"Materials-Cycle Optimisation in the Production of Major Finished Materials"
CHAPTER 1: SUMMARY AND OVERVIEW

by

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This chapter is part of a report made for the EC DGXII on a project entitled ***"Materials-Cycle Optimisation in the Production of Major Finished Materials"***. This project aims at facilitating the identification of longer-term R&D needs for materials-cycle optimisation, especially by using wastes, co-products, or by-products from one process as inputs to other processes. Book publication is envisaged. Following is the list of chapters:

All chapters are individually available as INSEAD Working Papers.

CHAPTER 1. SUMMARY AND OVERVIEW

1.1. Review of Study Objectives

The stated aim of the study was "Material Cycle Optimization in the Production of Major Finished Materials", with particular emphasis on identifying ways of reducing wastes and losses at all stages of the materials life cycle, with special reference to research priorities. This can be thought of as an engineering or technological view. An alternative, but no less valid, perspective comes from economics. Thus, another version of the objectives of the study might be the following: "to analyze current and potential technological opportunities for increasing resource productivity."

To make the conclusions and recommendations concrete we have analyzed 12 specific groups of non-energy materials, including metals (aluminum and gallium; copper, cobalt, arsenic & silver; chromium; zinc & cadmium), chemicals, (sulfur-based; phosphates, fluorine and gypsum; nitrogen-based; chlorine-based), finished materials (electronic grade silicon for semiconductors) and several types of wastes (plastic packaging, scrap tires, and coal ash). These materials were chosen to illustrate a variety of approaches to increasing resource productivity, including demand reduction, source substitution, use substitution and recycling. We also note a variety of interlinkages including input, output, co-product and by-product relationships.

1.2. Increasing Resource Productivity

Since the eighteenth century there has been a remarkable acceleration of economic growth. Indeed, it can be said with considerable accuracy that economic growth itself dates from that period, since output (and wealth) per capita scarcely changed from century to century (and actually fell in some centuries) until the 1600's and particularly since the industrial revolution.

Economists of the 18th century assumed that agricultural land and labor were the source of all wealth. The importance of capital was recognized only later. Land is now regarded as a type of capital. The special role of exhaustible resources was pointed out by Malthus (land), and again by Jevons (coal). However, the contribution of resource flows to economic growth *per se* is still neglected in much of the theoretical literature on economic growth, which still focusses largely on labor and capital. Present day economists generally think in terms of production functions. Thus, the total output of the economy F is thought of as a function of three generic "factors of production", namely labor (L), capital (K), and natural resource flows (R).

The most sophisticated view of natural resources is to regard them as "gifts of nature", i.e. accumulations of "physical information" (or "negative entropy") that are gradually exhausted and degraded by excessive use. This way of looking at the world treats petroleum, coal, iron ore, soil, ground water, forests, fisheries, biodiversity, and even the stratospheric ozone layer on a common conceptual basis [Boulding 1966; Georgescu-Roegen 1971; Ayres 1978]. All of these resources are finite; some are renewable and others not, but all can be exhausted by over-use. This is a relatively recent insight in economics.

There has been an unproductive controversy over the magnitudes of mineral reserves and rates of exhaustion. Some alarmists have prematurely predicted impending mineral resource crises. (e.g. the "limits to growth" debate in the early 1970's [Meadows *et al* 1972]). Some conservatives have reacted by asserting that such fears are absolutely groundless because impending shortages are invariably signalled by rising prices which, in turn, automatically call forth investment in technological alternatives. As regards most industrial materials extracted from the earth's crust, so far at least, the latter thesis has generally been confirmed by historical experience [Barnett & Morse 1962; Smith 1979]. It appears that resource scarcity has not constituted an effective "limit to growth", up to now.

However, economists have been slow to look at the other side of the coin. If lack of resources could conceivably put a brake on economic growth, it must follow that the availability of resources — especially fossil energy — has contributed significantly to past growth. This proposition seems eminently reasonable. Yet it has not been tested econometrically, as far as we know. The major econometric work to "explain" historical growth of output F in terms of the factors of production was carried out in the late 1950's [Abramovitz 1956; Solow 1956, 1957]. The major conclusion of that work was that aggregate growth could not be explained by increases in either labor or capital inputs. The missing ingredient, suggested by Solow and others, was "technological progress".

By convention, technological progress has been conventionally subdivided into two components, namely "labor productivity" and "capital productivity". These are, respectively, the ratios of total output to factor input. Productivity growth is thus defined as the rate of change of these ratios. Since the 18th century, the growth of real output has been almost entirely due to increasing labor productivity. (Capital productivity has only increased occasionally and for brief periods). Thus, based on this econometric analysis, the "engine of growth" appears to have been technological innovation and capital investment in labor-saving technology. Labor productivity thus defined has increased enormously (by a factor of several hundred) since the beginning of the 19th century. Indeed, in most public discussions of economic growth, "productivity" is confused with "labor productivity". The latter, in turn, is invariably taken to be attributable to capital investment in "labor saving" technology. The capital/labor ratio (K/L) thus becomes a significant explanatory variable.

Unfortunately, energy and other resource flows were not considered explicitly in the econometric work cited above.[1] In fact, resource inputs to production have increased enormously since the eighteenth century. It is likely that much of the observed economic growth would be attributed to the increased input of natural resources (especially energy) to the economy. Had resource flows been included as factors of production, it would have been necessary to introduce an additional productivity term, namely the productivity of resource inputs. Since resource inputs R have increased far more than labor supply L, (in other words the ratio R/L has increased over time) it is obvious that resource productivity has not increased nearly as fast as labor productivity.

In principle, aggregate production F can be increased by increasing any of the factors. Thus, it should be possible to increase labor inputs at the same rate as the growth of F, holding labor productivity constant, by increasing the productivity of capital K and energy/material resources R instead. This strategy has not been followed consistently in any country, up to now. On the contrary, most developing countries have regarded cheap capital, cheap energy and cheap materials as "engines of growth", disregarding the fact that this policy tends to encourage the (excessive) use of capital, energy and materials as a substitute for labor.

If labor were in short supply, these policies would make sense. However, given that labor is now in surplus supply virtually everywhere, it would make more sense to substitute labor for other inputs, rather than *vice versa.* In brief, encouraging more use of energy-consuming, labor-saving machinery and equipment will simply increase unemployment.

In addition, excessive use of energy and material resources on a finite earth results in excessive wastes, pollution and environmental pressure. Every increment of raw material extracted from the environment is a future waste or pollutant, after a delay of weeks, months, or (in a few cases) years. The production function, which is supposed to be an aggregate measure of social welfare, should reflect this negative aspect of increasing resource use. Moreover, excessive use of materials also means that limited resource stocks will be exhausted faster than need be. (We agree that there is no immediate threat of resource exhaustion, for most metals and fuels, but high quality resources are, nevertheless, finite in all cases.

Conservative business leaders neoclassical economists are wont to argue that market forces will determine the optimum rate of use of raw materials, and that government intervention is therefore inappropriate. We realize the debate will not be settled soon, but we argue that, on the contrary, most resource prices are too low — in some cases much too low — because of a market failure. The market failure (or "externality") is that the indirect social costs of pollution and environmental damage are not paid by the extractive industry. If those costs had to be paid by oil and gas companies and mining enterprises, the costs of resources themselves, and of resource-intensive products and services, would be significantly higher.

However, it is not our business here to theorize about the "right" prices for resources. We merely point out that, in the absence of a market mechanism that reflects environmental and other concerns, it is not at all inappropriate for government to intervene. In fact, governments do intervene in markets quite regularly, in a variety of ways, some beneficial, some counter-productive. Policy analysis strives to provide justifications to favor the former over the latter.

Returning to the question of increasing material resource productivity, we note four basic strategies for achieving this objective. These four strategies are:

(i) **"Dematerialization": more efficient use of a given material for a given function.**

(ii) **Substitution of a scarce or hazardous material by another material.** Again, either technology or policy can drive such a shift.

(iii) **Repair, Re-use, Re-manufacturing and Recycling**. For convenience we refer to this simply as the "recycling" strategy. Obviously all of these tend to reduce the need for virgin materials, and (indirectly) all of the environmental damage and energy consumption associated with the extraction and processing of virgin materials, *including their toxic by-products*. Aluminum cans, stainless steel automotive components, copper wire and galvanized iron/steel are particularly good examples of candidates for more recycling. Arsenic and cadmium exemplify toxic by-products that could be reduced thereby.

(iv) **Utilization of waste streams from (currently) unreplaceable resources as alternative sources of other needed materials.** For convenience we call this "waste mining" (in contrast to recycling). This strategy simultaneously reducing (1) the environmental damage due to the primary waste stream, (2) the rate of exhaustion of the second resource, and (3) the environmental damage due to mining the second resource.

All of the above strategies can be *technology (and economics) driven* or *policy driven.* They are summarized, with examples, in the following 4x2 matrix.

1A	*Dematerialization, technology-driven*: Example: micro-miniaturization in the electronics industry.	1B	*Dematerialization, policy driven*: Example: imposition of Composite Average Fuel Economy (CAFE) standards for automobiles in the 1970's (U.S.) led to significant reductions in vehicle weight.
2A	*Material substitution, technology driven*: Examples: substitution of PVC for cast iron or copper water/sewer pipe in buildings; substitution of optical fibers (glass) for copper wire for point-to-point telecommunications.	2B	*Material substitution, policy-driven*: Examples: ban on CFC's leading to replacement by HCFC's or HFC's in air-conditioners & refrigerators; ban on tetraethyl lead (TEL) leading to substitution by aromatics and alcohols (e.g. MTBE) as octane enhancers in gasoline.
3A	*Recycling, technology driven*: Examples: recycling of lead from starting-lighting-ignition (SLI) batteries used in motor vehicles; recovery of catalysts from catalytic convertors.	3B	*Recycling, policy-driven*: mandatory minimum levels of recycled pulp in paper products, e.g. in Germany; recycling of aluminum cans, Sweden; recovery of mercury from fluorescent lights, Sweden.
4A	*Waste "Mining", technology driven*: flue gas desulfurization (FGD) for oil and gas refineries with recovery of elemental sulfur; recovery of fluosilicic acid from ph osphate rock processing wastes in the U.S.	4B	*Waste "mining", policy driven:* enforcement of FGD in non-ferrous metal smelters, with recovery of sulfuric acid; enforcement of FGD for electric power plants, with recovery of lime/limestone scrubber waste for use in wallboard production, Denmark.

We now summarize our major findings in more detail, with respect to the materials considered in the study, putting the emphasis on research priorities. First, we consider the three strategies above, in order. Then, we review and summarize identified research needs for each material group.

1.3. The Dematerialization Strategy

Similarly, the early telegraph and telephone lines used simple twisted copper wires. But increased demand forced greater efficiencies. Coaxial cables were the next step in this evolutionary trend toward continuously increasing the number of messages that could be transmitted per unit mass of copper. More recently microwave transmission lines have continued the trend. Again, government intervention was not needed in this case.

Copper wire in power transmission and communication offers a less well-known example. The mass of wire needed to transmit a given amount of electrical energy was repeatedly reduced by raising the transmission voltage. (This was done mainly to cut transmission losses, incidently). Currently, transmission lines of 600,000 volts, and higher, are routine.

The high price of silver has induced significant progress in the chemistry of photography (film manufacture and developing). This has made it possible to reduce the silver content of a roll of film very significantly in recent decades. (It has also encouraged recycling).

There are no substitutes for sulfur, phosphorus and nitrogen in agricultural fertilizers. On the contrary these uses will inevitably grow. Thus, it is important to find ways of utilizing these nutrient elements more efficiently, both to conserve on energy and to minimize disruption of the nutrient cycles. Non-fertilizer uses of phosphates and nitrates (e.g. explosives), particularly, should be minimized for the same reason.

However in the case of chlorine and its compounds, it is essential to minimize losses to the environment to minimize potential threats to human health, especially from chlorinated organics that may be "estrogen-like". The use of chlorinated solvents should be minimized for this reason, and also because of threats to the ozone layer. It is not clear, however, to what extent it may be possible to increase chlorine use efficiency (i.e. reduce losses) as opposed to finding substitutes.

As mentioned previously, the electronics industry (including silicon "chips") is virtually the classical example of dematerialization. In fact, miniaturization has actually outpaced expansion, in recent years, with the result that there is considerable excess capacity in the basic materials segment of the industry. Direct government intervention was not needed, inasmuch as other technical factors interacted to create strong and continuing incentives for industry to miniaturize its products. (In fact, it is quite accurate to say that miniaturization was a necessary condition of most of the other attributes of performance that have been sought, including speed, reliability, long life, portability and low power consumption).

In the case of tires, the steel-belted radial tire has extended tire life and correspondingly reduced material use. This development, led by Pirelli and Michelin, was technology-driven. Further extensions of tire life appear to be technically feasible, but this will probably not occur without government intervention. Incidentally. a strictly enforced speed limit would be a very effective means of extending tire life, all other factors remaining equal.

The packaging sector contains several examples of dematerialization. For instance, there has been a steady reduction in tin requirements for tin-plate (thus keeping tin-plate competitive with aluminum) by improving tin-plate technology to reduce the thickness of tinplate. A parallel example arises in the case of aluminum cans, which have also been "dematerialized" significantly by improvements in aluminum rolling and forming technology that permit much thinner aluminum cans than was formerly the case. The same trend has also occurred with respect to plastic bottles, with improvements in forming and other innovations (e.g. multi-layering) combining to reduce the weight of material in a typical plastic bottle. To be sure, there is no dematerialization in this last case, unless the plastic bottle is re-used or recycled as often as the glass one. (Not normally the case, but possible, at least for PVC and PET). The proliferation of packaging waste does not appear at first glance to be a case of dematerialization (quite the contrary), but to some extent dematerialization has occurred within the sector.

1.4. The Material Substitution Strategy

Aluminum has found many new uses in recent decades, resulting increased demand for the metal. The most obvious case in point is the substitution of aluminum cans for tin-plated steel cans and glass bottles. Aluminum has displaced wood for window frames, which are now almost entirely prefabricated. (In the future, plastics could replace aluminum in this application). Aluminum has essentially replaced copper and galvanized iron sheet for roofing and siding purposes, and for exterior drainpipes. It has captured at least part of the market for brass "hardware" fixtures such as doorknobs, hinges and handles. Also, in many cases aluminum, now cheaper than copper, has replaced copper for some kinds of electrical wiring, especially for high power transmission purposes.

Copper has already lost many of its former markets, and others are being eroded. For instance, copper roofing is no longer used, and copper pipe is being replaced in many cases by PVC. Similarly, copper wire for telephone lines is now being replaced by optical fibers, while some transmission lines have switched to aluminum. Brass is being challenged for many applications, by aluminum as well as plastic, although it is not likely to be replaced completely. Copper chemicals have lost some markets, though copper sulfate continues to be widely used in viniculture, while copper remains important — with arsenic — as a component of copper-chrome-arsenic (CCA) wood preservative chemicals. In fact, this is now the biggest single use of arsenic. Yet the Japanese have found satisfactory substitutes for CCA, which may well be adopted elsewhere. Arsenic has already been replaced (by synthetic organic chemicals) in most of its former pesticide and herbicide applications.

Chromium remains irreplaceable in its major markets, which are corrosion resistant (stainless) steel, heat-resistant steel alloys, and corrosion-resistant plating and coatings. Markets for high temperature superalloys also continue to grow, though there is potential competition from ceramics for such applications as turbines and jet engines, if the manufacturing problems can be solved. Nevertheless, other applications of chromium, and chromium chemicals, are substitutable. In particular, alternatives to the use of chromium sulfate in leather tanning are already available and their use should be encouraged.

Zinc's major use is for galvanizing steel, especially in automobile and truck frames and bodies. This practice greatly increases corrosion resistance and has probably extended vehicle life by one or two years — with significant savings in terms of other resources consumed. On the other hand, galvanized iron sheet (e.g. for roofing) has been replaced by aluminum. Zinc castings for the auto industry are gradually being displaced by engineering plastics. There is no obvious substitute for zinc oxide used in the tire industry.

Metal-based pigments (cadmium, chromium, zinc) have been partly replaced by organic pigments, largely due to concern about toxicity. (More so in the U.S. than in Europe).

Organo-chlorine compounds are increasingly regarded as environmental risks, for several different reasons. Yet no serious attempt has yet been made to ascertain the extent to which alternatives may exist to the use of chlorinated compounds. In fact, substitutions have tended to be in the other direction. For example, PVC has replaced copper pipe in many cases; it has also replaced cast iron pipes). PVC is widely used in France for bottled water (in place of glass). Metal based pesticides, fungicides and herbicides have also largely been replaced by organic chemicals. At first the substitutes were primarily chlorinated compounds, but as a result of restrictions on chlorinated pesticides (DDT, chlordane, toxaphene, benzene hexachloride, pentachlorophenol, etc), these have since been replaced by a variety of other types. Similarly, the use of polychlorinated biphenyls (PCB's) as transformer fluids (and some other uses) was stopped almost overnight, without disaster. More recently, the phase-out of chlorine use as a bleach for paper pulp in Europe was accomplished (voluntarily) in less than a decade. The agreed phase-out of CFC's under the Montreal Protocol in favor of HCFC's and HFC's also appears to be on schedule.

In most of these cases, substitutes of comparable effectiveness were found without great difficulty, once the necessity was recognized. Indeed, it could be argued that bans of this sort have been quite useful in stimulating innovation in otherwise mature sectors. Nevertheless, a complete ban on chlorine (as proposed by some environmental organizations) would adversely affect a large number of industries and processes for which straightforward substitutes may not be found easily — or may not even be possible.

Substitution of light materials for heavier ones is especially important in transportation applications, because unnecessary weight imposes severe penalties in terms of fuel consumption. Thus aluminum cans have displaced steel cans and glass bottles, to a large extent, to reduce weight. Similarly, lightweight plastic packaging materials such as polyethylene bags or PET bottles have displaced glass bottles in some cases (e.g. for milk) and paperboard in others. Polystyrene foam has replaced papier maché in many cases for the same reason.

1.5. The Recycling Strategy

It is extremely important for energy reasons to increase the recycling rate for aluminum products. This applies especially to cans, but also to hardware, window frames, roofing, etc. The energy required to process a metric of aluminum from bauxite consumes 300 GJ (GigaJoules) of energy; by contrast, a metric ton of secondary aluminum from average scrap requires only 18 GJ, or 6% as much [Forrest & Szekely 1991]. This difference has a parallel impact on global carbon emissions, since even though aluminum smelters use only hydroelectric or nuclear power, the electricity they use could — in Europe and North America, at least — replace other electricity made by burning coal, at the margin. Energy saved in processing (and carbon dioxide not emitted into the atmosphere) is not the only benefit of recycling. Other benefits would include reduced demand for caustic soda for the Bayer process (also an energy-intensive product), reduced demand for fluorine (as aluminum fluoride) and, of course, reduced need to dispose of waste "red mud".

Yet the recycling rate for aluminum in Europe is only 25% (30% in Germany), which is remarkably low. Collection of scrap aluminum is not technically difficult, and the recycling rate for aluminum could be pushed up above 50% in the near term and probably to 70% in the longer term, with appropriate incentives. But such a policy will be strongly resisted by the primary producers, however, and to implement it will require government intervention or public outcry, or both.

The energy argument applies with almost equal force to copper and cobalt. Copper from high grade (1%) ore requires 100 GJ/tonne for digging, grinding, concentration, smelting and refining; in the worst case (0.3% ore) the energy requirement is over 200 GJ/tonne [Forrest & Szekely 1991]. A rough average for the U.S. might be 150 GJ/tonne, about half of that for aluminum. Yet secondary copper from high grade scrap copper (e.g. wire) requires only 14.4 GJ and even low-grade copper-bearing scrap can be recycled for 40 GJ/tonne [ibid]. These are not the only benefits by far. Copper not mined and smelted translates into less mine waste to dump, less chemical waste from froth flotation, less SO_2 emission from refineries (not all of the sulfur is recovered) and less arsenic and other emissions from smelters. Not only that, but less arsenic will be available for recovery and subsequent dissipative use.

Yet the recycling rate for copper, even in Germany, is only 42% [BDI 1984]. The problem is collection and separation. The technology can surely be developed, but again, primary producers will resist and fairly strong government intervention will be necessary.

Chromium in stainless steel, coatings, and chemicals is not being recycled effectively enough. Here the problem is to separate the stainless steel from other scrap metal, especially in the case of automobiles and consumer appliances. A technical solution is doubtless possible, but it will not be worthwhile for industry to develop on its own. The difficulty of recovery is even greater for chrome plate, of course. (This last problem may be effectively insoluble).

The recycling energy advantage for zinc is much less, but still significant. However, there is relatively little zinc scrap in pure form. In the case of zinc the problem is more complex. A very important new market has developed for zinc coating (galvanizing) of steel in the automobile industry for protection of auto bodies from the underside. Unfortunately, under present conditions, it is very difficult to recover any of this zinc. Another major use of zinc is for batteries, which are also rarely recycled.

It is particularly important to recycle nickel cadmium batteries, which are becoming very widely used, to prevent them from accumulating in landfills or (worse) going to incinerators. This should not be too difficult technically, if the collection problem can be solved. The latter will surely require government intervention.

Chlorinated solvents used in industry and also for "dry cleaning", can and should be recycled far more effectively than they are. CFC refrigerants can and should be recovered from discarded refrigeration and air-conditioning equipment. (A high tax on the new product would ensure this more effectively than a ban on use). PVC bottles can and should be recycled as such to prevent chlorinated plastics from being incinerated. The same is true of PET bottles. Public health authorities can help by permitting such re-use, subject to reasonable requirements for sterilization. Again, the primary producers will resist strongly. Polystyrene foam can be recycled. However most plastic packaging wastes — indeed, municipal wastes in general — should be gasified for fuel recovery.

By-products and waste products of electronic grade silicon (EGS) production constitute a significant loss, and possibly an environmental threat. Detailed data are extremely scarce, but indirect evidence from a variety of sources suggests that for each kilogram of polysilicon EGS produced, at least 5 kg was originally processed and 20 kg of chlorine was consumed. Potentially useful co-products and by-products were undoubtedly generated, but it is not clear how much of this material was beneficially used and how much was discarded as waste, or in what form. Clearly these chlorinated silicon compounds should not be released into the environment. The basic problem here is that the processes involved are apparently not carried out on a large enough scale to justify cost-effective recycling.

Scrap tires are the most compelling case for a recycling policy. At present most used tires are discarded on open fields or burned under uncontrolled conditions, despite the serious pollution problem thus created on the one hand, and the waste of high-quality energy on the other. In fact, tire life could be extended considerably (as noted under the heading "dematerialization") and worn tires can and should be re-manufactured several times — as truck and aircraft tires are now — before being discarded. The technology exists. But as long as tires are sold to consumers (or to car companies) the system will not change without government intervention. Such intervention will be resisted strongly by the tire manufacturers, since it would sharply reduce their sales (which is exactly the objective).

The most effective way to achieve this outcome would be for society to shift away from direct vehicle (and tire) ownership to leasing. This could be encouraged by appropriate tax policies, such as a VAT exemption for lessors, for instance. Tire lessors would, of course, have every incentive to minimize tire wear and ensure maximum recycling. At the end of a tire's life, it should be used as fuel in a cement plant or in some other way that takes advantage of either the energy value of the material or the peculiar properties of rubber.

1.6. The "Waste Mining" Strategy

Arsenic recovery from copper mining and smelting, and cadmium recovery from zinc mining and smelting, are both examples of "waste mining", since each metal is a minor constituent of the ore of another more important metal. Unfortunately, both of these metals are exceedingly toxic and the objective of public policy should be to minimize both production and dissipative use. Gallium, cobalt, silver and even gold are other examples of "waste mining" with a long history.

The recovery of elemental sulfur from natural gas and petroleum refineries is the classic case of recovering a useful material from a waste. This technology is already far advanced, and now accounts for a significant (and rising) percentage of the world sulfur supply. The recovery of sulfuric acid from copper, zinc and lead smelters is another example, although many smelters outside the industrialized countries have not exploited this opportunity, either due to lax environmental regulations, lack of local demand for sulfuric acid, or both.

Wastes that should be "mined" for resources, but are not as yet, include lime/limestone FGD scrubber wastes from electric power plants, and phosphate rock processing wastes, all of which can be converted to synthetic gypsum and used to replace natural gypsum. In the case of phosphate rock processing, it is also feasible to recover fluosilicic acid. This could replace most of the fluorspar (calcium fluoride ore) that is now mined (from which hydrofluoric acid is manufactured).

Another waste that should be more consistently exploited as a resource is coal ash. Given that coal will be a major source of energy in some countries for decades to come, it is important to make the best possible use of the enormous quantities of ash that are produced when coal is burned. This ash can be recovered (as currently) by means of electrostatic precipitators or, in future, from coal pyrolysis or gasification plants. The latter can also recover elemental sulfur. The ash, in turn, can be used as such in a variety of ways, including cement manufacturing.

However, the most attractive potential use of coal ash is as a source of metals, including aluminum and ferro-silicon. This would not only reduce a waste disposal problem, but would also cut down significantly on environmental damage from bauxite mining and processing. There are a number of technological problems involved in the use of ash, but the major obstacle will be resistance from the aluminum companies, especially those with long-term contracts for electric power at below-market rates. Thus, the most promising strategy for encouraging the development of newer technologies for aluminum recovery would be to eliminate subsidies to aluminum companies and — instead — provide ash disposal credits.

1.7. Technological Gaps

A few areas have been identified where a powerful new technology seems to be "in the cards" but where the missing ingredients for a breakthrough cannot be described precisely. What this means is that applied research of a rather fundamental nature may still be needed, and it is impossible to predict how long it may take or how costly it will be.

The outstanding example in this category that emerges from our study is the long sought bipolar cell with an inert (non-consumable) electrode. Such a cell would be applicable to any sort of "conventional" electrolytic reduction process, including aluminum smelting, copper refining, and chlorine/caustic soda production. It would also open the possibility of efficient separation of light metals from fly ash (or lunar soil) along a voltage gradient. This would be the electrolytic analog of a distillation column, which separates materials according to boiling point along a thermal gradient. In both cases, arbitrarily high levels of purification could (can) be achieved by recycling the outputs.

The problem so far encountered in developing an inert electrode is surface corrosion and the resulting variable electrical resistance, not to mention mechanical problems. Solutions might be sought in various directions (e.g. nitrides? diamond coatings?), but the answer is not yet in sight.

Another well-known example of this kind is the well-known problem of engineering ceramics for turbine blades and other components of turbo-machinery and rocket engines. If successful, ceramics could replace virtually all uses of "superalloys" and high-speed tool steels, thus sharply reducing the industrial demand for cobalt and, to a minor extent, for chromium. Here the problems are formability and elimination of defects.

The other category of technology gap applies to industrial processes. It has three parts. The first is the gap between designs on paper and laboratory or bench-test models. The second part is the gap between the laboratory version and the small pilot plant. Finally, there is another gap between the pilot plant and the industrial scale plant. In general, the scaling up process is a learning and optimization process, in the course of which many design parameters must be determined empirically. The dynamic behavior of a complex non-linear system cannot be completely predicted by computer simulation; the behavior of the actual system under various perturbing influences (voltage, pressure and temperature excursions, or input contamination, for instance) can only be verified by building and operating it. Finally, of course, there may be unexpected corrosion problems, side reactions and the like. For all of these reasons, the multi-stage scale-up is necessary.

At the level of paper design, process research is relatively inexpensive and we think it would be appropriate for DG XII to support some exploratory research on alternative processes as noted below:

(1) Extract metals (especially aluminum) from coal ash; hydrochloric acid leaching processes should be investigated in particular.

(2) Extract fluorine from phosphate rock process waste. Explore the ammonia route, in particular.

(3) Dehydrate, purify and utilize contaminated calcium sulfite/sulfate sludges in place of natural gypsum.

(4) Gasify mixed plastics (and other organic materials) at low temperatures, remove metals, hydrogen chloride and sulfur from the gas stream.

At the next two levels, bench testing and pilot plants, it would also be appropriate for the public sector to provide significant support. It is important in this regard to distinguish between areas where established industries have a positive incentive to contribute because a successful outcome would be of direct benefit to them in international competition, *vis a vis* those areas where established industries currently have major investments in older technologies that might be devalued and supplanted. It is basically unreasonable to expect a primary producer with large investments in mines and smelters to invest willingly in recycling technology, or even in alternative processes that compete with profitable existing ones.

In this connection it is helpful to recall that it was the Japanese who first adopted the (then) new Basic oxygen furnace (BOF) for steelmaking in the 1950's, although is was a European (Austrian) innovation. This happened because Japan was then in the process of expanding its steel industry rapidly, which meant building new plants, whereas the much larger U.S. steel-makers were then heavily committed to open hearth furnaces. Even so, the top executives of the Japanese steel companies, who knew the open hearth process, were very skeptical of changing from a "tried and true" technology to one in which they had no experience. The massive industry-wide Japanese adoption of BOF was brought about by a kind of "palace revolution" of younger engineering executives (who had familiarized themselves with the new technology in unofficial "skunkworks"), with critical support from technocrats in the Japanese Ministry of International Trade and Industry (MITI).[2] The success of this gamble, together with its subsequent adoption of continuous casting technology, gave Japan a worldwide lead in steel manufacturing technology which it has never lost. It also gave MITI the prestige to intervene successfully later in an even more critical area — the acquisition of basic integrated circuit technology in the 1960's.

It should be clear from these and other examples that the adoption of a basic new manufacturing technology can shift the competitive advantage in an industry from the established producer (whether a firm or a nation) to a new entrant. Toyota's *kan ban* (or "just in time") system gave it a similar lead in automobile manufacturing. In fact, the timely adoption of a basic new technology is, perhaps, the *only* way that such a shift can occur.

However, despite the potentially critical role of the public sector, it is clear that pilot plants can only serve a useful purpose when built and operated by a firm that is seriously interested in, and capable of taking the next and final step. Thus, government support at this stage should only be on a cost-sharing basis.

The ALCOA process for aluminum smelting offers a special opportunity — potentially comparable to the BOF case — since it is a process that has already been tested at the pilot stage. The tests revealed some potential pollution problems that were thought to be soluble, but the main reason for failure to proceed was a change in the strategic direction of the company. It was decided by an incoming chief executive that the firm should take advantage of opportunities to obtain long-term commitments to cheap resources, using "tried and true" technology, and devote its capital and R&D capabilities to developing high value aluminum alloys and to manufacture downstream components for the (then booming) aerospace sector.

While ALCOA may not be willing to commit large amounts of capital to building a plant based on a new process (given overcapacity in the industry and slow growth in demand), it might well be interested in a joint venture with a high-cost European firm. Government intervention and some research subsidies might smooth the way. On the other hand, should the process be successfully adopted by producers in Russia or China (for instance), the BOF story could repeat itself.

It is worth noting, once again, that many of the opportunities for increasing resource productivity — especially in the area of recycling — do not require any new technology. They are being held back by other barriers, especially resistance by established (and politically influential) primary producers that would lose market share. Research into innovative ways of creating "incentive packages" for such firms might be helpful in overcoming such barriers.

1.8. Policy Implications

There is now a fairly general and robust consensus among policy analysts that the necessary and appropriate role of government is, above all, to create incentives for individuals and firms to do what is good for society as a whole and to refrain from doing what is bad. Thus, one arm of government, the central bank, is now generally viewed as the custodian of macroeconomic policy, through its control over interest rates and the money supply. This mechanism of social control is less onerous and far more efficient than direct price controls, which are the means relied on in less developed countries, including the "centrally planned" economies.

In other domains, such as energy policy, transportation policy, materials policy, and environment policy, most governments exert influence partly by financing infrastructure (e.g. building roads and airports) and partly through subsidies, quotas, standards, and other regulations. The latter controls are typically administered by officials of various kinds — with a variety of administrative and police powers — and ultimately enforced by the courts. It is well known that many of these regulations are inefficient, some are counterproductive or even contradictory. Others are unenforced and some are unenforceable. (The lesson of Prohibition in the U.S. is easily forgotten). This problem is especially acute in the environmental area, because the number of applicable regulations has multiplied greatly in recent years.

There is a growing backlash against the regulatory approach, as it has been practiced in recent years, due to its growing costs and decreasing cost-effectiveness. Indeed, some of the U.S. legislation (notably RCRA and "superfund") has been extraordinarily costly — resulting in protracted and expensive lawsuits — with little progress to show for it. While no major environmental legislation has yet been "rolled back", the case against adding to the existing regulatory burden is growing stronger every year.

Coincidentally, western Europe is being forced to recognize that even economic recovery does not seem to bring with it any growth in employment. Unemployment has been rising on the average, if not quite monotonically, for over twenty years. The social "safety net" that eases the pain for the unemployed and which undoubtedly has helped prevent any social protest, has become unreasonably costly to those who are still employed. In western Europe, the direct burden on wages of social security charges amounts to over 50% in most countries and closer to 80% in Germany. In the European Union (EU) central government revenues are overwhelmingly (>80%) based on labor or income from labor, while only a small proportion is arguably based on capital or resource consumption. (The gasoline tax is the primary example of the latter).[3]

In November 1993 Jacques Delors, President of the European Commission, presented a "White Paper"[4] setting forth an agenda for a "new approach" to economic growth. Given the political process involved in preparing the paper, it is not surprising that much of the emphasis was on new investment in infrastructure such as high speed railways and high technology, especially "multi-media" and "information superhighway". However, Chapter 10 of the paper also suggested something much more radical: a gradual change of the tax system to reduce the excessive burden on labor and to shift the burden, instead, to energy, pollution and traffic congestion. This paper drew its inspiration partly from two influential books: "Erdpolitik" [von Weizsaecker 1991] and "Ecological Tax Reform: A Policy Proposal for Sustained Development" [von Weizsaecker & Jesinghaus 1992]

While academic economists have argued for many years in favor of using taxes rather than emission standards or quotas as a more effective and efficient instrument of environmental policy, the environmental movement in the U.S., at least, has strongly resisted this approach on the moralistic ground that taxation of pollution amounts to a "license to pollute". The unholy alliance against environmental taxes has long included businessmen, who obsessively oppose taxation of any kind, lawyers who naturally prefer legislative approaches that can lead to lawsuits, and public finance economists who have argued that taxes should not be used for "social engineering". However, the growing resistance to direct regulation may have begun to turn the tide.

At any rate, a seminar "Towards a new approach to development" sponsored by the EEC (Directorate XI, Environment, Nuclear Safety and Civil Protection) was held in Brussels, November 24 and 25, 1994. The Commission circulated a number of papers for discussion, including one on tax reform and sustainable development which presented the results of background work by a number of groups during the year since the original White Paper. The most important new research presented at the conference was a major econometric analysis carried out by economists at Data Resources Incorporated (DRI), together with a number of consultants [DRI *et al* 1994].

In brief, the study compared three scenarios out to the year 2010. The three were (i) an extrapolation of current economic trends, termed the "reference" scenario, (ii) a modified scenario, assuming implementation of policies currently under serious consideration (such as the carbon/energy tax) and (iii) a scenario reflecting a range of fiscal and other measures integrated into sectoral policies, including increased energy taxes, charges for water, congestion charges and auction systems to set upper limits on environmental resource use, with all incremental tax increases being recycled as reductions in income or other taxes on labor. Even though the assumed tax adjustments were comparatively minor, the impact was clear and unmistakable: the third "integrated policy" scenario was both significantly more effective at reducing pollution and more effective at increasing employment — hence overall growth — than either of the other two [DRI *et al* 1994].

The DRI analysis assumed only modest changes in the structure of the tax system, and the postulated increases were mostly on fossil energy and traffic congestion. In the following, we note a number of other more specific opportunities for using taxes, tariffs, and related economic instruments, such as returnable deposits, to cut down on pollution and waste. Such instruments are especially needed to encourage recycling of secondary materials and more efficient use of hitherto wasted materials such as phospho-gypsum and coal ash. We believe that, if an econometric analysis of the aggregate impacts of these measures were done (a difficult task, admittedly), it would confirm the potential for even more startling gains both in terms of environmental quality and in terms of employment and welfare.

1.9. Information Needs for Environmental Policy Analysis

The need for economic data to support policy analysis — as exemplified by the European Commission studies cited in the foregoing paragraphs — is widely recognized. It is to provide for such needs that Census data are collected and National Accounts data are compiled and published in internationally comparable form by government statistical offices, and coordinated by the UN Statistical Office. The importance of this activity is not seriously questioned, even though it employs thousands of statisticians and economists, and tens of thousands of clerks and other support personnel, worldwide.

Since energy became a major international priority concern in the mid 1970's, energy statistics (production and consumption, by category) have also been compiled by most countries. Indeed, the International Energy Agency of the OECD was created to coordinate these data on an international basis. Unfortunately, the need for comparable data covering production, processing and use of other environmentally important materials — especially metals and chemicals — has not yet been adequately recognized. To be sure, the UN Statistical Office compiles and publishes "Industrial Statistics" on outputs of about 550 major commodities, ranging from agricultural, forest and mineral products, fuels, metals, chemicals and finished industrial goods.

However, while better than nothing, the global coverage is very incomplete, and the categories are far too aggregated for detailed analysis of materials. For instance, fewer than 50 basic chemicals are included (e.g. ammonia, chlorine, ethylene, sulfuric acid) which means that no data are reported for the vast majority of chemicals of environmental concern. Even in the U.S., where the data on chemicals and minerals are most complete, many important chemicals are produced by fewer than four companies, whence data are suppressed on the grounds that publication might tend to reveal the activities of a private firm. In other words, such data are treated as proprietary and "confidential", regardless of the possible public interest. In Europe, there are virtually no public sources of data on minerals and chemicals production and use beyond the level of detail found in the UN "Industrial Statistics".

The difficulty of obtaining reliable quantitative data on chemicals and minor metals production and use, as well as waste outputs and disposal, is clearly illustrated in a number of the case studies that follow. In many cases, the only sources of data are private consulting firms that charge sizeable fees. Even with the help of such proprietary data bases (whose accuracy cannot be verified) it is effectively impossible to make a complete accounting of environmentally important (and potentially toxic) materials, such as arsenic, cadmium, chromium or chlorine and their compounds.

The EU should undertake a serious program of minerals/metals and chemical statistics collection and compilation in the coming years. Without such data, intelligent policy choices in a number of fields, ranging from taxes to environment, cannot be supported by serious quantitative analysis.

A detailed discussion of the data sources used in the present study is included as an Appendix to the study.

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Endnotes(1)

1. To introduce resource flows is not simple, for two reasons. First, energy and material resources are not normally expressed in comparable units. A ton of iron ore is not equivalent to a ton of coal. Fuels can be equated with each other in terms of heating value (e.g. BTU's or Joules). This difficulty can be overcome only by introducing sophisticated thermodynamic measures. Second, some fuels are also an item of final consumption. To be consistent, fuels consumed as intermediates in the production process would have to be broken out and considered separately from fuels used by households. This would be a major statistical effort.

2. The full story of this "palace revolution" is told in the book "How Japan Innovates" [Lynn 1982].

3. Figures compiled by the statistical office of the European Union (EUROSTAT) for 1992 indicate that taxes of all kinds took 41.28% of European GNP (of which taxes on labor, consumption and capital accounted for 23.44%, 10.86% and 6.98%, respectively); revenues linked in any way to environmental problems added up to 2.65% of GNP, or which taxes on vehicle ownership and fuels accounted for 2.37%. See "Economic Growth and the Environment: Some Implications for Economic Policy Making" Communication from the Commission to the European Parliament and Council, Brussels, October 27, 1994.

4. The full title is "Growth, Competitiveness, Employment — The Challenges and Ways Forward Into the 21st Century" White Paper. European Commission. ECSC-EC-EAEC Brussels, Luxembourg, 1994.