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Response to Comment on "The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices"

Shadman and McManus (*1*) reject our conclusion that "the widespread assumption that the microchip represents a prime example of dematerialization is misleading at best and probably false" (*2*). The reason put forward is that "the study's conclusion is itself misleading because using weight as the basis for comparison is arbitrary, nonscientific, and inaccurate".

If we had been comparing microchips with other products on the basis of weight, this objection might have some validity. Our point was, and is, simply that the amount of materials used to manufacture a computer chip these days is hundreds, if not thousands, of times greater than the quantity actually embodied in the chip. This makes the weight of the chip a misleading indicator of the amount of materials used, and it means that people like Alan Greenspan and Frances Cairncross, who have cited microelectronics as an example of radical "dematerialization", have misunderstood the situation.

Assessing the microchip industry vis-à-vis other industries or technology alternatives in terms of social/environmental benefits and costs was not the purpose of our paper. Such a synthetic analysis would be a completely different paper, and we believe one not yet possible to write given that understanding of the environmental implications of information technology is still in its infancy. We do believe there are many applications of information technology that are actually or potentially beneficial to the environment (such as telecommuting). Indeed, some of us are engaging in research to understand and maximize these benefits. However, the environmental management of production, use, and disposal of hardware—and associated production wastes—is research that can and should be addressed on its own, as distinct from its applications.

Given our intention to characterize the resource intensity of semiconductor manufacturing, we believe our analytic method and choice of indicators are appropriate. Widely accepted definitions of "dematerialization" refer to weight of the materials or energy used to manufacture industrial end products. We have expressed this resource (materials/energy) intensity of the network of manufacturing processes in an easily understood quantitative form. That this intensity is high is surely no surprise to the industry, as environmental reports of all major firms include data and substantial discussion on their efforts to reduce energy and materials use and emissions. If the environmental intensity per unit mass of chips produced was comparable to conventional goods, energy and materials use would be a nonissue, which clearly is not the case.

While not the topic of our paper, we agree with Shadman and McManus (*1*) that the semiconductor industry has been improving its environmental performance. We have yet to see, however, that this progress has been sufficient to counteract growth in demand so as to realize net decreases in material and energy used by the industry. According to the U.S. Census statistics and consulting firm data, wafer, chemical, and energy use of the semiconductor industry increased 6−10% annually in the late 1990s. While this rate of increase is less than the economic growth of the industry (about 15% on average), it is still substantial. The evolution of materials intensity at the product level is an interesting question as well. While the smaller feature size of newer generation chips could imply less materials use per transistor, the increased complexity of processes, the requirement for ever-declining defect densities, and the need for purer starting materials have the opposite effect: the ratio of indirect to direct materials consumption may actually be increasing. This would be an interesting study, which we think should be done. In fact, we invite Intel, the world's largest manufacturer of chips, to provide the relevant data.

Regarding the Shadman and McManus (*1*) critique of the microchip−automobile comparison, we suggest that they check our paper and its main references more carefully. Our figure for energy intensity of automobile manufacturing comes from a life cycle study that includes production of raw materials, parts, and assembly, not simply the final assembly stage as they suggest. If anything, the difference in intensity is larger than we reported, as our analysis gives a lower bound on chip manufacturing that does *not* include the energy and materials associated with the production of high-grade chemical inputs, the life cycles of manufacturing tools and other equipment, and other ancillary processes such as transport of materials through the supply chain. Regarding data quality, one reason the study generated such widespread interest was precisely because we went far beyond most prior studies in the field, collecting several data sources for most processes, including one modern chip fabrication facility (that shall remain anonymous). We must admit that we did not make direct measurements ourselves. Given that we relied on secondary sources, we cannot rule out the possibility that there was collusion between reporters to the U.S. Bureau of the Census, the industry committee that contributed to the MCC life cycle study (which included Motorola and SEMATECH), and the Semiconductor Industry Association (SIA) to overstate energy use.

Finally, Shadman and McManus (*1*) misquote a sentence from our paper, which they then claim proves that we have admitted a lack of pertinent input/output data. The correct statement in the paper was "Quantitative information on input/outputs to the *assembly* process is scarce" (italics added). Assembly is one process step among many considered, and the one data source identified does not suggest that it is a dominant contributor.

More to the point, are Shadman and McManus (*1*) intending to suggest that one cannot comment meaningfully on environmental impacts of an industry without complete primary data from all individual facilities? This is a radical stance to take, to say the least. We are surprised that Intel chides us for not having information that they possess in abundance and invite them to challenge our results by publishing verifiable data in sufficient detail so as to allow comparison with our results and other existing sources.

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Eric D. Williams*

United Nations University
5-53-67 Jingumae
Tokyo, 150-8925 Japan

Robert U. Ayres

INSEAD
Boulevard de Constance
Foutainebleau, 77305 Cedex, France

Miriam Heller

National Science Foundation
4201 Wilson Boulevard
Arlington, Virginia, 22230

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