a true environmental externality, but the significance of TMR in terms of actual environmental impacts is difficult to assess.

A recent MFA study indicates that the E.U. economy has become more eco-efficient in terms of material intensity, since the ratio of DMC to gross domestic product (GDP), or resource efficiency, has slowly declined from about 1.2 kg/€ in 1992 to about 1 kg/€ in 2000.[15] However, the absolute DMC has slightly increased, so that actual decoupling of material use from economic growth has not been achieved; that is, DMC continues to grow with GDP. The study concluded that the average DMC per capita for the EU-25 in the year 2000 was approximately 16.5 t, although individual countries ranged from less than 10 t to more than 30 t per capita. Similarly, another study showed that between 1980 and 2000 EU-15 DMC per capita declined from 16.2 t to 15.6 t, while overall material efficiency increased by 52% and GDP grew by about 70%.[16] Thus, it can be asserted that to support the lifestyle of the average European resident requires

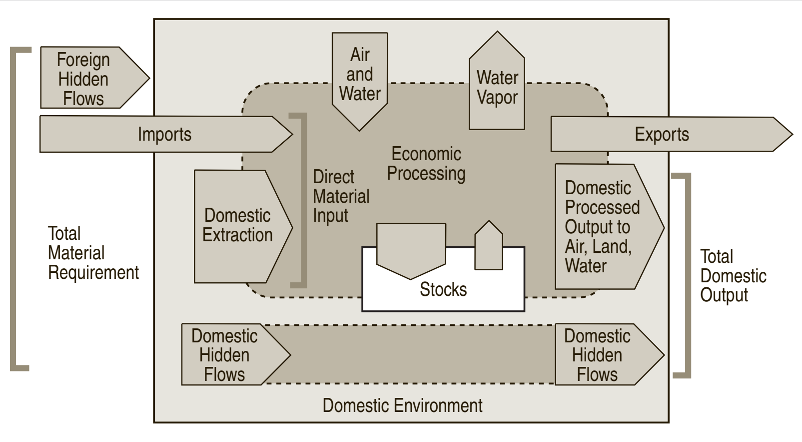

Figure A. An overview of national material flow accounting model (Source: World Resources Institute [WRI]).

poverty, earning under $2/day. Many of these populations are suffering social disintegration due to the displacement of their traditional lifestyles by rapid industrialization and urbanization.

At the same time, income gaps in society are growing. The ratio between income earned in countries with the richest 20% of the population compared to the poorest 20% widened from 30:1 in 1960 to 60:1 in 1990 to 74:1 in 1997. This gap is reflected in the disproportionate share of materials consumption among global nations. The richest 20% of the world population accounts for 86% of total private consumption expenditures; consumes 58% of the world's energy, 45% of all meat and fish, and 84% of paper; and owns 87% of cars and 74% of telephones. Conversely, the poorest 20% consumes 5% or less of each of these goods and services.[5] Thus, continued economic growth and resilience are important elements in assuring quality of life not only for affluent societies, but also for disadvantaged populations.

a direct material consumption of about 44 kg/day. The majority of these materials are construction minerals, fossil fuels, and biomass from agriculture. (The TMR, including the material rucksack, is estimated to be about five times greater, or about 220 kg/day.)

Material flow analysis can be used to focus on particular substances, geographic areas, or industries. More in-depth investigations may be necessary to support policy-making regarding intervention in particular material flow pathways. Figure B depicts a substance-specific analysis; it shows that arsenic use in agricultural applications has declined, but its use as a wood preservative has risen nearly 25-fold in the United States, which may pose a threat to soil and water quality when wood products are discarded. In 2001, the U.S. Environmental Protection Agency adopted a stricter standard for arsenic in drinking water and reached agreement with the wood treatment industry to phase out arsenates.

Obviously, not all materials are created equal in terms of their environmental impact; for example, sand and gravel represent a large proportion of material flow by weight, but are much less significant than other materials in terms of their adverse effects. Similarly, while metals and fossil fuels are often lumped into the category of non-renewable resources, the elemental structure of metals means that they are perpetually recyclable and not subject to the degradation that occurs with materials composed of complex molecules.[17] Generally speaking, variations in toxicity, reactivity, flammability, environmental fate, bioaccumulation, and persistence will alter the ultimate impact of different substances that are released to the environment. In addition, the geographic location, flow rate, and medium of discharge can introduce uncertainties about the environmental impacts associated with such releases. Accounting for all of these differences at a national or global level appears to be an intractable problem. Therefore, aggregated economy-wide material flow indicators should be utilized with caution.

Finally, a reliance on mass flow indicators can be deceptive because of the hidden environmental burdens associated with manufactured products. For example, the miniaturization of electronic products gives the appearance of dematerialization, yet a more careful analysis reveals that large quantities of chemicals, materials, and energy are required as inputs to the manufacture of these products.[18] In the case of imported electronic devices, these hidden flows will not be counted, not even as part of the ecological rucksack associated with the products. Instead, they will appear in the domestic material flows for the nations that manufacture the components. In an economy where global sourcing is increasingly the norm, the question of allocating accountability for these upstream material flows remains challenging.

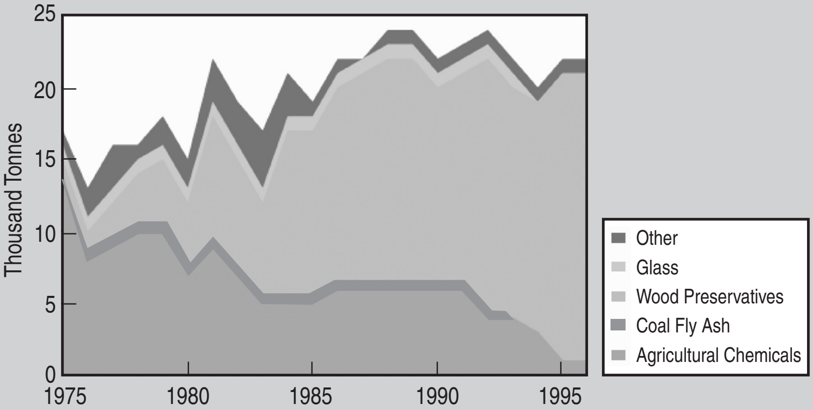

Figure B. Potential arsenic outputs to the U.S. environment, 1975–1996 (Source: WRI).

The adverse environmental impacts of economic growth might be mitigated by decoupling the rate of material throughput relative to economic growth, yet recent empirical studies question whether the shift to new technologies in the information age leads to reduced materials intensity.[6] It has been hypothesized that, in developed countries, rising resource intensity will flatten out and begin to decrease as income rises, but some economists argue that a new phase of "rematerialization" or re-linking can occur.[7] Establishing an efficient level of decoupling ideally would require that all external environmental costs are reflected in material and product prices, allowing the market to determine the appropriate level of material use.[8] However, it is unlikely that environmental resource protection will be a priority as long as these resources are perceived to be free and limitless,[9] thus, in the absence of perfect markets, more active interventions appear to be necessary.

The following definition is intended to help both government policy-makers and business decision-makers to develop proactive strategies for managing material flows. *Sustainable materials management* (SMM) is an integrated approach toward managing material life cycles to achieve both economic efficiency and environmental viability. Material life cycles include all human activities related to material selection, exploration, extraction, transportation, processing, consumption, recycling, and disposal.

It follows that SMM practitioners will seek to reduce the material throughput required for sustained economic prosperity and to minimize the adverse impacts of material usage upon environmental and social well-being. Strategies for SMM can be separated into two categories: dematerialization and detoxification.

Dematerialization

Dematerialization refers to the reduction of material throughput in an economic system, and can include the following approaches: increase of material efficiency in the supply chain, thus reducing waste; eco-design of products to reduce mass, packaging, or life-cycle energy requirements; reduction of transport in the supply chain, thus reducing fuel and vehicle utilization; recovery and beneficial recycling of post-industrial or post-consumer wastes; substitution of electronic services for material-intensive services; substitution of services for products.

Dematerialization has been popularized in proposals such as Factor 4, which suggests doubling global economic wealth while halving material resource use.[10] Some argue that for industrialized nations to reach long-term sustainability, a Factor 10 transformation is necessary.[11]

Detoxification

Detoxification refers to the prevention or reduction of adverse human or ecological effects associated with materials use, and can include the following approaches: material substitution, replacing toxic or hazardous materials with benign ones; cleaner technologies, reducing the toxic or hazardous properties of waste streams; reduction of greenhouse gas emissions associated with fossil fuel combustion; material regulation, placing restrictions on the use of specified materials; waste modification through chemical, energetic, or biological treatment; waste containment or isolation to prevent human and ecological exposure; and in-situ waste treatment, reducing the effective concentrations or adverse impacts of wastes that have previously been discharged into the environment.

While detoxification reduces the environmental pressure of materials use, dematerialization can actually decouple material use from industrial growth, either by reducing material requirements or by substituting recycled materials for virgin raw materials.

Provided that ecological limits are recognized, decoupling material consumption from economic growth appears to be a reasonable aspiration. For example, the proven reserves of non-renewable resources continue to increase, largely due to technology improvements. It is estimated that the present terrestrial stock of fossil fuels represents about a 1,000-year supply at the present rate of consumption, which is equivalent to about 7 billion metric Gigatons of oil per year. To sustain the availability of this stock for perpetuity would require decoupling fossil fuel consumption from economic growth and decreasing it by 0.1% per year, a realistic goal.[12] Of course, efforts to limit atmospheric carbon emissions may require even further reductions in fossil fuel consumption.

Concerns about the environmental impacts of non-renewable resource consumption will likely outweigh concerns about resource scarcity for the foreseeable future. Increased material consumption presents a threat to the sustainability of renewable resources such as forests and fisheries, as well as the quality of environmental media such as arable land and fresh water. Thus, the key to SMM is to understand and mitigate the adverse impacts of material flows upon ecological and societal systems rather than simply constraining material flows. For example, the global transport of materials from producing countries to consuming countries, while it may appear economically efficient, can have undesirable side effects upon natural resources (e.g., land appropriation or accidental spills). A well-balanced policy approach might internalize these negative impacts into transport costs.

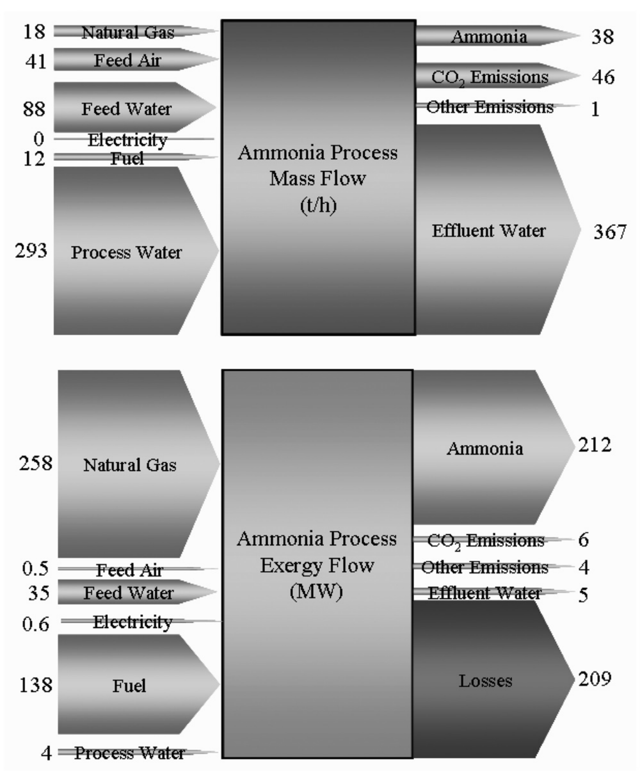

Figure 2. Comparative analysis of mass flow and exergy flow for an ammonia process.

ANALYZING THE IMPACTS OF MATERIAL FLOWS

The sidebar on page 16 describes how material flow analysis (MFA) can be used to understand material flow patterns. However, analysis of material flows in terms of mass alone does not account for differences in their environmental impacts. The following two techniques can augment MFA by considering environmental implications.

Ecological Footprint Analysis

Ecological footprint analysis is a technique for estimating the amount of productive capacity needed to support a specified economic activity, quantified in terms of the total land area hypothetically required. This can be interpreted as the burden placed on the carrying capacity of ecosystems due to economic activities and material flows. In some cases, technological intervention (e.g., use of biotechnology to increase agricultural productivity) can increase the carrying capacity of a resource. However, in practice, renewable resource systems such as forests have an upper limit on the amount of replenishment per unit time that they can support without impairment.

The amount of biologically productive capacity worldwide has been estimated for the year 2000 as 2.1 hectares per capita, of which 1.6 hectares are land-based ecosystems such as forests, pastures, and arable land and 0.5 hectares are ocean areas.[19] Setting aside a small fraction as protected areas leaves about 1.8 hectares per capita. Ecological footprint analysis can be used to estimate the human demand, based on the biological capacity required to support both resource consumption and waste absorption. Given numerous assumptions and uncertainties, the methodology conservatively estimates the average footprint in 1996 to be 12.3 hectares in the United States, 7.7 hectares in Canada, and 6.3 hectares in Germany. The average global footprint for all nations is estimated at 2.8 hectares per capita, suggesting that humanity's ecological demands already exceed what nature can supply. Thus, humanity has arguably moved into what is termed ecological overshoot, and is effectively depleting the available stock of natural capital rather than living off the interest.

The components of the ecological footprint are heavily dependent upon material consumption patterns. For example, in lower-income nations, over 50% of the footprint is due to agricultural and forest products, and about 18% is due to energy production (mainly fossil fuels). In higher-income countries only about 28% is due to agricultural and forest products, while close to 60% is due to energy production.[20] From this perspective, it appears that decoupling material consumption and waste generation (especially CO_2) from industrial growth is essential for the global economy to reverse the overshoot and return to a sustainable path.

Ecological footprint analysis can be applied at any level of granularity, from an entire nation to a single individual. Thus, it offers a method for testing the burden associated with economic enterprises, supply chains, or communities.[21] However, it should be noted that the concept of carrying capacity merely addresses survivability, rather than sustainability in terms of quality of life for human populations.

Thermodynamic Analysis

Thermodynamic analysis is an approach for modeling material flows in complex systems based on the laws of thermodynamics. The underlying concept is exergy, defined as the available work that can be extracted from a material; for example, the exergy content of a fuel is essentially its heat content.[22] More generally, exergy tends to be correlated with material scarcity and purity, since it measures the difference of a material from its surroundings. In fact, embodied exergy can serve as a common currency for aggregating material flows and provides a more meaningful weighting of waste flows in terms of potential impacts. Since energy (actually exergy) is the ultimate limiting resource, and since embedded energy is a common characteristic of all materials, it is possible to measure material flow patterns in terms of exergy flows.

The energy intensity of materials is very different from their mass intensity, and is arguably more closely correlated with the life-cycle natural resource impacts of material inputs as well as the economic value and/or environmental impact of material outputs. As a result, there has been a growing interest in the use of thermodynamic indicators to represent the impacts of industrial processes.[23] In fact, all of the factors of industrial production—energy, materials, land, air, water, wind, tides, and even human resources—can be represented in terms of exergy flows. Therefore, exergy can be used as a universal currency to measure growth, efficiency, and sustainability in industrial-ecological systems.[24]

Figure 2 provides a simple comparison of alternative analysis methods for an ammonia process. The top of the figure shows a typical MFA, with the width of each arrow corresponding to the quantity of material inputs or outputs. Due to the law of conservation of mass, the sum of materials entering the process equals the sum of the materials leaving. The bottom shows a similar analysis, except that each material or energy flow is measured in terms of exergy, including embodied chemical or physical energy (expressed in Megawatts). The differences are evident. For example, water accounts for over half the mass flow, but has low exergy content because it can be piped directly from a natural source. In contrast, the mass inputs of fuel and natural gas are low, yet their exergy content is high, reflecting their combustion potential. Similarly, the exergy content of ammonia is high, reflecting its value for subsequent processes involving energy extraction. The mass flow of electricity is zero, yet the impact of electricity use can be significant. Due to the second law of thermodynamics, some exergy is inevitably lost as "waste" energy, and thermodynamic efficiency can be measured as the ratio of exergy produced to exergy consumed.

BUSINESS VALUE OF SMM

In the private sector, business processes that involve materials management—including sourcing, inventory management, warehousing, logistics, and distribution—are increasingly viewed as strategic levers in enhancing business competitiveness. This is due partly to the drive toward more efficient asset utilization, and partly due to increasingly complex supply networks that result from globalization and outsourcing. At the same time, environmentally conscious purchasing practices and increased awareness of corporate social responsibility have elevated corporate concerns about product stewardship and waste minimization. Companies recognize that environmental issues can no longer be addressed in a reactive fashion. They are increasingly expected to take responsibility for the disposal of products and packaging at the end of their useful life, so that designing for reverse logistics has become a strategic approach for converting wastes into assets and thus generating shareholder value.[24] As a result of these trends, SMM is fully compatible with the business goals of leading multi-national companies.

Recent research has demonstrated a correlation between shareholder value in capital markets and excellence in sustainability, including both social responsibility and environmental management.[25] Specifically, there are two types of business value creation associated with improved sustainability performance.

Liability and Cost Avoidance

Liability and cost avoidance is the traditional domain of corporate environmental management, and includes compliance with regulations and standards, minimization of product or process-related risks, and environmental stewardship. Materials management practices such as pollution prevention, reduction in hazardous materials use, waste minimization, and improvements in material logistics (e.g., pallet geometry) are important contributors to reducing operating and capital costs.

Economic Value Creation

Economic value creation is increasingly recognized as an opportunity area for corporate environmental managers, working in conjunction with cross-functional teams. An example of value-creating practice is raising productivity of business processes through material conservation, eco-efficiency, and conversion of wastes into by-products. New technologies such as process intensification and micro-reactors have demonstrated the potential for order-of magnitude increases in process yield and capital productivity. Supporting environmentally responsible design of products, services, and process technologies enhances product differentiation, customer satisfaction, and stakeholder confidence. Market share can be increased by accelerating time to market and conforming to new market requirements such as restricted substances and eco-labeling.

Because material use and emissions are the most visible and concrete evidence of sustainability performance, these are frequently the indicators that companies choose to utilize in sustainability reporting and other efforts to communicate their environmental performance to stakeholders.

Thus, there are significant business incentives for companies to embrace SMM practices. Examples of SMM in action are numerous.[26] For example, Intel has saved millions of dollars annually by developing lighter-weight plastic trays used to move microprocessor units through the fabrication process and deliver them to customers. They are also working to develop closed-loop systems for re-use of the trays.

Motorola's distribution managers discovered that they could reduce occupational injuries and reduce solid waste disposal by controlling the quality of wooden pallets, yielding estimated savings in lost time and expenses of over $5 million per year.

Dow AgroSciences LLC developed a termite colony elimination system that uses pest monitoring techniques to eradicate an entire colony with only one ten-thousandth of the chemicals traditionally applied to protect homes.

The international aluminum sector and Alcoa have been modeling present and future global flows of materials to ensure sustainable flows of bauxite ore as well as reduced energy needs, for example, by increasing the use of recycled aluminum products.

These experiences demonstrate that environmentally conscious material use can lower total life cycle costs and thus raise enterprise profitability. It follows that government policies can be devised to encourage economically efficient dematerialization and/or detoxification efforts in new product development and operations management. Policies that reward business innovation and provide flexibility are generally preferable to policies that prescribe specific technical solutions, which can result in unproductive, adversarial debate. Leading companies have often taken the initiative to

SMM POLICY OPTIONS

Continued economic growth will result in increased material throughput as well as waste generation. These pressures on natural resources can lead eventually to irreversible system impacts, including depletion of resource stocks (e.g., timber) or degradation of environmental quality (e.g., climate change). The inherent resilience of ecological systems allows them to tolerate such pressures up to a certain degree, but once a threshold is reached the resulting impacts can be sudden and severe.[28]

Ideally, public authorities would internalize these negative impacts in the prices facing firms and consumers, but it may not always be feasible to design policy instruments that provide the appropriate economic signals. Policy-makers concerned with global environmental sustainability need to find a balance among the following major options. One option is to decrease material throughput, especially of materials with high negative environmental impacts. This may involve increasing the technological efficiency of material processing (e.g., through eco-design, eco-efficiency, green engineering, and life-cycle management). A second option is decreasing the demand for resource consumption. This may involve reducing the availability or increasing the price of primary resources used for energy and raw materials, reducing societal demands for material-intensive products and services (dematerialization), or spurring smarter consumption through dematerialized products and services. Another alternative is reducing the adverse impacts of material flows. This may involve improving the methods for detoxification or containment of hazardous waste streams to minimize their impacts upon ecosystem structure or function. A final option is increasing the resilience of ecological systems. This may involve modification of ecosystem structure or function to increase resource efficiency, or establishment of protected zones in which pristine ecosystems can flourish.

Recognizing that current patterns of resource consumption are not sustainable, the European Commission launched a comprehensive 25-year strategy in 2003 to develop an integrated overall policy for sustainable management of natural resources.[29] Similarly, the government of Japan has adopted a comprehensive regulatory approach toward reducing material throughput.[30] Although Japan is already far ahead of the United States and the European Union in resource efficiency, it has established a goal of 50% reduction in final waste disposal by 2010. The Japanese legislative framework, adopted in 2000, includes laws governing waste management, resource recycling, and green purchasing, with specific regulations targeting packaging, home appliances, construction materials, food recycling, and end-of-life vehicle recycling. China is considering similar legislation under a new policy framework designed to promote a "circular economy," and is pursuing new initiatives in green accounting and material flow accounting.[31] Likewise, other countries including the United States, Canada, Australia, and Korea have been exploring the use of material flow accounting. In the United States, a recent government study noted that material flow information is already used as a strategic tool by leading corporations, and concluded that the establishment of a nationwide system for material flow tracking would have benefits in terms of economic efficiency, natural resource management, and national security.[32] A U.S. government interagency task force has been formed to investigate the potential uses of material flow analysis (MFA) for improving public policy in the areas of trade, security, technology, resources, and environmental management.[33]

Viewed from a systems perspective, as shown in Figure 1, policy frameworks generally can be distinguished in terms of their positioning with regard to material flow cycles. Natural resource policies (e.g., the Minerals and Metals Policy of Canada) address material flow cycles that link natural and industrial systems, including extraction, harvest, and transport of raw materials to processing facilities; and direct utilization of natural resources for purposes of fulfillment of human needs, including food, space, and recreation.

collaborate with governmental agencies and develop voluntary standards, thus pre-empting the need for regulation.

Finally, in a world of increasing complexity, global enterprise strategies are evolving from a mechanistic emphasis on predictability and control to a more organic worldview that stresses adaptability in the face of continual change. As enterprises strive to increase their long-term resilience, they recognize that their success is inevitably coupled with the resilience of the social and ecological systems in which they operate.[27] Pursuit of SMM thus becomes not just an ethical question, but a matter of corporate self-interest—assuring the sustainability of the enterprise itself.

See the sidebar for more elaboration on SMM policy options.

CONCLUSIONS

Sustainable materials management provides a valuable perspective for encouraging the decoupling of resource consumption from industrial growth. Existing international knowledge and ongoing initiatives related to SMM suggest the following conclusions.

Sustainable materials management encompasses the social, ecological, and economic dimensions of sustainability, since a tension exists between society's interest in environmental protection and increasing demand for materials associated with economic growth and improved quality of life. Despite improvements in eco-efficiency, decoupling of material utilization from economic growth has not occurred in developed nations. Moreover, based on current trends, developing nations will increase their material throughput. Therefore, SMM is an essential component in pursuing the goals of sustainable development.

Sustainable materials management policies require an integrated perspective covering the full life cycle of materials, including trans-boundary flows. Unless accompanied by improved environmental protection in developing countries, material burdens may simply be transferred with no real improvement or even a decline in global sustainability. Furthermore, progress in SMM will require insights into the relative impacts of resource consumption and waste accumulation for different categories of biotic and abiotic materials—metals, wood, plastics, etc. Analytic methods based on mass flow alone do not provide sufficient information regarding these impacts and, therefore, other tools such as thermodynamic and ecological footprint analysis warrant further exploration.

Material flow analysis tools and indicators, as well as other relevant tools such as life-cycle analysis and cost-benefit analysis, are important for comparability of international performance results and consistent policy making.

Sustainable materials management policies should take advantage of the natural synergy between the goals of dematerialization and industrial profitability, and emphasize business value drivers that promote increased resource productivity.

To achieve global integration of SMM efforts is a formidable challenge. Despite the efforts of international bodies at harmonization, the state of materials management remains highly fragmented, with individual countries implementing a variety of different policies. Many of

Product life-cycle policies (e.g., the E.U. Integrated Product Policy) address material flow cycles that link industrial systems and societal systems, including manufacturing, distribution, and consumption of products and energy to fulfill societal demands; and the recovery of waste materials for purposes of recycling or re-use in industrial systems.

Waste management policies (e.g., the Japanese Fundamental Law for Establishing a Sound Material-Cycle Society) address the flows of waste materials into natural systems, including disposition of industrial wastes, such as airborne emissions, aquatic discharges, and industrial waste disposal; and disposition of societal wastes, such as municipal wastes, non-point-source pollution, and other anthropogenic waste streams.

Within each of these policy areas, depending on the national circumstances, SMM policy-makers have a variety of options for placing economic, physical, or operational constraints upon the industrial activities that drive material flow patterns. Such interventions may include emission regulations, economic instruments, (e.g., taxes on energy and end-use), land use restrictions, and waste management requirements. Explicit regulations can be effective for directly restricting the flows of specific types of materials; examples include bans on harmful substances and emission limits for by-products such as heavy metals. However, flexible policies that influence the causes of material flows may be more cost-effective.

Natural resource policies can discourage the depletion and degradation of natural resources. For example, energy efficiency requirements and renewable energy targets will influence the consumption of materials, especially fossil fuels.

Product life-cycle policies, such as eco-design and eco-labeling programs, can stimulate greater material efficiency, increased use of renewable materials, and reduced material intensity in procurement, manufacturing, distribution, and use of products. Likewise, regulations and economic instruments aimed at waste prevention tend to decrease material consumption and increase material re-use.

Waste-management policies, including waste disposal charges, landfill bans, and recycling targets, can reduce material throughput and encourage material and energy recovery. For example E.U. policies that focus on end-of-life product recovery have created incentives for improved design of electronic products and automobiles.[34] Waste policies can also stimulate markets for secondary materials; however, overly ambitious recycling targets may not be justifiable on economic and/or environmental grounds.[35]

In addition to policies that directly promote SMM, there may be opportunities for governments to intervene indirectly in ways that create favorable business conditions. When companies compete to be leaders in environmental responsibility, social benefits are generated without the burden of prescriptive regulation. Thus, it is important for policy-makers to consider the natural business drivers for SMM. Policies such as market-based incentives, which take advantage of the business value drivers described earlier, are, in principle, more effective than policies that create business constraints. Information disclosure policies, such as the Toxics Release Inventory in the United States and the Pollutant Release and Transfer Registries in several European countries, have encouraged pollution reduction simply by making material flow data available to the public.

Finally, an important issue that should not be neglected in development of SMM policies is socio-economic equity and the related concept of environmental justice. The burdens of material use do not always fall equally upon affected human populations. Workers and local residents in primary resource extraction or basic manufacturing industries may earn lower incomes and be exposed to greater environmental pressures than those in higher value-added industries or consumers who enjoy the benefits of final products. Consideration of equity across different social strata, across national boundaries, and across generations will require extension of current economic and physical modeling frameworks.

these policies focus on narrow components of the overall materials flow cycle. A truly integrated approach must recognize the physical, ecological, and economic implications of SMM policies, and assure that they do not simply shift the burden elsewhere or reduce the efficiency of resource utilization. For example, regulating the emissions of specific materials, such as toxic air pollutants, may impose economic burdens and additional material requirements whose adverse impacts far outweigh the intended human health benefits of the regulations. Thus, policy integration should address SMM issues in a way that transcends traditional boundaries between substances, material categories, environmental media, and industry sectors.

Finally, development of SMM policies should be coordinated with policies aimed at other sustainability goals. In particular, poverty reduction is one of the paramount goals of sustainable development and needs to be aligned with SMM. For example, the Organization for Economic Cooperation and Development is sponsoring a poverty-reduction initiative focused on the relationship between inequality, economic growth, and poverty reduction in developing countries, whose aims include helping the poor to benefit from growth and globalization.[36] An integrated approach toward SMM will provide a starting point for advancing toward a more sustainable global society, in which economic prosperity is achieved in ways that avoid adverse impacts of material usage upon environmental and social well-being.

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