# LONG-TERM TRENDS IN U.S. MANUFACTURING ENERGY CONSUMPTION: THE EFFECTS OF STABLE PRICES

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## INTRODUCTION

The International Energy Studies group of the Energy Analysis Program at the Lawrence Berkeley Laboratory has studied energy consumption associated with manufacturing for nearly twenty years. Efforts have produced analyses of manufacturing energy-consumption trends in countries throughout the world, including Sweden, Denmark, Japan, Germany, England, China, Estonia, Italy, France, and the United States.[1,2]

These papers developed a method that enables a disaggregation of changes in economic output, process intensity, and industry structure from changes in the aggregate energy/GDP ratio or total energy consumption. This present study is the latest effort in that series. It extends the previous studies on U.S. manufacturing energy consumption in two key ways. First, acquiring new data enables us to extend the period of study from 1958 to 1991. This extension enables us to evaluate two distinct periods of stable energy prices, 1958 to 1973 and 1985 to 1991. We can now compare those periods to the periods of rising prices, 1973 and 1985. Second, adapting the method to consider carbon emissions allows us to examine historical trends and the impact of factoral changes on carbon emissions.

## DEFINITIONS

We define several key terms used in this report as follows:

### Activity

Activity expresses the main enterprise(s) in each sector, that is, the underlying purpose for which energy is used.[3] Some studies have used physical measures, such as tons of steel or number of computers produced , as the units of activity, arguing that these physical measures provide the fewest complications and distortions to measure manufacturing output.[4] Driven in part by methodological considerations, our work uses value-added or Gross Domestic Product (GDP) as the measure of output in the manufacturing sector. There are two primary shortcomings in the use of physical measures of output: the lack of compete data sets and the incommensurability of the various units. Although there are disadvantages to the use of economic measures, we contend that the availability of complete production data in value-added[4] along with the capability of aggregating output in ways that are impossible using physical units provide methodological benefits outweighing the shortcomings of the measure.

### Structure

Structure refers to the mix of different activities within a sector. In the manufacturing sector, structure refers to the share of total manufacturing value-added produced within the individual subsectors. Structural change alone may increase or decrease sectoral energy consumption. Shifts from energy-intensive activities, such as the production of aluminum, to non-energy-intensive activities, like meat packing, will decrease energy consumption and manufacturing energy intensity, all else being equal.

### Intensity

Intensity (or energy intensity) refers to the amount of energy used per unit of activity. In the manufacturing sector, intensity is measured as energy consumption per dollar of value-added and can be computed for the individual ubsectors or for the sector as a whole. We believe that the aggregate intensity measure can be misleading because of the various effects that may be confounded in the measure. We prefer to use subsector intensities as measures of process efficiency. Our indicator combines both the technical and operating efficiencies of the production processes. In theory, it would be preferable to distinguish between these two effects, but this is not generally practicable.

**Final (or Delivered) Energy Consumption**

Final energy consumption is the energy consumed directly by end users. Final energy provides the energy services desired by the users. As such, it does not include the energy "lost" in the production and delivery of energy products (mainly the generation and transmission of electricity).

**Primary Energy Consumption**

Primary energy consumption is the sum of final energy consumption and the production and distribution losses. This measure is particularly significant in the analysis of carbon emissions from energy consumption.

**Carbon Intensity**

Carbon intensity refers simply to the ratio of carbon emissions per unit of energy consumption, effectively measuring the impact of fuel mix. Shifts from coal to natural gas, for example, either for direct use as fuel or in the generation of electricity, will, all else equal, tend to reduce carbon emissions. The carbon intensity effect is calculated by holding activity, structure, and energy intensity constant and allowing carbon intensity to vary with actual energy consumption.

## METHODOLOGY

Total energy use for a given time period can be disaggregated as the total sectoral activity (VA) times the sum of the share of total value-added for each type of activity times the energy intensity of each activity. This may be expressed mathematically as:

$$E_t = VA_t \sum (VA_{kt}/VA_t)(E_{kt}/VA_{kt})$$

where $k$ refers to the type of activity and $t$ is the time period. We use this identity to examine the implied impacts of changes in activity level, industry structure, and energy intensity by holding two factors constant and allowing one to vary over time. For the purposes of this study, we hold factors constant at their values in the base year of 1973.

We then calculate what we refer to as the activity-, structure-, and intensity-effect levels of energy consumption. The activity effect, for example, calculates what energy consumption would have been if industrial structure and intensity were fixed at base-year levels, given actual activity levels for each year. In this way, we can isolate the impact of changes in activity (and each of the other factors) alone on total energy consumption.

We have chosen to disaggregate the output of the manufacturing sector into six 2-digit SIC code subsectors, with the exception of distinguishing between ferrous and non-ferrous metals at the 3-digit level, and a residual or other subsector comprised of the remaining subsectors between SIC 20 and SIC 39, except for petroleum refining. Unlike most other analyses, we do not include petroleum refining in the manufacturing sector, concluding instead that this activity more closely resembles the electricity and gas industries and is more appropriately considered in the energy sector. We have chosen five of these subsectors, (i) paper and pulp, (ii) chemicals, (iii) stone, clay and glass, (iv) ferrous metals, and (v) non-ferrous metals, based on the high energy intensities of these activities. A sixth subsector, food, was selected because of the magnitude of the activity level.

## COMPARING THE U.S. AND THE OECD

Public discussion has taken place about the declining importance of the manufacturing sector in the U.S. economy. At least with respect to the value-added contribution of manufacturing, however, such conclusions may not be justified. As Figure 1 displays, in 1970 the U.S. ranked near the bottom of OECD (Organization for Economic Cooperation and Development) nations in terms of the share of total national GDP contributed by the manufacturing sector. By 1991 however, the share within the U.S. had increased slightly (from just over 20% in 1970), but because of declines in other nations, the U.S. ranked in the middle of the pack. The contribution from the U.S. manufacturing sector is somewhat below the mean level of contributions as represented by the OECD-10 line and the recent trend, in any case, is declining.

With respect to final energy intensities, the U.S. has continued to rank high between 1970 to 1991, below only three Scandinavian countries that possess enormous resources of inexpensive hydro-electric power (see Figure 2). Over the period, the U.S. manufacturing intensity has declined from about 33MJ/1980 US$ to below 20, representing a 2.7% average annual decrease. This decline will be disaggregated into changes in subsector intensities and industry structure later in this paper.

Figure 1. Manufacturing GDP as a Share of Total GDP for the OECD-10.

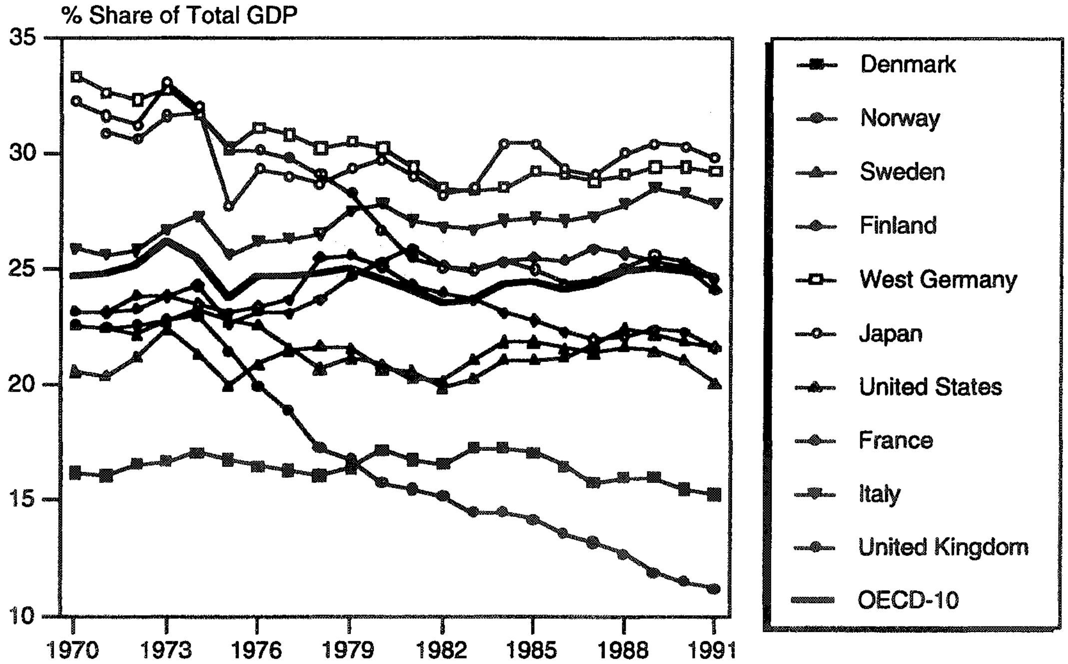
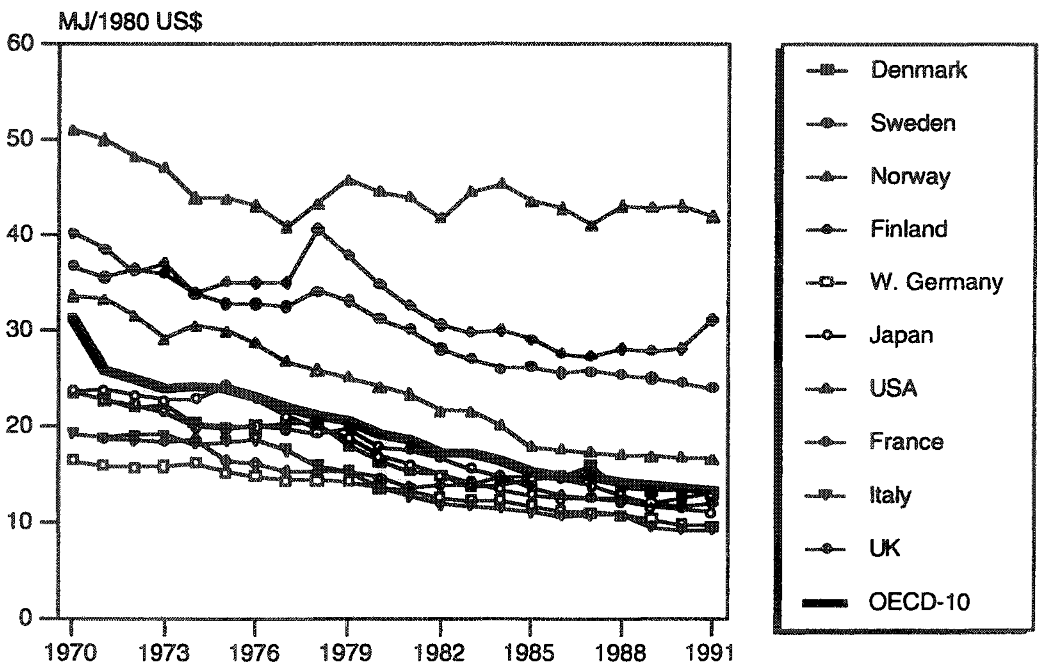



Figure 2. Manufacturing Final Energy Intensities in the OECD-10.



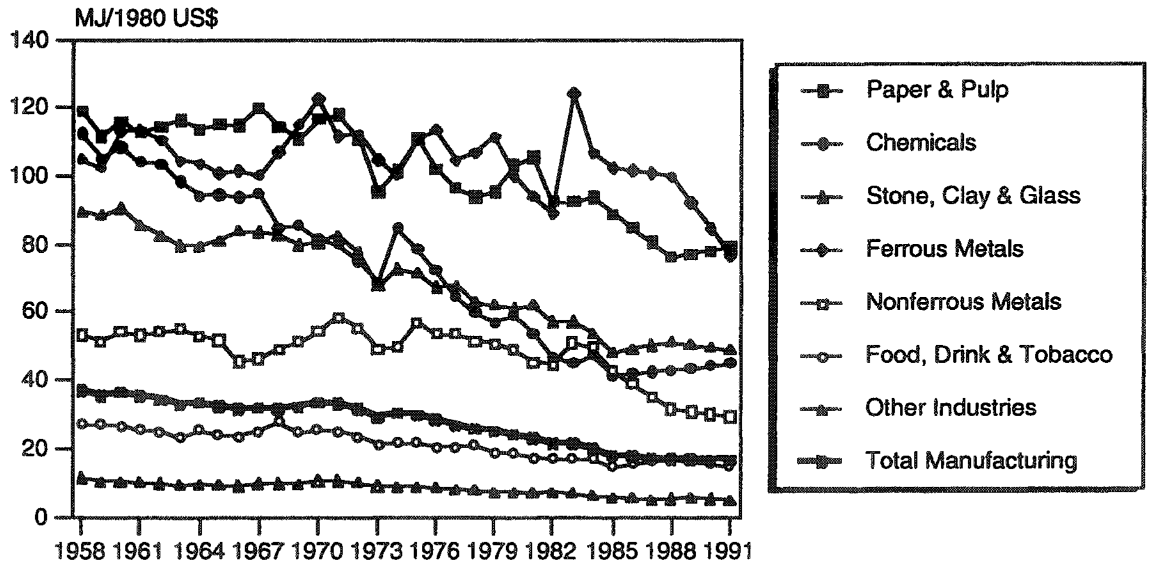

## U.S. RESULTS

Figure 3 presents the basis for our selection of subsectors. The energy intensities of these subsectors in 1991 (with the exception of food) are generally about an order of magnitude greater than the Other subsector. The significance for total manufacturing energy intensity and total energy consumption of structural shifts among these subsectors is greatly magnified because of these high intensities.

Figure 3 shows that the final energy intensities of each of the subsectors, as well as that of manufacturing as a whole, declined between 1958 and 1991. The stone, clay, and glass subsector was approximately one-third less energy intensive by 1991 as it had been in 1958. The decline for chemicals has been even more precipitous, from nearly 120 MJ/1980 US$ to below 50. In the non-ferrous metals subsector, energy intensity fluctuated slightly between 1958 and 1982, at which time it began a decline from 60 MJ/1980 US$ to just over 30, a decrease of nearly 50% in only nine years. We are unable to offer a firm explanation for the marked increased in intensity in the ferrous metals subsector between 1981 and 1983, although it is likely this change reflects declines in capacity utilization or industry profitability, rather than technical or behavioral efficiency. The energy intensity for the manufacturing sector as a whole has declined nearly 50%, from 37 MJ/1980 US$ in 1958 to 19 in 1991.

While providing useful insights, the weakness of energy consumption per value-added as an intensity measure can be seen from the sharp changes evident in some of the sectors. Because technology is embedded in capital stock, which turns over relatively slowly, it is highly unlikely that aggregate technical efficiency shifts in this manner or even that technical and behavioral changes together have produced such dramatic shifts from year to year. These changes in the indicator more likely reflect confounding from economic changes reflected in value-added.

Figure 3. US Manufacturing Final Energy Intensities by Subsector.




It has been suggested that the use of gross output as a measure of economic activity may overcome the short-term fluctuations of value-added and provide a more realistic picture of efficiency trends. The use of gross output is problematic with respect to aggregating output values because of double counting, but Figure 4, which presents a comparison of final energy intensities using both value-added and gross output as measures of activity for selected subsectors, provides at least some visual confirmation of this hypothesis. We can observe in this figure that the trends in both measures closely parallel one another, although the gross output lines are without the sharp increases and decreases seen in the value-added lines. Further development of the theoretical and practical issues surrounding the use of economic output measures will be necessary to resolve the value of these measures as indicators of technical or behavioral efficiency.

One issue of particular interest, especially with respect to carbon emissions, is the mix of fuels used in the manufacturing sector. Figure 5 displays the shares of final manufacturing energy use by fuel type. The most dramatic change has been a shift away from solids (coal). In 1958, coal use accounted for more than 40% of manufacturing energy use, whereas in 1991, this share had declined by one-half, to 20%. The share of wood use doubled over the same period, primarily as a result of increased utilization by the paper and pulp subsector. Increased electrification of manufacturing processes led to a near doubling of the electricity share. By 1991, natural gas had become the dominant fuel in the sector, accounting for a nearly 40% share, up from 28% in 1958. Petroleum use declined slightly over the period from 13% to 8%, peaking at 16% in 1978 before the second oil price shock.

Figure 4. Final Energy Intensities in Select US Manufacturing Subsectors

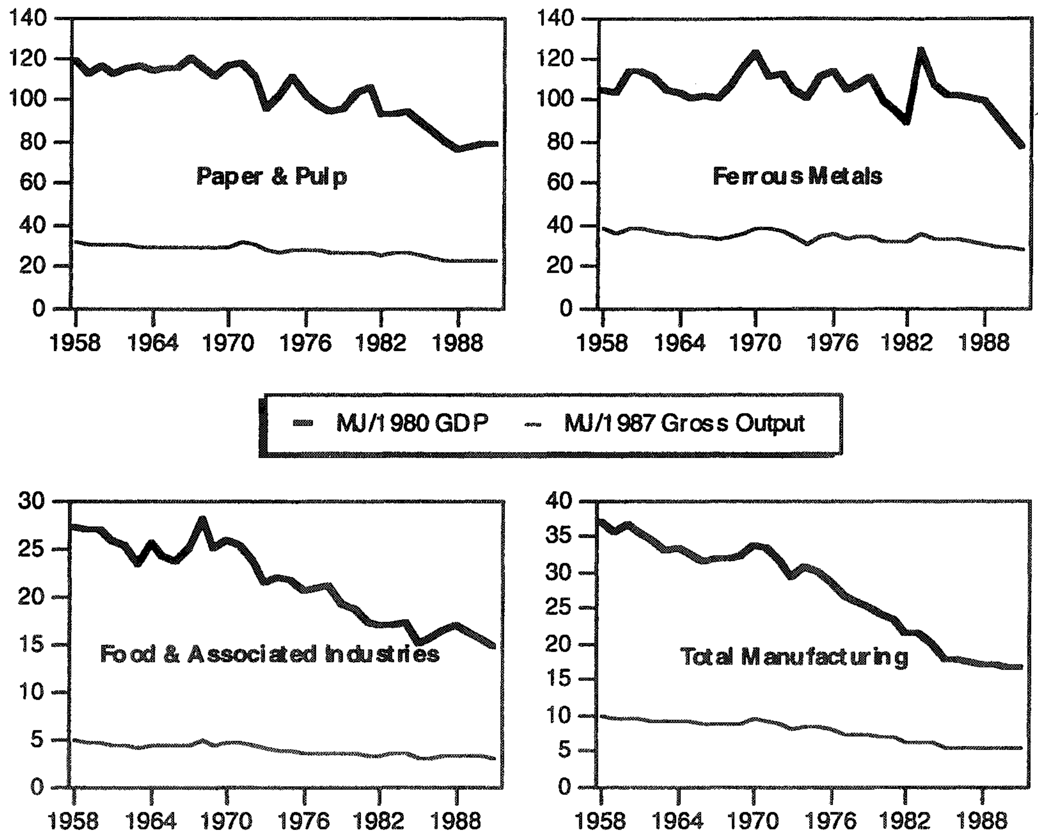



Figure 5. Shares of Final Energy Use by Fuel Type in US Manufacturing.

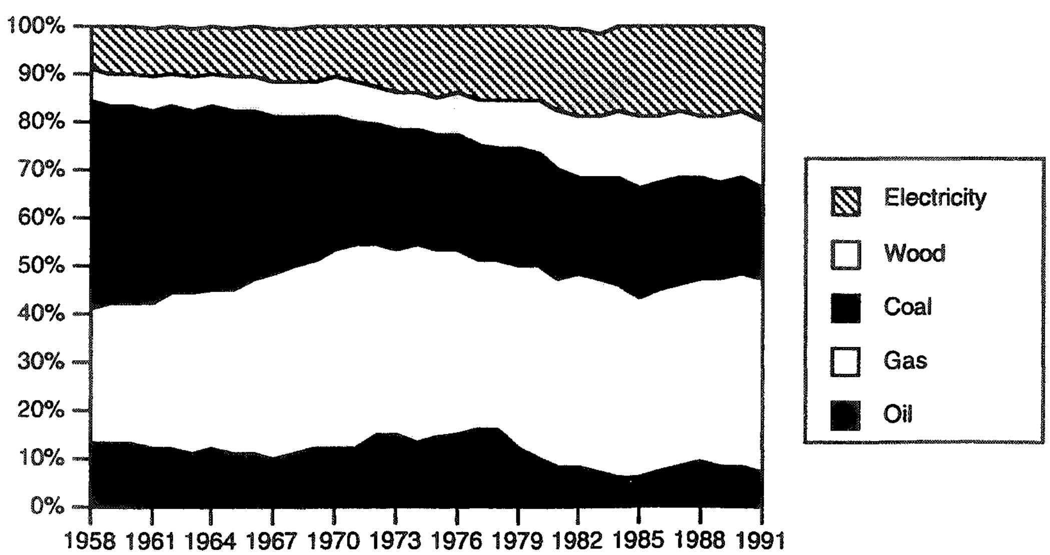



Figure 6 represents the heart of the analysis of energy trends. This graph displays total actual manufacturing energy consumption and the various energy-consumption effects for the period 1958 to 1991 in terms of percent change from the 1973 base year. Actual energy consumption, increasing an average of approximately 3.5% per year from 1958, peaked in 1973 and 1974. Substantial declines in actual consumption followed each of the energy price shocks, reaching a low for the period in 1982 of only 78% of 1973 levels. By 1991, actual consumption had returned to only 85% of base year consumption. Actual consumption decreased following both the recessions of the early 1980s and 1990s. The decline in 1984-85 was driven by decreases in energy intensity, rather than economic activity.

Activity effect shows the impact of changes in activity only on total energy consumption. As such, this effect displays clearly the periods of economic growth and decline. Increases in manufacturing value-added alone would have doubled energy consumption an average annual increase of 4.7% between 1958 and 1973. Slower value-added growth rates since the early 1970s led to an increase of only 50% between 1973 and 1991, an average annual increase of 2.3%. In the absence of structural and intensity changes, manufacturing energy consumption would have been more than 75% higher than what we actually observed.

Declines in energy intensity played the dominant role in limiting actual consumption. Between 1958 and 1973, intensity declined an average of about 1% per year. In the periods 1973 to 1985 and 1985 to 1991, intensity declined an average of nearly 2% per year. Intensity increased briefly in 1974-75 and again in 1983, but has decreased steadily in all other years. Given base year activity levels and industry structure, 1991 intensity levels would have reduced consumption by 30%.

Shifts in industrial structure have had a smaller but significant role in constraining actual consumption increases. By 1991, the change in structure alone would have reduced consumption by 20% from 1973 levels. In other words, shifts in the mix of manufacturing activities over the period from 1973 to 1991, independent of changes in overall activity levels (manufacturing GDP growth) or energy intensities, would have decreased consumption by one-fifth.

Figure 6. Impacts of Changing Activity, Structure, and Intensity on Final Energy Use in US Manufacturing (Indexed to 1973 Final Energy Use).

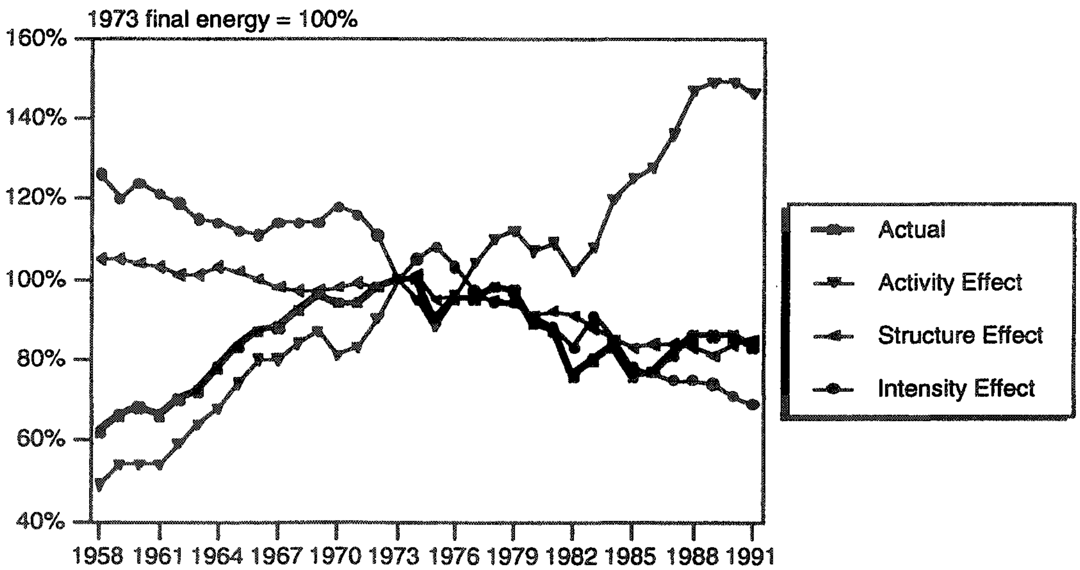
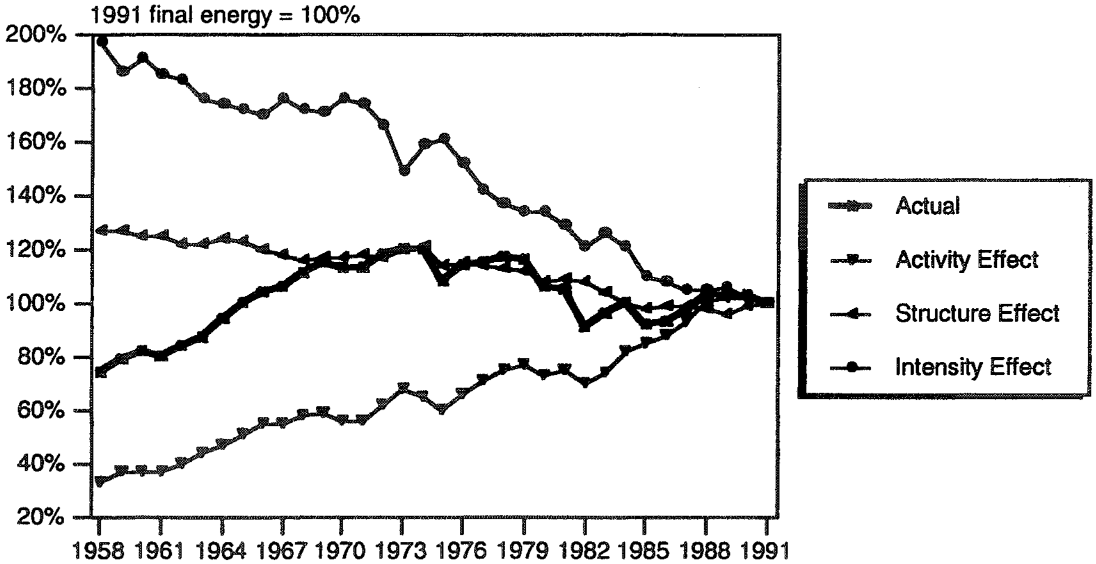



Figure 7 displays the activity, structure, and intensity effects calculated on the basis of a 1991 base year. We observe that declines in energy intensity reduced actual 1991 consumption by one-third from what we would have observed given 1991 activity and structure, but 1973 intensities. Of course, adjusting the base year in this manner does not affect rates of change or actual consumption, but it does facilitate analysis of the magnitude of the various effects, given two factors fixed at 1991 levels. We can now observe, for example, that given 1991 intensities and industrial structure, and 1958 (or 1973) activity levels, energy consumption would have been only 50% of actual consumption in those years. In other words, changes in intensities and structure since 1973 would have reduced consumption by one-half had they occurred at those times. Likewise, energy consumption in 1991, had intensities remained at 1958 levels, would have been double what we actually consumed.

Figure 7. Impacts of Changing Activity, Structure, and Intensity on Final Energy Use in US Manufacturing (Indexed to 1991 Final Energy Use).

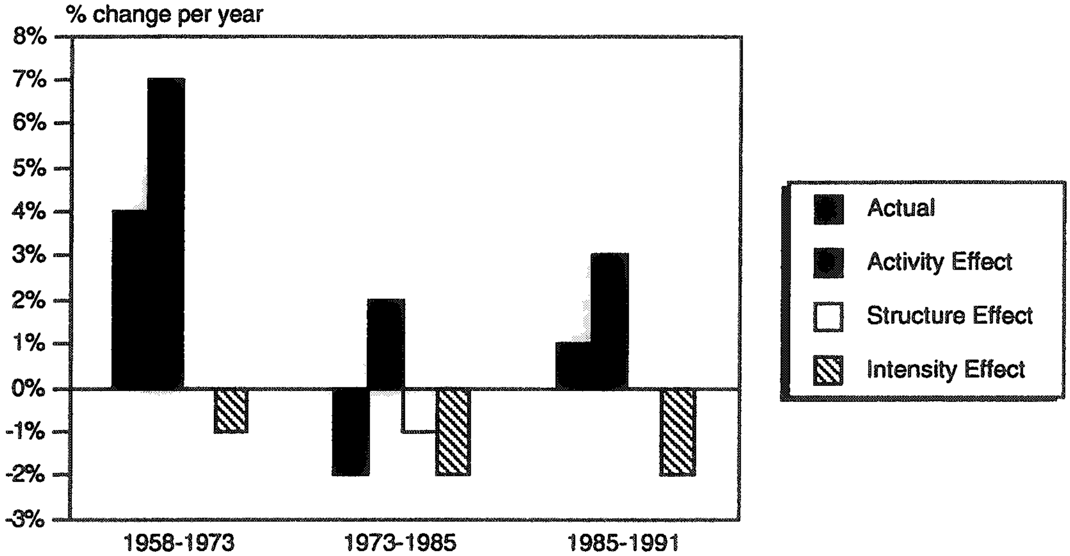



Finally, the trend in industry structure from 1988 to 1991 tended to increase consumption, all else being equal. Publication of 1994 energy consumption values will be required to determine if this trend has continued.

Although prices are not explicitly accounted for in our method, Figure 8 does provide insight into the response of the manufacturing sector to various price conditions. We have compared trends across three periods, 1958 to 1973, 1973 to 1985, and 1985 to 1991, in order to examine the behavior of the industry in periods of price increase, compared to periods of stable prices. While we cannot draw any hard conclusions from this graph, the dramatic drop in the activity effect growth rate from the first to the second period and the subsequent small increase in the third, suggest that rising prices had an inhibiting effect on economic growth. The impact of increased global competition in manufacturing probably limited the return of activity growth to earlier levels following the stabilization of prices.

Likewise, the negative growth rates in actual consumption during the period of rising prices, combined with positive rates during the stable periods suggests that rising prices had a significant impact of actual energy consumption. These results are consistent with theory. What is revealed by this analysis, however, is that declines in intensity appear to be relatively independent of price trends, while industry structure is stable during periods of stable prices and shifts away from energy-intensive industries during periods of increasing prices. These results were unexpected. We had anticipated finding that changes in intensity followed price changes closely, while structural change was independent of prices. Our findings suggest that increases in efficiency are now seen by the manufacturing sector as a part of an overall competitive operating strategy, rather than merely a response to price increases. It will be interesting to observe whether these trends continue when more recent data become available.

Figure 8. Average Annual Rates of Growth in Actual Final and STRINT Effects Energy Use in US Manufacturing.




## CARBON EMISSIONS

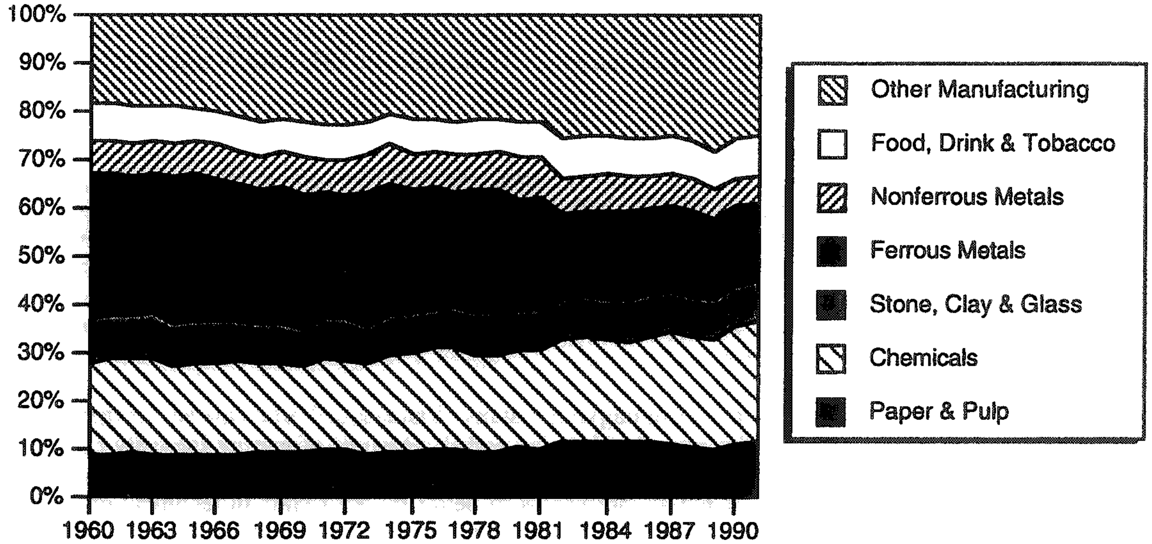
In light of increasing scientific and social concern, understanding the sources of carbon emissions has become one of the bases for energy and environmental policy. To meet international commitments to constrain such emissions, understanding the relationship between energy consumption and carbon emissions has assumed an even greater significance.

The method used to decompose trends in energy consumption is applicable to analyzing carbon emissions as well. Using carbon coefficients[7] to transform our results for energy consumption into carbon emissions, we have been able to evaluate the impact of activity, structure, energy intensity, and carbon intensity (carbon emissions per unit of energy consumption) on total carbon emissions. Understanding these relationships is vital to the development of effective policies to constrain future emissions.

The U.S. manufacturing sector is responsible for approximately 260 Mtonnes C or slightly less than 20% of the total U.S. energy consumption-related emissions of carbon[6] as of 1991. Sectoral carbon emissions reached their highest level to date in 1973, nearly 340 Mtonnes C. Emissions declined briefly, but sharply, following the first oil price shock, increased briefly in 1976-77, before declining to their low for the period 1958 to 1991 of 250 Mtonnes C in 1982.

Figure 9 displays the shares of total manufacturing carbon emissions by subsector. Aside from the residual subsector, chemicals represent the largest single contributor with 25%, up from 19% as recently as 1980 and despite producing less than 10% of manufacturing sector value-added. Ferrous metals, on the other hand has declined from a high of 30% in 1960 (the first year of data) to 17% in 1991, while declining from 9% to 3% of sectoral value-added. Pulp and paper peaked at 12% in 1982, declining slightly through the end of the decade and returning to peak levels by 1991.

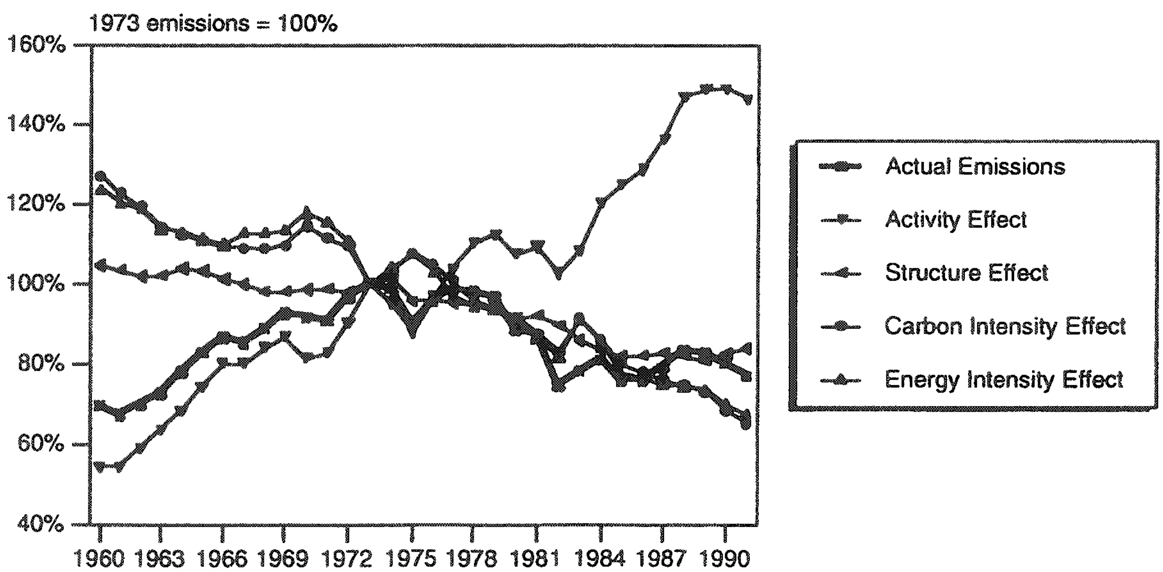
Figure 9. Carbon Emissions from US Manufacturing by Subsector.




Food, stone, clay and glass, and non-ferrous metals each accounts for less than 10% of total sectoral emissions.

Figure 10 presents a disaggregation analysis of carbon emissions comparable to Figure 6 for energy. The equation used to generate these calculations is the same presented in the Methodology section, with the addition of the term, "carbon emissions per unit of energy," transforming the calculation from total energy to total carbon emissions.

Figure 10. Impacts of Changing Activity, Structure, and Intensity on Carbon Emissions from US Manufacturing (Indexed to 1973 Emissions).




By 1991 actual carbon emissions from manufacturing energy consumption had declined approximately 25%, as displayed in Figure 10. The structure, energy intensity, and carbon-intensity effects all worked to constrain emissions in light of activity increases that, all else equal, would have increased emissions 50% from 1973 to 1991. We observe a dip in both the actual emissions and activity effect lines in 1991 resulting from the economic recession of that time, along with continuing declines in energy and carbon intensity. Changes in industry structure alone in the late 1980s and early 1990s would have tended to increase both energy consumption and carbon emissions.

Between 1960 and 1973 we observe a rapid increase of more than 40%, or 2.8% per year, in actual emissions. Industry structure was stable during this period, having little impact on changing emission levels. Both carbon intensity and energy intensity alone would have reduced emissions on the order of 20% over this period, combining to limit the impact of a near doubling in activity.

## FUTURE RESEARCH

This study has raised a number of questions that require additional research. Of particular significance are questions about the role of prices in determining changes in technical efficiency. Because our method has not explicitly accounted for prices, answering these questions has been problematic. Therefore, future research will involve the development of methods that explicitly account for energy prices. In addition, our method relies on the assumption that the magnitude of "cross-terms," that is, the interaction between the specific terms such as activity and structure or structure and intensity, is negligible. This assumption has not yet been tested to our satisfaction. Future work will focus specifically on testing this hypothesis.

Unresolved issues also remain surrounding the choice of output measures. Value-added offers the advantages of easy aggregation and consistent availability. On the other hand, value-added measures of energy intensity conflate a variety of factors and are not fully adequate measures of technical efficiency. Gross output does not allow aggregation because of the double-counting of inputs, but seems to better reflect trends in technical efficiency. Physical measures, not considered in this analysis, offer advantages in terms of reflecting output directly, but suffer from incommensurability. Tons of steel cannot be added to number of computers. Likewise, there are questions about adding 386 computer models to 486 models. None of the options is perfect. Future research should examine the relative merits of the various measures and ascertain the best application of each.

## CONCLUSIONS

This paper has presented a number of firm and speculative conclusions including the following:

- Energy intensities of the five most intensive subsectors are, on average, an order of magnitude higher than the other subsectors of the manufacturing sector.

- With the exception of some brief upturns in certain subsectors, energy intensities for all the intensive subsectors and for the sector as a whole declined consistently between 1958 and 1991.

- Using gross output, rather than value-added, as a measure of economic activity may yield a more "realistic" picture of trends in technical efficiency, although the use of gross output is problematic for several reasons.

- There has been a marked long-term shift from coal to natural gas in the manufacturing sector. This shift has had a significant impact on carbon emissions from manufacturing energy consumption.

- Actual manufacturing energy consumption in 1991 was only 85% of consumption in 1973. Reductions in energy intensity are primarily responsible for this decline. Structural change has had a lesser, but significant impact in constraining consumption as well.

- Given 1991 activity and structure, energy consumption for the year would have been double what we actually observed had intensities remained at 1958 levels.

- The primary response of the manufacturing sector to rising energy prices appears to be structural adjustment. Declines in energy intensity appear to be relatively independent of price, at least since the mid-1980s.

- Improving energy efficiency appears to have become an integral component of competitive strategy in the manufacturing sector, as opposed to merely a response to price increases.

- The manufacturing sector was responsible for approximately 260 Mtonnes C or slightly less than 20% of total U.S. energy-related emissions.

- Manufacturing-sector carbon emissions peaked in 1973 at nearly 340 Mtonnes C, before declining to a low in 1982 for the period 1958 to 1991.

- The chemical subsector contributed 25% of total sectoral emissions in 1991, despite producing less than 10% of sectoral value-added.

- Declines in energy and carbon intensity had significant impact in constraining carbon emissions. Structural change had a lesser, but still important, effect.

## ACKNOWLEDGMENTS

This work was supported by the U.S. Environmental Protection Agency, Office of Policy Analysis, Division of Climate Change, through the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

## NOTES

Lee Schipper can be reached at the International Energy Agency, Paris, through October 1996.

## REFERENCES

1. Howarth, R.B., L. Schipper, P.A. Duerr, and S. Strom. 1991. "Manufacturing Energy Use in Eight OECD Countries: Decomposing the Impacts of Changes in Output, Industry Structure and Energy Intensity." *Energy Economics* 13:135-42.
2. Howarth, R.B. 1991. "Energy Use in U.S. Manufacturing: The Impacts of the Energy Shocks on Sectoral Output, Industry Structure, and Energy Intensity." *The Journal of Energy and Development* 14(2):175-191.
3. Schipper, L. and S. Meyers. *Energy Efficiency and Human Activity: Past Trends, Future Prospects.* Cambridge: Cambridge University Press.
4. Ross, M. and R. Hwang. 1992. *A Model for Long-Term Industrial Energy Forecasting (LIEF).* U.S. Department of Energy.
5. Boyd, G., J.F. McDonald, M. Ross, and D.A. Hanson. 1987. "Separating the Changing Composition of U.S. Manufacturing Production from Energy Efficiency Improvements: A Divisia Index Approach." *The Energy Journal* 8(2):77-96.
6. Energy Information Administration. 1994. Emissions of Greenhouse Gases in the United States: 1987-1992. DOE/EIA-0573, U.S. Department of Energy. Washington, DC.
7. Marland, G. and A. Pippen. 1990. "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy* 14:319-336.