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THE EFFECTS OF ENVIRONMENTAL TAX SHIFTING ON U.S. CAPITAL FORMATION

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ABSTRACT

This paper examines the impact on U.S. capital formation of policies that combine higher taxes on pollution and energy consumption with reduced taxes on work, saving, or investment. We find that there could be potentially important short-run disruptions from an energy tax increase, but that these could be ameliorated by revenue recycling programs directed to the reduction of capital costs. In particular, a contemporaneous investment tax credit of between 5 and 10 percentage points might offset the energy-tax disruption completely, provided that the energy tax is gradually phased in.

I. INTRODUCTION

Although pollution-control efforts in the United States have traditionally focused more on regulation than taxation, recent efforts to move toward more rational methods of dealing with pollution have been explored. For example, the Clean Air Act of 1990 set up a system of fully tradable pollution permits, and has been evaluated quite favorably (Stavins 1998). The wide acceptance among analysts of the view that market-based solutions may be superior to regulation suggests that increased attention should be given to tax options. Like regulations, taxes provide a means of managing pollution. Unlike regulations, however, taxes also raise revenue. These funds, broadly speaking, can be used to increase government spending, pay down government debt, or reduce other taxes.

Using the revenue from pollution taxes to reduce other taxes generates the possibility of a "double dividend," whereby the tax shift both reduces pollution and improves the economic efficiency of the tax system at the same time. The potential for a double dividend has inspired a large literature, reviewed recently by Sanstad and Wolff (1998). In general, the literature shows that double dividends can occur (Ballard and Medema 1993), but that the presence and magnitude of a double dividend hinges crucially on a number of underlying assumptions (Bovenberg and de Mooij 1994; Goulder 1995; Fullerton and Metcalf 1998; and Eissa and Blundell forthcoming).

In this paper, we examine the effects of policies that combine higher taxes on pollution with reduced taxes on other activity. However, unlike previous work on the double dividend—which has focused on analyzing the welfare effects of tax policy in sophisticated general-equilibrium models—we examine the impact of tax-shifting policies on capital formation in the manufacturing industry in the United States. Both intuition and prior economic research suggest that the principal impact of a carbon tax would relate to investment behavior rather than saving. Thus, the main focus of our analysis is on the impact on investment.

In section 2, we review previous work on how energy prices affect the macroeconomy, and on whether capital and energy are complements or substitutes. We interpret the latter literature as showing that capital and energy are complements in the short run and substitutes in the longer run, which is consistent with the finding in the macroeconomic literature that large oil price shocks cause significant short-run disruption to economic activity.

In section 3, we present new evidence from vector autoregressions (VARs) of the impact of energy prices on investment and output. The VARs include energy prices, the user cost of capital, investment, and output. Using aggregate data on the U.S. manufacturing sector, we find that higher energy prices reduce investment in the short run but cause an increase in investment in the medium term. Using industry-level data in manufacturing, we show that the impact of energy prices on investment is larger in more energy-intensive sectors and in sectors where investment is believed to be lumpy or irreversible. These results are consistent with the view that capital and energy are complements in the short run and substitutes in the longer run. They also provide reconciliation between the literature on macroeconomic effects of energy-price increases and the literature on capital-energy complementarity.

In section 4, we derive the implied effects of carbon taxes on investment. Specifically, we examine the impact on investment in the U.S. manufacturing sector of a carbon tax proposal put forward by Hamond et al. (1997). We argue that the carbon tax would operate through an increase in energy prices. We estimate the implied increase in energy prices, and simulate the VAR model using the implied energy-price increase due to carbon taxes. We find that a carbon tax of $70 per ton in isolation would reduce short-run investment significantly. But we also find that such effects can be greatly offset by revenue-recycling programs that are directed to reducing capital costs. For example, when combined with a revenue-neutral investment tax credit (ITC), the carbon tax would have only a modest negative impact on short-run investment, and the capital stock would be larger than it otherwise would have been in the long run. All of these effects refer to unanticipated carbon taxes; anticipated carbon taxes would likely have smaller, negative short-term effects.

In section 5, we turn to an analysis of saving. There is, to our knowledge, virtually no prior research on how energy prices or carbon taxes would affect household saving behavior. Thus, rather than reviewing such work, we briefly outline recent trends in saving and discuss some of the major determinants of household saving behavior.

In section 6, we discuss the impact of carbon taxes, payroll tax cuts, and other tax policies on household saving behavior. We conclude that the direct effects of a carbon tax combined with a payroll tax reduction would be essentially a nonevent for household saving.

In section 7, we briefly discuss possible general-equilibrium effects of tax shifting. This discussion indicates how the conclusions stemming from separate analyses of investment and saving might need to be modified in a broader model of the economy.

Section 8 is a brief conclusion.

II. RELATED WORK ON ENERGY PRICES AND INVESTMENT

Previous research has focused on the macroeconomic effects of energy-price increases and the extent of complementarity or substitutability between capital and energy in the production process. We describe each literature briefly and then draw some links between them.

A. MACROECONOMIC IMPACTS OF ENERGY-PRICE CHANGES

Hamilton (1983) showed that all but one of the post-war U.S. recessions through 1980 had been preceded by a dramatic increase in the price of oil. Since then, the economy has experienced two more recessions. In 1981, the Iran-Iraq war led to a sharp increase in the price of oil and a recession followed. In 1990, Iraq's invasion of Kuwait precipitated a run-up in oil prices, and a brief recession followed. Thus, the evidence seems to suggest that disruptions to the flow of inexpensive energy have negative effects on the economy.

However, the link between oil prices and the economy may not be as robust as it first appeared. Hooker (1996) finds that the relationship appears to have softened considerably in recent years. However, Mork (1989, 1994), Ferderer (1996), Lee et al. (1995), and Hamilton (1996a) present evidence supporting Hamilton's original claims. These papers tend to imply that nonlinearities play an important role, so that large oil price increases generate significant reductions in economic activity, but oil price declines and oil price changes that occur in periods of unusually high price volatility have small impacts. Hooker (1997) finds some support for these views, but notes that standard methods find large effects of oil prices only when they use nonstandard specifications. Whether such specifications are appropriate is an open question.

Most of the analyses of this question focus on either a bivariate relationship between oil prices and output, or on small systems of macrotime series that include both output and oil prices. Thus, the theoretical underpinnings of large oil price effects have not been explored very carefully. However, Bernake et al. (1997) use the oil price data constructed by Hamilton and show that, even with this series, oil price effects may be significant only when they stimulate contractionary monetary policy. Thus, they argue that monetary policy is the conduit through which oil prices act. This contrasts somewhat with the channels proposed by previous authors. Hamilton (1996b), for example, notes that large increases in oil prices might lead businesses to delay or reduce purchases of capital goods, and consumers to delay or reduce purchases of durable goods. Detailed analysis of these channels has not been undertaken, but such evidence is an obvious precursor to understanding the true mechanism for oil price effects.

B. CAPITAL-ENERGY COMPLEMENTARITY

The impact of a carbon tax on capital formation depends in part on how the demand for capital goods changes when the price of energy rises. On *a priori* grounds, there is no clear answer. Machines and energy may appear to be complementary, since machines generally require energy to run, but investments in highly efficient machines can reduce the amount of energy that goes into any product, making machines and energy substitutes.[1]

The empirical literature has generated mixed results. The classic paper on this subject is Berndt and Wood (1975). They perform an iterative, three-stage least-square estimation of a capital-labor-energy-materials translog cost function using aggregate U.S. manufacturing price- and cost-share data for the period 1947–1971. They assume that production exhibits constant returns-to-scale and that technical change is Hicks-neutral for all inputs. They find that energy and capital display substantial complementarity. They also note that the result has interesting policy implications: "since investment tax credits and accelerated depreciation allowances reduce the price of capital services, [energy-capital complementarity] implies that these investment incentives generate an increased demand for capital and for energy. To the extent that energy conservation becomes a conscious policy goal, general investment incentives may become less attractive as fiscal stimulants."

Since Berndt and Wood, nearly fifty articles have looked at this issue. (Thompson and Taylor [1995] provide a review of the literature. We examine several of the articles in detail in the appendix.) Almost all of the work is based on estimates of translog cost functions and the majority of this work was conducted in the decade following the work of Berndt and Wood.

According to Thompson and Taylor (1995), analyses using time-series data have tended to find that capital and energy are complements, whereas analyses using cross-sectional data have tended to indicate substitutability. Apostolakis (1990) and Griffin and Gregory (1976) argue that the cross-section results are likely to reflect the long-term

1. Textbook microeconomics usually employs a production function that turns capital and labor into output. In such a world, increases in the price of labor necessarily lead the firm to substitute away from labor and into capital. When there are more than two inputs, however, the inputs need not be substitutes.

relation between energy and capital, while the time-series estimates are likely to reflect the short-term effects. If so, this implies that capital and energy are substitutes in the long run and complements in the short run. It is natural to expect a difference in the long-term and short-term relationship between capital and energy, since capital is a quasi-fixed input.

C. RECONCILIATION

The macroeconomic literature finds that oil price shocks have a negative effect on the economy, and that this relationship may be highly nonlinear. The microempirical literature suggests a possible channel for this macroeffect. In the short run, energy and capital appear to be complements, and the increase in energy prices decreases the demand for capital services. In the longer run, they appear to be substitutes, as old machines are replaced with new, more energy-efficient ones. Thus, the story that rationalizes the energy-capital complementarity debate is precisely the view proposed by Hamilton to explain the concurrence of oil price shocks and recessions.

Whether the reconciliation proposed above is correct is crucial to understanding the impact of a carbon tax on capital formation. Unfortunately, it is impossible to draw firm conclusions from the existing literature. Thus, we turn to an examination of investment behavior at the aggregate and industry level. From the point of view of the energy-capital literature, the exploration of dynamic responses, as is standard in the macroliterature, can shed light on whether the dynamic suggested here is supported by the data.

III. NEW EVIDENCE ON ENERGY PRICES AND INVESTMENT BEHAVIOR

In the tradition of Hamilton (1983) and Hooker (1997), we proceed by exploring the impact of energy prices on investment, first at the level of aggregate manufacturing, and second, at the two-digit industry level. Our methodology is to employ a simple vector autoregression (VAR) relating the ratio of investment to capital to its neoclassical determinants (the ratio of output to capital and the user cost of capital) and to the log-difference of the relative price of energy. In this specification, which has been relied upon in various applications in the investment literature, the variables are all stationary and issues of co-integration and error correction can therefore be ignored. The VAR approach has the additional benefit that the dynamic effects of shocks to variables in the system can be traced, allowing for differing impacts at different time horizons.

A. DATA

We use data from the National Bureau of Economic Research Manufacturing Productivity (MP) database. This database contains capital, energy, labor, and materials input data for approximately 460 individual (four-digit SIC code) industries for 1958 to 1994.[2]

The variables in the dataset can be segmented into Annual Survey of Manufacturers (ASM) data and price deflators. The ASM, based on a sample of approximately 60,000 manufacturing firms, has been conducted by the U.S. Census Bureau since 1949 and contains information on the location, activities, inputs, and outputs of U.S. manufacturing firms. U.S. law mandates that firms respond to the survey. We use the ASM data on value of shipments, gross investment, and energy expenditures.

2. This dataset was first constructed in 1980 for the U.S. Census Bureau, but numerous updates have since occurred. In its present format, this dataset was originally constructed and made available by Eric Bartelsman and Wayne Gray in 1996. Recently, the data has been again updated and expanded to include the three most recent years of data. Complete documentation of the data corresponds to a 1996 data release and not the updated, currently available data. Until the updated documentation is made available by the authors, we will rely on Bartelsman and Gray (1996) for dataset construction details.

We use capital stock data from the Federal Reserve Board. The data are based on three-digit industries and are converted to the four-digit level, assuming equivalent industry-asset type flows. The output deflator we use is constructed from two sources. For 1958 through 1971, the deflator is based on Bureau of Labor Statistics data of properly weighted producer price indexes. From 1972 forward, we use Bureau of Economic Analysis (BEA) five-digit product deflators. Industry-specific output deflators are constructed from these product deflators by matching them to "Make" tables for the years 1972, 1977, and 1987. The materials deflator is a weighted average of price deflators for 529 separate inputs. Weights are based on industries' proportional consumption of each input, based on the Census Department's Input-Output tables.

The energy-price deflator is based on a weighted average of each industry's consumption of six types of energy (electricity, residual fuel oil, distillates, coal, coke, and natural gas). There are two data sources for this deflator. For 1958 through 1985, we use the National Energy Accounts database; from 1986 forward, we use the Energy Department's *State Energy Price and Expenditure Report.* The price data are weighted by expenditure shares to create an energy deflator.

For our empirical analysis, we aggregate the data in two ways. First, we combine the data into a simple, aggregate time-series dataset. Second, we aggregate the data into twenty-nine, two-digit SIC code industries for industry-specific analysis. In both aggregations, price deflators are calculated as nonweighted arithmetic means of industry-level deflators.

Finally, we construct a user cost of capital (UCC) from a time-series of tax parameters for the manufacturing industry under the following construction.

$$UCC = [(1 - K - (\tau Z)/(1 - \tau)] * (r + \delta - \Delta P_I/P_I) * P_I/P_Y$$

Data on the investment tax credit (K), depreciation allowances (Z), and corporate tax rate ($1-\tau$) are taken from Cummins et al. (1994, table 1). The interest rate (r) is Moody's AAA corporate bond rate, as reported in the *Economic Report to the President, 1997.* Depreciation is assumed to be constant at a geometric rate of 10 percent. P_I/P_Y is the investment price deflator.

B. RESULTS: AGGREGATE TESTS

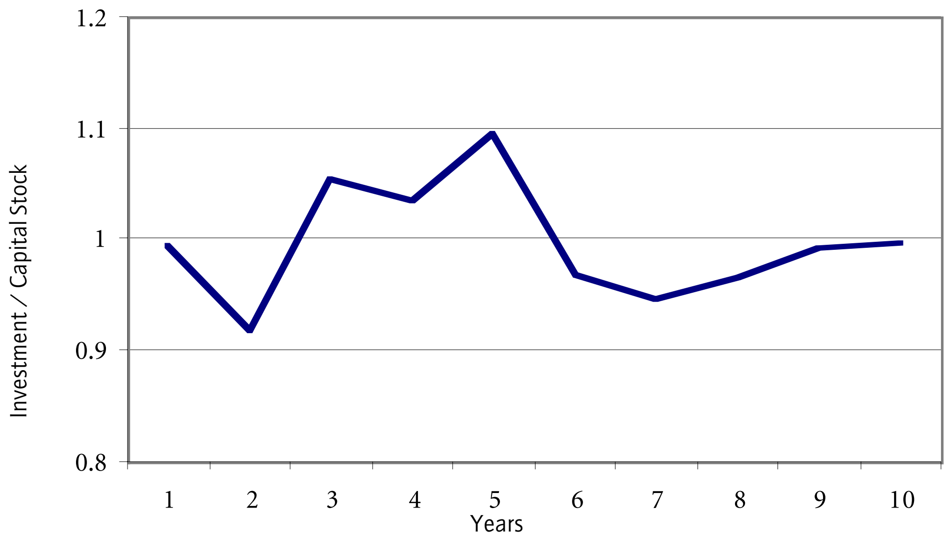
Table 1 contains each of the estimated equations for the aggregate VAR system, with t-statistics in parentheses. As is standard practice in the time-series literature, each variable is in log form. The first column relates the change in the relative price of energy to three lags of itself and to the other variables in the system: the user cost, the investment-to-capital ratio, and the output-to-capital ratio. None of the variables is significant, which suggests that the price of oil may be well approximated by a simple random walk, or that it is exogenous.

TABLE 1: **AGGREGATE DATA REGRESSIONS**

Dependent Variable	DLRPE	LUCC	LIK	LYK
DLRPE(-1)	0.364 (1.413)	-1.227 (-0.987)	-0.787 (-1.382)	-0.160 (-0.498)
DLRPE(-2)	0.149 (0.584)	0.979 (0.797)	2.009 (3.567)	0.580 (1.831)
DLRPE(-3)	-0.038 (-0.155)	-1.590 (-1.349)	-1.206 (-2.232)	-0.589 (-1.939)
LUCC(-1)	-0.086 (-1.836)	0.490 (2.182)	-0.230 (-2.230)	0.011 (0.1970)
LUCC(-2)	0.013 (0.234)	0.097 (0.375)	0.113 (0.960)	-0.024 (-0.359)
LUCC(-3)	-0.019 (-0.398)	-0.172 (-0.751)	-0.154 (-1.467)	0.033 (0.559)
LIK(-1)	-0.012 (-0.129)	-0.086 (-0.201)	0.464 (2.359)	-0.009 (-0.086)
LIK(-2)	-0.075 (-0.919)	0.197 (0.502)	-0.234 (-1.301)	0.005 (0.052)
LIK(-3)	0.074 (1.084)	0.018 (0.054)	0.063 (0.412)	0.014 (0.166)
LYK(-1)	-0.233 (-1.228)	-0.358 (-0.390)	0.791 (1.882)	0.971 (4.110)
LYK(-2)	0.201 (0.865)	-1.555 (-1.390)	0.157 (0.306)	-0.224 (-0.777)
LYK(-3)	-0.035 (-0.203)	0.960 (1.167)	-0.571 (-1.513)	0.078 (0.369)
Constant	-0.130 (-0.353)	0.124 (0.070)	-2.532 (-3.099)	0.211 (0.460)
Adj. R2	0.452	0.410	0.619	0.820
Obs.	33	33	33	33

The user-cost equation reveals some serial correlation, but the other variables appear to have little feedback. Column 3 of table 1 contains the aggregate investment equation. As has often been found in the past, investment depends on lags of itself, lags of output, and lags of the user cost of capital. The correlation with output appropriately suggests that investment is highly procyclical. The user-cost responsiveness is significant, with the elasticity of about .25 being typical of time-series studies (Clark 1993), but lower than is often found in panel studies (see Hassett and Hubbard 1997 for a discussion of this divergence).

FIGURE 1: **EFFECT OF A 10 PERCENT ENERGY SHOCK ON INVESTMENT**

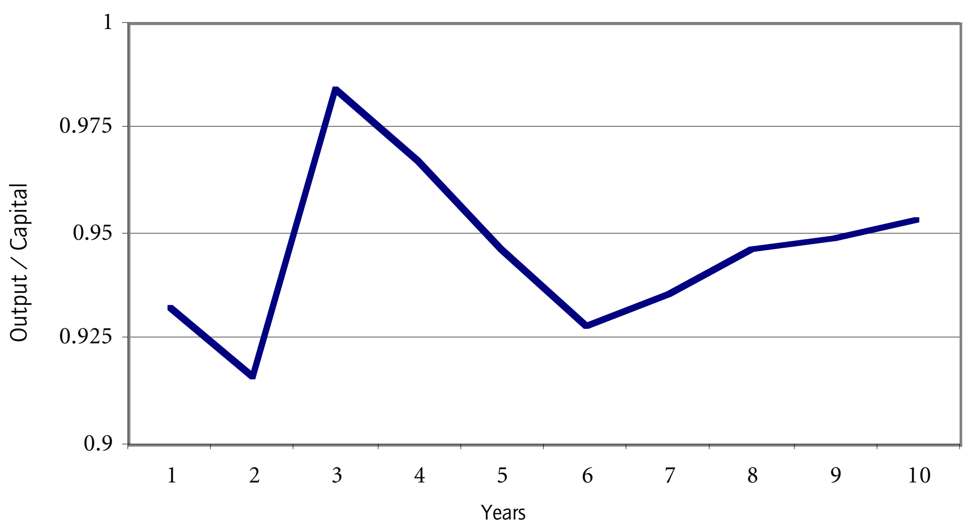


Energy prices are highly significant in the investment equation, with a negative effect in the first year, a positive effect in the second, and a negative effect again in the third year. Because energy prices enter the other equations as well, identifying the dynamic impact requires performing an impulse response analysis. This is provided in figure 1, which plots the impact of a 10 percent increase in the price of energy. The graph shows the level of investment in the economy for the ten periods following the shock, using a hypothetical index set equal to one in year zero. Over the first two years, investment drops almost 10 percent, but then a rapid "retooling" occurs, with investment ramping up significantly and rising well above the baseline. By the tenth year, investment has dropped back to about where it started. This is a clear "recession-like" effect, and may well explain the results of Hamilton (1983). Moreover, since the user cost of capital is in the VAR, and a separate effect of energy is statistically significant, our results cast some doubt on the conclusions of Bernake et al. (1997), who argue that the monetary transmission mechanism is the source of the interaction between energy prices and economic activity.

Column 4 provides the results for the output equation. The ratio of output to capital is highly serially correlated. The relative price of energy has complicated and offsetting effects on output in the regression, with the effects being borderline significant at the 5 percent level. Clearly, the relationship between oil prices and output is not as clean as that between oil prices and investment. Figure 2 plots the impulse-response function for output, assuming there is a 10 percent positive shock originating in the oil price equation. Output drops immediately by about 7 percent, and continues to show negative effects throughout the ten-year horizon.

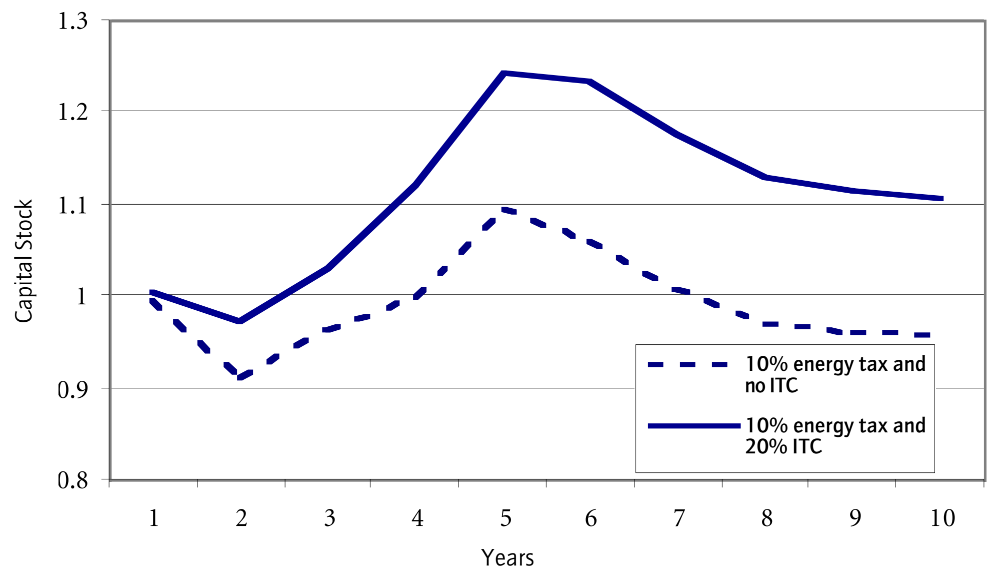
Figures 1 and 2 show sharp changes in investment following energy-price shocks, but should be interpreted cautiously. First, the point estimates for the impulse-response graph are the predicted effect from the model. Energy prices have a significant impact on the investment path in both figures, but were barely significant in the output equation. Moreover, changes in the underlying regression specification—adding lags, including additional variables, and so on—can often change impulse responses significantly.

FIGURE 2: **EFFECT OF A 10 PERCENT ENERGY SHOCK ON OUTPUT**



Next, we combine the effects of an energy-price shock with an investment tax credit (ITC). Figure 3 plots the impulse-response to a simultaneous shock to the price of energy and a negative shock to the user cost of capital (analogous to an investment tax credit) to the capital stock. The dotted line represents the effect of an energy tax and no investment tax credit. A 9 percent decline in the capital stock in period 2 confirms the "recession effect" also indicated in figure 1. In period 10, the capital stock is 4.5 percent lower than it would be absent an energy tax. The solid line plots the capital stock given a 10 percent energy tax combined with a 20 percent ITC. The decline in capital in period 2 drops to only 3 percent, and in subsequent periods, capital is significantly higher. Although not shown, the investment tax credit necessary to eliminate completely any decline in the capital stock from an energy tax would be about 30 percent. However, a 10 percent energy tax, along with an investment tax credit of just 10 percent, would result in a long-run capital stock *increase* of 3 percent.

FIGURE 3: **COORDINATED POLICY AND THE CAPITAL STOCK**



One caveat to the results is that the taxes are modeled as an unanticipated shock. This would likely exaggerate the short-term effect, but may change the long run much less.

C. RESULTS: INDUSTRY TESTS

Investment changes like those in figure 1 are consistent with models that assume that investment is lumpy or irreversible. Thus, it would be comforting if the effects in the aggregate are driven by disaggregated industries, which are believed to be better described by such models. One also would be reassured if the effects of energy-price increases tended to be the largest in industries that are relatively energy intensive. To explore these issues, and to generate added intuition regarding the impact of energy-price shocks, we turn now to industry-level tests.

Table 2 reports the investment equations from VARs calculated for each of the two-digit manufacturing industries. The energy-price effects are most significant in Food and Kindred Products, Lumber and Wood Products, Paper and Allied Products, Rubber and Misc. Plastics Products, Leather and Leather Products, Stone, Clay, Glass, and Concrete Products, Primary Metals, and Electrical and Electronic Equipment. With the exception of the Electrical Machinery industry, the effects appear to be bunched in those industries that process raw materials. These enterprises tend to have highly specialized plants, and are often heavy consumers of energy. For example, as can be seen in the bottom row of table 2, the industries with the large effects are, with the exception of the lumber industry, far more energy intensive than the industries that do not show an effect.

TABLE 2: **INVESTMENT EQUATION FROM 2-DIGIT VECTOR AUTO-REGRESSION**

Variable	Food and Kindred Products	Tobacco Products	Textile Mill Products	Apparel, etc.	Lumber and Wood Products
DLRPE (-1)	-0.817 (-2.128)	-0.472 (-0.304)	-1.899 (-1.782)	-0.014 (-0.006)	-1.235 (-1.661)
DLRPE (-2)	0.659 (1.633)	2.099 (1.256)	0.077 (0.068)	-2.321 (-0.937)	-0.160 (-0.216)
DLRPE (-3)	0.047 (0.126)	1.482 (0.958)	0.505 (0.404)	-1.040 (-0.468)	-1.650 (-2.367)
LUCC (-1)	-0.021 (-0.113)	-0.398 (-0.620)	-0.284 (-0.726)	0.0422 (0.101)	-0.316 (-0.957)
LUCC (-2)	-0.102 (-0.469)	0.565 (0.686)	0.052 (0.130)	0.273 (0.584)	-0.009 (-0.026)
LUCC (-3)	-0.046 (-0.221)	-1.316 (-2.487)	0.144 (0.371)	-1.132 (-2.692)	-0.502 (-1.585)
LIK (-1)	0.594 (2.705)	-0.054 (-0.260)	0.226 (1.107)	0.271 (1.352)	0.348 (1.787)
LIK (-2)	-0.396 (-1.647)	-0.174 (-0.765)	0.012 (0.047)	0.226 (0.987)	0.182 (0.890)
LIK (-3)	0.211 (1.102)	0.170 (0.802)	0.119 (0.525)	0.101 (0.471)	-0.024 (-0.143)
LYK (-1)	0.073 (0.256)	1.358 (1.091)	-0.101 (-0.176)	0.625 (0.701)	-0.517 (-0.801)
LYK (-2)	0.337 (1.086)	-2.177 (-1.448)	-0.109 (-0.137)	0.498 (0.446)	0.743 (0.859)
LYK (-3)	-0.032 (-0.128)	1.103 (1.071)	0.604 (0.946)	-0.701 (-0.793)	-0.744 (-1.056)
Constant	-2.198 (-2.17)	-5.593 (-2.820)	-2.026 (-1.456)	-2.947 (-2.781)	-2.239 (-2.109)
Adj. R2	0.776	0.260	0.245	0.575	0.430
Energy/Value Add	0.0246*	0.0465*	0.0535**	0.0184**	0.0318

NOTES:

CONTINUED ON NEXT PAGE

Dependent Variable is LIK.

DLRPE is the one-period difference of the log of the relative price of energy (PE/PY).

LUCC: log of user cost of capital.

LIK: log of investment/capital.

LYK: log of output/capital.

Mean of Energy/Value Add is 0.0347.

* Statistically different from sample mean at 95% confidence level.

** Statistically different from sample mean at 99% confidence level.

TABLE 2—*CONTINUED*

Variable	Furniture and Fixtures	Paper and Allied Products	Printing and Publishing	Chemicals and Allied Products	Petroleum and Coal Products
DLRPE (-1)	-1.186 (-0.811)	-1.582 (-1.146)	0.478 (0.568)	1.033 (1.030)	0.070 (0.043)
DLRPE (-2)	0.429 (0.374)	3.058 (2.361)	0.698 (0.869)	1.090 (1.068)	-2.480 (-1.422)
DLRPE (-3)	-0.402 (-0.352)	-2.457 (-2.263)	0.686 (0.830)	-0.040 (-0.050)	0.840 (0.433)
LUCC (-1)	0.433 (1.054)	0.061 (0.184)	-0.080 (0.326)	-0.353 (-1.092)	-0.650 (-0.772)
LUCC (-2)	0.073 (0.163)	-0.329 (-0.822)	0.030 (0.117)	0.052 (0.140)	0.754 (0.732)
LUCC (-3)	-0.401 (-0.839)	-0.132 (-0.340)	0.061 (0.282)	0.144 (0.417)	-1.704 (-1.866)
LIK (-1)	-0.285 (-1.066)	0.427 (1.986)	-0.076 (-0.388)	0.263 (1.094)	0.382 (1.833)
LIK (-2)	-0.198 (-0.670)	0.079 (0.325)	0.530 (2.844)	-0.326 (-1.394)	-0.032 (-0.134)
LIK (-3)	0.126 (0.493)	-0.146 (-0.581)	0.032 0.160	0.085 (0.384)	0.191 (0.822)
LYK (-1)	1.483 (1.675)	0.342 (0.641)	0.851 (1.817)	-0.437 (-0.670)	0.445 (0.333)
LYK (-2)	0.326 (0.305)	-0.202 (-0.304)	-0.349 (-0.664)	0.702 (0.782)	-1.531 (-0.879)
LYK (-3)	0.723 (0.784)	0.391 (0.888)	-0.826 (-1.860)	0.626 (0.809)	1.254 (1.061)
Constant	-6.993 (-2.129)	-2.826 (-1.663)	-0.749 (-1.802)	-3.324 (-2.591)	-4.203 (-2.411)
Adj. R2	0.473	0.313	0.658	-0.023	0.295
Energy/ Value Add	0.0198**	0.0530**	0.0154**	0.0419	0.0855**

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TABLE 2—*CONTINUED*

Variable	Rubber and Misc. Plastics Products	Leather and Leather Products	Stone, Clay, Glass, and Concrete Products	Primary Metal Industries	Fabricated Metal Products
DLRPE (-1)	-2.144 (-2.386)	0.835 (1.046)	5.910 (3.922)	-1.726 (-2.093)	2.840 (1.802)
DLRPE (-2)	1.077 (1.265)	1.474 (1.742)	-1.320 (-0.788)	0.218 (0.205)	-0.346 (-0.290)
DLRPE (-3)	-1.500 (-1.912)	-1.843 (-2.40)	2.518 (1.907)	-0.006 (-0.008)	-0.168 (-0.148)
LUCC (-1)	-0.234 (-1.309)	-0.588 (-1.169)	-0.711 (-1.541)	-0.300 (-0.819)	-0.417 (-1.461)
LUCC (-2)	0.281 (1.423)	1.577 (2.189)	1.260 (2.329)	0.084 (0.208)	0.328 (0.833)
LUCC (-3)	-0.249 (-1.272)	-1.898 (-3.373)	-0.619 (-1.197)	0.116 (0.358)	-0.223 (-0.767)
LIK (-1)	0.661 (3.038)	-0.344 (-1.891)	-0.173 (-0.773)	0.194 (0.880)	-0.346 (-1.443)
LIK (-2)	-0.386 (-1.516)	-0.353 (-2.009)	0.451 (2.230)	0.348 (1.631)	0.322 (1.226)
LIK (-3)	0.112 (0.563)	-0.525 (-2.223)	0.162 (0.733)	0.284 (1.312)	0.106 (0.647)
LYK (-1)	0.413 (0.792)	-1.488 (-2.036)	1.847 (2.936)	-0.142 (-0.402)	1.198 (1.672)
LYK (-2)	-0.895 (-1.285)	1.807 (1.797)	-1.293 (-1.342)	-0.087 (-0.188)	-0.371 (-0.327)
LYK (-3)	0.057 (0.113)	1.300 (1.327)	-0.094 (-0.141)	-0.225 (-0.619)	-0.846 (-1.051)
Constant	-1.386 (-2.155)	-10.707 (-5.500)	-1.884 (-1.189)	-0.401 (-0.533)	-3.089 (-1.817)
Adj. R2	0.592	0.447	0.733	0.529	0.131
Energy/ Value Add	0.0428	0.200**	0.0598**	0.0592**	0.0304

NOTES:

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Dependent Variable is LIK.

DLRPE is the one-period difference of the log of the relative price of energy (PE/PY).

LUCC: log of user cost of capital.

LIK: log of investment/capital.

LYK: log of output/capital.

Mean of Energy/Value Add is 0.0347.

* Statistically different from sample mean at 95% confidence level.

** Statistically different from sample mean at 99% confidence level.

TABLE 2—*CONTINUED*

Variable	Industrial Machinery and Equipment	Electrical and Electronic Equipment	Transportation Equipment	Instruments and Related Products	Misc. Manufacturing Industries
DLRPE (-1)	1.371 (1.130)	-3.306 (-3.256)	-0.778 (-0.737)	-0.719 (-0.614)	-1.193 (-0.776)
DLRPE (-2)	0.887 (0.817)	0.925 (0.924)	0.141 (0.136)	-0.245 (-0.191)	-0.229 (-0.165)
DLRPE (-3)	1.080 (0.894)	1.400 (0.921)	0.698 (0.753)	-0.780 (-0.533)	0.795 (0.515)
LUCC (-1)	-0.160 (-0.560)	-0.227 (-0.856)	0.009 (0.021)	-0.381 (-0.906)	-0.242 (-0.749)
LUCC (-2)	0.159 (0.513)	0.240 (0.953)	1.348 (2.788)	0.451 (0.925)	-0.151 (-0.427)
LUCC (-3)	-0.502 (-1.734)	-0.412 (-1.952)	-0.780 (-1.811)	-0.312 (-0.866)	0.026 (0.088)
LIK (-1)	0.046 (0.200)	0.722 (2.911)	-0.048 (-0.237)	0.518 (2.486)	-0.079 (-0.280)
LIK (-2)	-0.046 (-0.205)	-0.625 (-1.951)	0.102 (0.488)	-0.115 (-0.453)	0.216 (0.837)
LIK (-3)	0.003 (0.014)	0.474 (1.564)	-0.003 (-0.12)	0.107 (0.501)	0.011 (0.038)
LYK (-1)	0.974 (1.416)	0.786 (1.183)	1.026 (1.704)	0.719 (1.404)	-0.240 (-0.416)
LYK (-2)	0.250 (0.255)	0.567 (0.609)	-0.172 (-0.179)	-0.618 (-1.011)	1.006 (1.292)
LYK (-3)	-0.740 (-1.023)	-1.122 (-1.623)	0.343 (0.464)	0.233 (0.510)	-0.180 (-0.295)
Constant	-3.792 (-3.343)	-1.936 (-2.604)	-3.004 (-2.459)	-2.241 (-1.610)	-3.552 (-1.831)
Adj. R2	0.466	0.725	0.645	0.409	0.245
Energy/ Value Add	0.0218**	0.0148**	0.0174**	0.0173**	0.0194**

Figure 4 plots the impulse-response functions, analogous to figure 1, that trace the impact of a 10 percent increase in the price of energy on investment in each industry. Focusing on the industries that showed the statistically significant effects, Food, Paper, Rubber, and Primary Metals all have the "recession" shape, whereas Lumber, and Stone, Clay, and Glass increase quickly and then level off. Leather shows a relatively flat response, and Electrical Machinery shows a steady decline.

Thus, the industry-level results provide additional details that support the view that the aggregate swings are not merely figments of the data.

FIGURE 4: **INDUSTRY RESPONSES TO 10 PERCENT ENERGY PRICE SHOCK**

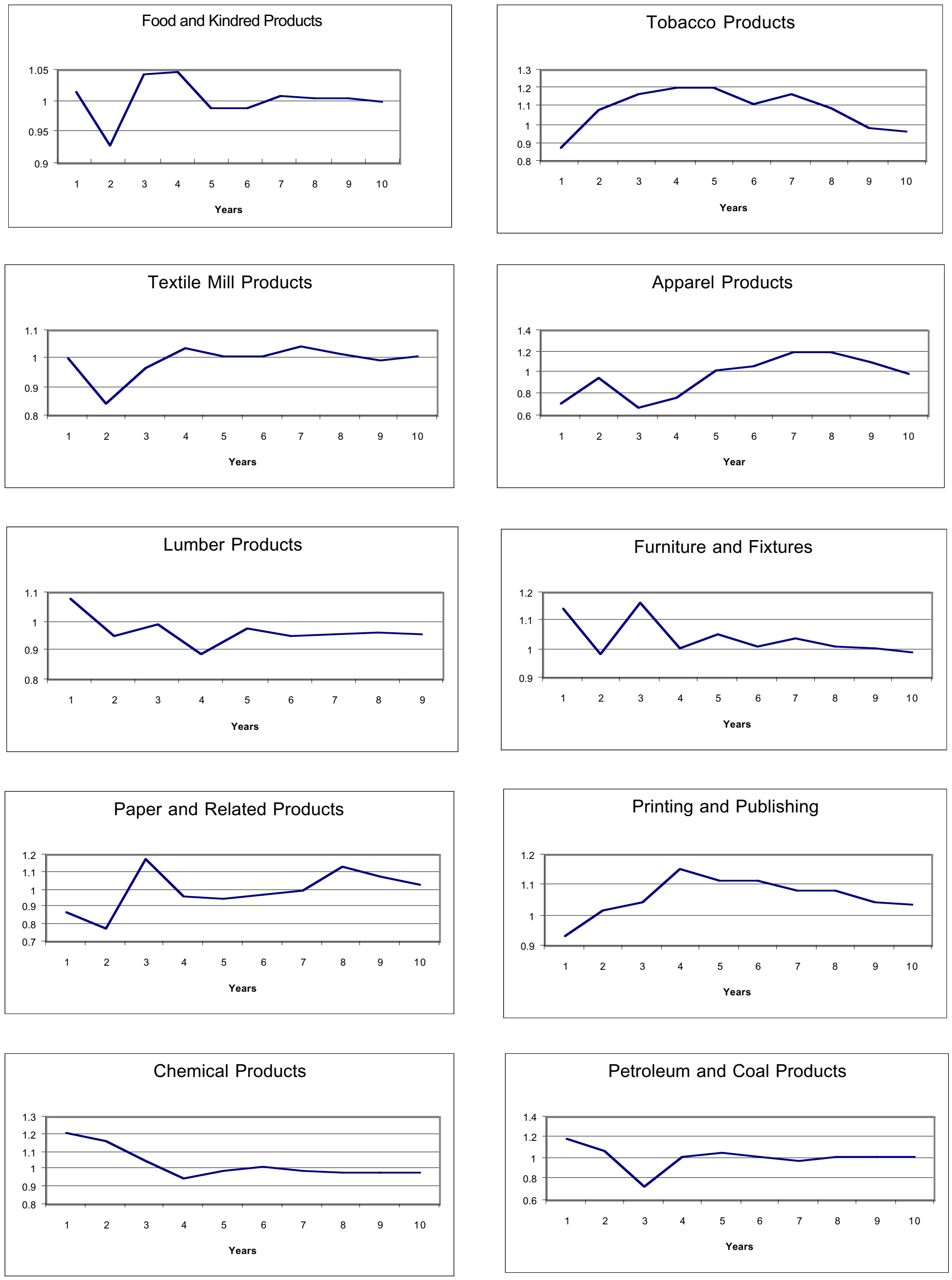

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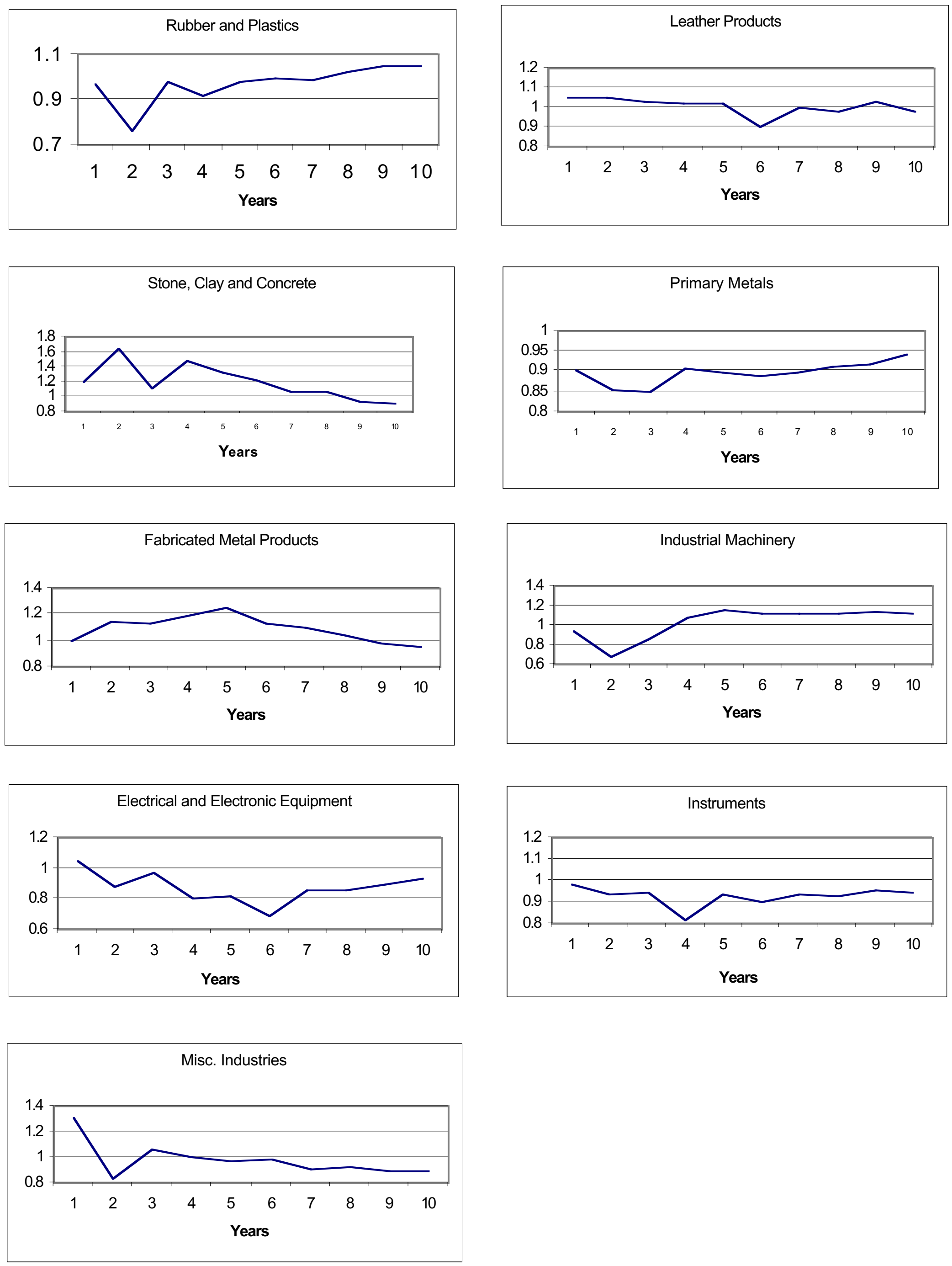
FIGURE 4—*CONTINUED*



D. SUMMARY OF ENERGY-PRICE RESULTS

The results show that energy-price shocks can significantly change the path of aggregate investment, and that there is significant diversity in the impact of such shocks at the industry level. These results are consistent with the macroliterature, which found that energy prices are significant determinants of economic fluctuations, and with the production function literature, which found that energy and capital are complements in the short run and substitutes in the long run.

The results also show that when shocks to the price of energy are combined with cuts in the user cost of capital, the initial investment decline is moderated and, in the long run, the capital stock is greater than it otherwise would have been.

IV. IMPLIED EFFECTS OF CARBON TAXES ON INVESTMENT BEHAVIOR

In this section we use the results in the previous section to explore the impact of a tax shift on the path of aggregate investment. The key to this analysis is to translate a carbon tax of a given magnitude into an energy-price increase of the appropriate size. Once that is done, the analysis of the carbon tax can proceed using the analysis of energy prices in the preceding section.

A. FROM CARBON TAXES TO ENERGY-PRICE INCREASES

A carbon tax would operate by raising the price of energy, which in turn would affect investment and output through the channels described in section 3. A precise estimate of the impact of a carbon tax on energy prices in the manufacturing sector requires modeling that is beyond the scope of this paper. As a result, we present a rough, but we hope transparent, way of estimating the link between carbon taxes and energy-price increases.

Metcalf (1998) calculates that a $40 per ton carbon tax would raise electricity prices by 12 percent, natural gas prices by 19.6 percent, and fuel oil and coal prices by 12 percent. Hamond et al. (1997), in their second scenario, call for a carbon tax of $70 per ton, and note that this would raise about $83 billion in revenues. We assume, based on Metcalf's figures, that the carbon tax would raise energy prices by about 20 percent.

B. EFFECTS OF CARBON TAXES ON INVESTMENT

Taking these effects as given, and assuming that the VAR model that generated figure 1 is the correct model, the carbon tax would reduce aggregate investment by about 18 percent over the first two years after its introduction. Investment would then swing in the opposite direction for two years, and then settle in at about its previous steady-state level after about the seventh year. The large reduction in the first two years would certainly be significant for the macroeconomy. Assuming that fixed investment starts at about $1 trillion (in 1992 dollars), a reasonable level to assume given its 1998 level, the carbon tax would reduce aggregate investment by about $200 billion, which, looking forward, would be in the range of 3 percent of GDP.

These estimates, however, refer to the effects of unanticipated taxes. Carbon tax proposals typically advocate phasing in such taxes, which would likely reduce the negative, short-term impact. Another strategy for reducing the transitional costs is to introduce investment incentives at the same time that the carbon tax is introduced. We examine the effects of such a policy below.

C. EFFECTS OF COMBINING CARBON TAXES WITH INVESTMENT TAX CREDITS

If the entire extra revenue from the carbon tax were used to finance only a general investment credit (which, unlike past investment tax credits, applied to structures as well as equipment), then a credit of about 7 to 10 percent would be revenue-neutral if the energy tax raised $84 billion (with an aggregate investment of approximately $1 trillion). Given the investment elasticities in our VAR model, the credit would lead to about a 2 percent increase in investment (compared to an 18 percent reduction from the energy tax). However, given the elasticities that flow from disaggregated studies—of between 50 and 100 percent (see Hassett and Hubbard 1997 for a review)—the credit could conceivably offset about half of the effect of the completely unanticipated carbon tax. If the carbon tax were gradually phased in, then the two policies could easily be combined in a manner that smoothes out completely the cyclical trough caused by the sudden imposition of the energy tax.

An alternative policy would combine the carbon tax with reductions in corporate income tax rates. This would reduce the cost of capital, but a corporate tax cut will have a smaller impact on investment than an equivalent investment tax credit. This is because the benefits of corporate income tax cuts are spread across the returns on already existing capital and on new investment, whereas the benefits of an ITC are concentrated solely on new investment.

D. EFFECTS OF COMBINING CARBON TAXES WITH PAYROLL TAX CUTS

Hamond et al. (1997) propose combining carbon taxes with reductions in payroll taxes. One motivation for this particular combination of policies is distributional. Payroll tax cuts can be structured to provide benefits to lower-income workers, which would help offset concerns about the regressivity of carbon taxes. See Metcalf 1998 for an analysis of the distributional impact of carbon taxes and related policies.

The effect of this policy combination on investment is likely to be similar to that of a carbon tax analyzed in isolation (as in section B above). If labor is supplied inelastically, workers bear the brunt of the payroll tax, and changes in the payroll tax do not affect firms' labor costs. Under these circumstances, payroll tax cuts would have virtually no impact on the demand for capital goods. This observation accords well with previous work, which generally has found little support for the inclusion of labor-side variables in investment equations (see Hassett and Hubbard 1998 for a discussion) and the labor-supply literature, which generally has found small labor-supply elasticities with respect to wages, especially for men.[3] In contrast, if labor is supplied elastically, the cut in payroll taxes could reduce firm's labor costs and raise employment.

3. This assumption would be violated if one could demonstrate that payroll tax reductions could arguably lead to large macroeconomic changes. Such a case has not, to our knowledge, been made, and is beyond the scope of this paper.

V. TRENDS AND DETERMINANTS OF HOUSEHOLD SAVING

We now turn our attention to household saving issues. Household saving is defined either as the increase in wealth over time or the difference between income and consumption. If wealth, income, and consumption are measured consistently and comprehensively, the alternative definitions would always yield the same answer. However, due to differences and flaws in measurement, different measures often yield very different quantities of saving.

A. RECENT TRENDS

By most measures, personal saving in the United States is low. The personal saving rate, as measured in the National Income and Product Accounts, fell below zero in the first quarter of 1999. This event was preceded by a long decline in personal saving, from about 6 percent of GDP in the 1970s, to 3 percent in the early 1990s to essentially zero at the end of the decade. Adjusting the data in ways that treat retirement accounts, durable goods, inflation, and tax accruals in a manner more consistent with economic theory raises the level of saving and reduces the extent of the decline but still shows a decline. If capital gains are included as saving, then current saving rates are the highest in forty years rather than the lowest. However, whether such gains should be included is controversial (see Gale and Sabelhaus 1999 for a discussion). Low saving is not an artifact of aggregate data in general. Evidence indicates that a significant portion of American households save very little if at all (Bernheim and Scholz 1993; Gale 1997; Poterba et al. 1994).

Low saving rates are a cause for concern for several reasons. At the aggregate level, higher saving facilitates additional capital accumulation, growth, and higher future living standards, unless an economy is small and open. Empirically, countries that tend to grow strongly over long periods of time tend to finance investment with "home-grown" saving. At the household level, saving provides many important benefits: retirement income security; a nest-egg to use for down payments or entrepreneurial activity; a rainy-day fund for uncertain health expenses or drops in income; and the opportunity to make transfers or bequests to family members.

For these reasons, trying to raise the saving rate has been a key goal of policymakers for many years, and the impact on saving is an important component of the analysis of all tax policy, including a tax shift caused by carbon tax hikes. To understand how a tax shift would affect saving, it is useful to examine alternative models of saving and alternative views of why saving fell.

B. MODELS OF SAVING AND REASONS FOR THE SAVING DECLINE

The standard framework for evaluating saving is the life-cycle/permanent-income hypothesis developed by Modigliani et al. in the 1950s. In this model, households are forward-looking, rational decisionmakers who allocate their saving over time to smooth consumption. In simple life-cycle models, people save only for retirement. It is straightforward to add other reasons for saving as well: down payments, precautionary motives, bequests, and borrowing constraints. In any case, the life-cycle model suggests that saving should depend on age, family size, rates of return, current and expected future labor income, the uncertainty of labor wage and consumption expenses, government safety-net programs, inheritances, desired bequests, and the presence of pensions, and Social Security. The life-cycle model, however, is criticized on many grounds: it is computationally too complex to believe the typical household follows its dictates literally, it does not capture saving behavior of the extremely wealthy, aggregate saving patterns are hard to explain in a life-cycle framework, and so on.

Alternative models of saving postulate psychological motives, either mental accounting (Thaler 1994) or hyperbolic discounting (Laibson et al. 1998). In these frameworks, the form of income matters tremendously for saving, but it can also matter in the life-cycle framework as well.

Despite active debate on the best model of saving, there are no convincing explanations for the decline in saving. The main causes put forth in the academic literature and popular press include:

- The rise in intergenerational transfers to the elderly, which reduced the need for retirement saving
- The rise in social safety-net programs, which reduced the need for precautionary saving
- The slowdown in wage growth, which—if people did not adjust their living standards—would have reduced saving
- Financial market liberalization, which made credit cards and debt more widely accessible, and reduced down payment requirements
- Capital gains in the stock market, which raised wealth and, hence, encouraged people to spend more (save less)
- Changes in the form of income toward more cash-oriented forms and away from less liquid forms, which made it easier to spend income

To be clear, many factors have changed over time that are consistent with the decline in saving. But the pattern of the saving decline over time is not well captured by any of the purported causes.

A notable exception from the above list of explanations of the saving decline is taxes. In many ways, in fact, tax policy has increasingly encouraged saving over the last twenty years. Individual Retirement Accounts (IRAs) were widespread before being restricted in the 1986 tax act; 401(k) accounts have proliferated. In 1997, excess taxes were removed from pension payouts, and Roth IRAs were established. The proportion of saving in tax-preferred forms has increased over the past twenty years, while the proportion of saving in other forms has declined.

VI. TAX POLICY AND SAVING BEHAVIOR

A. INCOME TAXES

Three classes of income tax cuts are often considered as ways to raise saving. First, lower tax rates across the board would raise the rate of return on saving and, thus, may encourage people to save more. Conversely, they may also encourage people to save less, since a higher return means that people can reach the same saving target with lower initial contributions. Moreover, the largest effects on income of such tax cuts go to the highest income households, who tend to save the most, and these effects on income are likely to cause reductions in saving. Empirically, tax rates were cut dramatically in 1981 and 1986, and the saving rate fell after both tax cuts.

The second way that taxes can affect saving is through targeted saving accounts. There is significant debate about the extent to which tax-preferred saving incentives raise savings (see Engine et al. 1996; and Poterba et al. 1996). The debate over saving incentives is problematic because it is difficult to determine what households with saving incentives would have saved if they did not have saving incentives. This is a difficult problem because of the heterogeneity of saving noted above. It is also difficult because households with saving incentive accounts tend to be households that save a lot anyway. Our reading of the evidence, however, suggests it is unlikely that the IRA program raised national saving by much, if at all.

The third way taxes could affect saving is through targeted investment incentives, in particular, capital gains tax cuts. Reducing capital gains taxes would raise the return to one form of saving and entrepreneurial activity. However, it would also raise the value of existing assets. This raises the wealth of asset holders and increases their consumption, which would have the perverse effect of reducing their saving. The net effects of these different channels are controversial, but significant amounts of evidence suggest that the saving effect of capital gains tax cuts would be minimal (see the review in Burman 1999).

B. CARBON TAXES

Fuels costs as a percent of total income are significantly higher for low-income households than for high-income households. Evidence on saving behavior indicates that most saving is concentrated in very high income households, and that low-income families' saving rates are nearly zero. Therefore, a rise in the price of energy would be expected to have little effect on the saving behavior of high-income families because their energy expenditures are relatively low, and it would have little effect on the lower-income families because their savings are already nil.

C. PAYROLL TAXES

As noted above, the general presumption in the academic literature is that workers bear the burden of payroll taxes. If this is correct, then a payroll tax cut will result in higher after-tax take-home pay. However, neither an overall cut in payroll taxes or a payroll tax exemption on the first several thousand dollars of earnings would raise saving noticeably for two reasons. First, the cuts would provide no incentive on the margin for the vast majority of households to raise their saving. Second, for many households, the propensity to save is quite low, as discussed above.

D. SUMMARY

Taken together, the results in sections B and C above suggest that the combination of a carbon tax hike and a payroll tax cut would be essentially a "nonevent" for personal saving. Note, however, this does not imply that the tax shift must have no effect on investment. In an open economy, tax changes can induce differing effects on saving and investment, with the difference being made up by international capital flows.

It is probably worth noting that using the carbon tax revenues to pay down the national debt is probably the surest way to raise national saving. All of the possibilities for raising private saving, in contrast, are somewhat suspect.

VII. GENERAL-EQUILIBRIUM EFFECTS

Ultimately, a complete picture of the impact of tax shifting on capital formation will require combining lessons from the results above for saving and investment. However, even at this stage, several comments about the general-equilibrium results are appropriate.

If the United States were a small, open economy, a policy—such as an ITC—that raised U.S. business' demand for capital goods would have no impact on the interest rate. Nor would there be an impact on the price of capital goods, which are set in world markets. The general-equilibrium outcome would look like the partial-equilibrium response. If, on the other hand, the United States were a closed economy, increases in investment demand would create higher capital formation only if savers responded as well.

The empirical literature on *financial* capital mobility begins with Feldstein and Horioka (1980), who first documented that there is a nearly one-to-one correlation between changes in national saving and domestic fixed investment. Many subsequent studies have demonstrated the robustness of this finding. This is a puzzle because it appears to contradict the empirical evidence that international interest rates are closely linked (Frankel 1991), and suggests that the assumption that the savings-investment interaction can be ignored is not fully supported by the literature.

Even if investment funds are imperfectly mobile, capital goods may be quite mobile. Indeed, for most of the past thirty years, the empirical literature relating taxes to investment through the user cost of capital has assumed that firms are price-takers in the market for capital goods (see, e.g., Jorgenson 1963; Hall and Jorgenson 1967; Auerbach and Hassett 1991; and Cummins et al. 1994, 1996). This assumption simplifies empirical work significantly: if the price of capital goods were set in world markets, then one might ignore the response of the price of capital goods to tax policy, and estimation of the parameters of the investment-demand function would not be obscured by this source of simultaneity problems. Because these studies have explored the responsiveness of real investment under the perfectly elastic supply assumption, an upward-sloping supply curve would imply even higher elasticities of investment demand with respect to tax changes than are reported.

Goolsbee (1998) recently explored the link between investment tax policy and capital-goods prices, and found that U.S. prices for capital goods appear to respond to investment incentives. This result also has support in the empirical international economics literature, where "purchasing power parity" is often rejected (see, e.g., Bordo and Choudry 1976; Kravis and Lipsey 1971; and Officer 1986). However, Hassett and Hubbard (1998) show that the result depends on whether the price series used by Goolsbee is stationary. They present evidence that the price series is nonstationary and that under that assumption, the link between taxes and capital goods prices disappears. Thus, general-equilibrium effects are likely to be important to a greater degree with respect to interest rates than with respect to the price of capital goods.

VIII. CONCLUSION

The results of Hamilton (1983) suggest that carbon taxes, operating through increases in the price of energy, could be highly disruptive to the economy, perhaps for macroeconomic reasons that are ignored by the general-equilibrium models employed by those in the double-dividend literature. This paper documents that, to some extent, such concerns are warranted. Energy prices appear to have significant effects on investment, effects that could, if ignored in constructing the tax shift, lead to a significant recession. The effects demonstrated here are statistically significant, and also mesh well with studies in the production-function literature that have studied the complementarity of energy and capital, and with investment studies that argue that (S,s) type stock-adjustment models are most consistent with aggregate investment fluctuations (Caballero et al. 1994).

However, the identification of these effects provides insight as to the type of policies that might be constructed to avoid causing severe harm. Specifically, the introduction of revenue recycling, with the revenues channeled through an investment tax credit, can significantly offset the short-term decline in investment caused by the carbon tax, and can lead, in the long run, to an increased capital stock. Moreover, since the effect of an energy shock is to cause investment to swing sharply downward and then sharply up, there is strong reason to believe that an anticipated shock would require forward-looking firms to smooth their investment plans and soften the short-run blow considerably. An immediate investment credit, combined with a phased in energy tax, might have negligible cyclical effects.

IX. APPENDIX

In this appendix, we review previous work on energy-capital complementarity that followed in the work of Berndt and Wood (1975). Several features of the Berndt and Wood data are noteworthy, in particular because the same data are used repeatedly by others in subsequent years. The relevant variables include P_K (price of capital), P_L (price of labor), P_E (price of energy), P_M (price of other material inputs) and Y (gross output). P_K is a rental price of capital services based on nonresidential structures and producers' durable equipment adjusted for variations in effective tax rates, rates of returns, capital gains, and depreciation. P_L is calculated as total wages divided by man-hours of production and nonproduction workers, adjusted for changes in educational attainment using indexes constructed by Christensen and Jorgenson (1970). P_E and P_M are constructed in a similar manner as P_L, namely total expenditure divided by total quantity. In both of the latter price series, Divisia quantity indexes are constructed from data supplied in Faucett (1973).

Griffin and Gregory (1976) express a number of concerns about Berndt and Wood's findings and employ a nine-country international manufacturing dataset for the years 1955, 1960, and 1965, which they propose is more appropriate because the data are likely to reveal long-run elasticities. Another notable difference in the Griffin and Gregory translog model is a KLE (capital-labor-energy) model rather than the KLEM model of Berndt and Wood because of data availability limitations. Therefore, they impose weak separability between KLE and materials.[4] In addition, the capital cost data for Griffin and Gregory were calculated as a residual (value-added minus wages) rather than using a service-price approach. Concerns over this method will be addressed below in the discussion of Field and Grebenstein (1980). Griffin and Gregory contend that their pooled dataset is more apt to capture long-run elasticities. One motivation of the approach undertaken by Griffin and Gregory is that price volatility using only U.S. data is rather small. Furthermore, the national policies of different countries will affect energy prices significantly and price differences across countries will result in long-run cost function estimations.

4. In their notation, the cost function $\Phi = \Phi(Y, P_K, P_L, P_E, P_M, t)$ can be written $\Phi = \Phi[Y, (_1(P_K, P_L, P_E,) P_M, t]$.

Their results indicate K–E substitutability (Φ_{KE}) for the nine countries ranging between 1.02 and 1.07. Other own-elasticities and cross-elasticities of inputs estimated in Griffin and Gregory have the same signs as in Berndt and Wood. Φ_{KL} estimates range from 0.39 to 0.52 (with the exception of the United States for which $\Phi_{KL} = 0.06$). There is notably less than the 1.01 estimate in Berndt and Wood. Griffin and Gregory note that their results are consistent with other CES KL-elasticity estimates and that intracountry cross-section estimates will be biased toward unity (see Mayor 1969).

Fuss (1977) estimated a multi-input cost function by examining production inputs in Canadian manufacturing firms. Using capital, energy, materials, and six types of energy, he developed a two-stage model in which the energy function is nested within the general production function under the assumption of separable disaggregated factors.

Fuss's results indicate that substantial interfuel substitution is possible and, like Griffin and Gregory, that energy is substitutable with capital. He estimates that a 1 percent increase in aggregate energy prices leads to only a 0.03 percent increase in average production cost. Although he recognizes the inadequacy of a static, rather than dynamic, equilibrium model, Fuss estimates that a doubling of energy prices leads to a 2 to 4 percent increase in average production costs based on a calculated arc elasticity of average cost. However, because the variation in prices in the data is rather small, estimates of the effects of such magnitude may be somewhat suspect.

Magnus (1979) employs a time-series dataset from the manufacturing sector in the Netherlands from 1950 to 1976. Using a generalized Cobb-Douglas (rather than the more common translog) cost function with capital, labor, and energy being the factor inputs, his findings support E-K complementarity findings.

In an attempt to identify the appropriate functional form model, Berndt and Khaled (1979) employ the data used in Berndt and Wood (1975) in a Box-Cox model, which has as special cases the generalized Leontif, generalized least-square quadratic, and translog cost function. They reject constant returns to scale and neutrality of technical change. Notably, technical change has been significantly capital- and energy-using and labor- and intermediate-material saving. Supportive of the findings of Berndt and Wood, the energy-capital complementarity relationship is found to hold for all functional forms. Depending on the Box-Cox specification with regards to assumptions regarding returns to scale and technical change, Φ_{KE} ranges from –3.1 to –1.4. The former results assume homogenous returns to scale, and the latter results assume constant returns to scale, both with no technical change. Another conclusion is, "...higher energy prices have a slight dampening effect of total factor and average labor productivity; however, higher energy prices increase the average productivity of capital and energy, while investment incentives, which lower [the price of capital] increase total factor productivity and decrease the average productivity of energy. Further, due primarily to significant economies of scale, the average productivity of each of the four inputs increases with growth in gross output."

Field and Grebenstein (1980) point out not only the cross-section versus time-series controversy but also the different methodologies employed in calculating cost of capital. Griffin and Gregory, along with Fuss, use a value-added approach (value-added minus payroll) while Berndt and Wood use a service-price approach (quantity of physical capital multiplied by a service price). The first approach includes much more than simply reproducible capital such as working capital, land, and so on. "The different results [of substitutability and complementarity]...could in part be traceable to the fact that two quite different types of capital inputs are involved and these two forms of capital, physical capital and working capital, behave in quite different ways, at least as regards their relationship with energy inputs."

Field and Grebenstein construct a four-input model employing physical and working capital separately along with labor and energy. Materials are not included. Iterative three-stage least-square estimation on a cross-section of ten, two-digit U.S. manufacturing industries indicate that cross-elasticities between physical capital and energy are negative (complements) and significant in four of the ten industries and negative (but not significant) in three industries. The remaining three industries have positive but insignificant cross-elasticities. Therefore, there is no clear evidence that physical capital and energy are substitutes. However, cross-elasticities between working capital and energy are positive in all cases and significant in five of the ten tested industries.

Pindyck (1979) constructs a model similar to Fuss (1977) in which first a fuel-type choice is made to minimize the price of energy and then total costs are minimized by choosing levels of capital, labor, and energy. The data are similar to those used by Griffin and Gregory, namely an international dataset of ten developed countries. Like Griffin and Gregory, no data on material inputs were available, so Pindyck assumes that K, L, and E are weakly separable from materials. Unlike Griffin and Gregory though, Pindyck uses annual data rather than data in five-year intervals. Pindyck finds capital and energy (as well as labor and energy) to be substitutes. Φ_{KE} ranges from 0.36 (U.K.) to 1.77 (U.S.).

Pindyck and Rotemberg (1983) construct a dynamic model that simultaneously estimates a total cost function, an energy cost-share equation, and the Euler equations for capital and labor using three-stage least squares. Their data is that of Berndt and Wood (1975) and unlike Pindyck's previous work with international data, he finds capital and energy to be complements in the long run. Like Berndt and Kahled (1979) they reject the hypothesis of constant returns to scale. Simulation runs of their model include the effect of a 10 percent increase in energy costs (both unexpected and anticipated). Dramatic decreases in the use of energy along with more gradual decreases in capital are observed while labor and material uses increase slightly.

Greene (1980) constructs a flexible frontier production model, based on translog, the production function, and the use of Berndt and Wood's data. His results are nearly identical to Berndt and Wood (1975).

Finally, Thompson and Taylor (1995) summarize elasticity results of a number of previous articles and find the mean Allen Elasticity of Substitution between capital and energy is 0.17, with a variance of 20.60. About 70 percent of the estimates are positive and 30 percent are negative. Thompson and Taylor point out that Morishima elasticity measures (MES) are more appropriate and recalculate the MES based on the estimates of other articles. MES results are far more consistent with the mean $MES_{(EK)}$ of 1.01 and mean $MES_{(KE)}$ of 0.76. The variances are 0.54 and 0.25, respectively. Furthermore, 96 percent and 98 percent, respectively, of the estimates are positive. Clearly, using Morishima elasticities, capital and energy are substitutes.

While it is true that Allen elasticities can be misleading, it is impossible to say whether the Thompson and Taylor results would generalize across all of the types of data discussed here. A cautious conclusion suggests that they would not generalize, and that the evidence appears to support different elasticities, however measured, in the short run and the long run.

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