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Materialization and Dematerialization: Measures and Trends

INTRODUCTION

"REVENGE THEORY" POSTULATES that the world we have created eventually gets even with us, twisting our cleverness against us.[1] Helmets and other protective gear have made American football more dangerous than its bare predecessor, rugby. Widened roads invite more vehicles, which mitigate gains in average traffic speed and flow. In short, human societies face unintended and often ironic consequences of their own mechanical, chemical, medical, social, and financial ingenuity.

In 1988 Robert Herman, Siamak Ardekani, and Jesse Ausubel began to explore the question of whether the "dematerialization" of human societies is under way.[2] At that time, dematerialization was defined primarily as the decline over time in the weight of materials used in industrial end products or in the "embedded energy" of the products. More broadly, dematerialization refers to the absolute or relative reduction in the quantity of materials required to serve economic functions.

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Dematerialization matters enormously for the human environment. Lower materials intensity of the economy could reduce the amount of garbage produced, limit human exposures to hazardous materials, and conserve landscapes. From time to time, fears arise that humanity will imminently exhaust both its material and energy resources. Historically, such fears have proven exaggerated for the so-called nonrenewable resources such as metals and oil. Yet if the human economy were to carelessly metabolize large amounts of Earth's carbon or cadmium, the health and environmental consequences could be dire. Meanwhile, the so-called renewable resources, such as tropical woods, are proving difficult to renew when demand is high. Thus, a general trajectory of dematerialization would certainly favor sustaining the human economy over the long term.

Is dematerialization occurring? Certain products, such as personal computers and beverage cans, have become smaller and lighter over the years. However, revenge effects may still countervail. A vexing case is that total paper consumption has soared despite claims that the electronic information revolution would create a paperless office. Americans now use about a kilogram of paper per day on average, twice the amount used in 1950.

In this essay we report further analyses of materialization and dematerialization, mostly for the United States during this century, and lay the basis for a systemwide assessment. We segment our analysis to consider measurements: *1)* at the stage of resource extraction and the use of primary materials, such as minerals, metals, and wood; *2)* in industry and industrial products; *3)* at the level of the consumer and consumer behavior; and *4)* in terms of the waste generated. At each stage one can ask whether dematerialization is taking place, what drives it, and what are its future trajectories and their consequences. Our studies consider materials in absolute terms, per unit of economic activity (measured by means of gross national product, GNP, or its slight "domestic" variant, GDP), and per capita. We assess changes in both volume and weight.

Materials consumption is analytically less tractable than energy use. It cannot be satisfactorily reduced to single elementary indicators such as kilowatt-hours or British thermal units. To illustrate this point, a pound of gold cannot be simply compared with a pound of lead, to the frustration of the alchemists. And neither one can be easily compared with a pound of plutonium. Materials possess unique *properties,* and those properties provide value, define use, and have environmental consequences. To capture these and other interactions, we must consider an ensemble of measures under the rubric of dematerialization.

The pattern of materialization and dematerialization, and the database from which it is drawn, helps frame the new field of industrial ecology.[3] Industrial ecology is the study of the totality of the relationships between different industrial activities, their products, and the environment. It is intended to identify ways to optimize the network of all industrial processes as they interact and live off each other, in the sense of a direct use of each other's material and energy wastes and products as well as economic synergism. The macroscopic picture of materialization can help raise key research questions and set priorities among the numerous studies of materials flows and networks that might be undertaken. It puts these in a dynamic context of both technical and market change.

DEMATERIALIZATION AND PRIMARY MATERIALS

In analyzing primary materials, it is helpful to begin with a profile of the total "basket of stuff" that a human society consumes. For this purpose, let us consider first "demandite," an imaginary, composite material representative of the nonrenewable resources we use. Demandite reveals our elemental preferences. All the materials that make up demandite are quantified in terms of the total moles of each element (or selected compounds) they contain; demandite is characterized by the fraction of moles for each element or compound divided by the total mole number.

First proposed by Goeller and Weinberg,[4] demandite includes both the energy materials (the hydrocarbon fossil fuels: coal, oil, and gas) and other materials, such as iron, copper, sulfur, and phosphorus, that are mined and used in the production of goods. Demandite omits some (crushed) stone that is used to build roads and other structures; the amount mobilized is quite large (about 1 billion metric tons in the United States in 1990) but this stone resource is practically infinite, and its elemental composition is