NOTES

THE CAPITAL-ENERGY SUBSTITUTABILITY DEBATE: A NEW LOOK

Peter Thompson and Timothy G. Taylor*

Abstract—Over the last twenty years, many studies have been made of the elasticity of substitution between capital and labor. The reported estimates are highly variable, and reveal an apparent dichotomy between cross-sectional and time-series studies. The former suggest that capital and energy are substitutes while the latter suggest the converse. All these studies reported Allen partial elasticities of substitution. We suggest that the Morishima elasticity may be a more useful measure for the issues of concern to capital-energy substitution. We calculate the Morishima elasticities from parameters estimated in a selection of earlier studies and find no excessive variability, nor any evidence of the time-series/cross-section dichotomy. Capital and energy are Morishima substitutes.

Concern with the elasticity of substitution between capital and energy, σ_{KE}, became evident after the first energy crisis of 1973 and continued through the 1970s and 1980s, during which time a large number of estimates have appeared. The relationship between capital and energy employment in production was considered important in view of the uncertainty regarding future energy prices and availability. If capital and energy are complements, increases in prices would perhaps induce a reduction in the demand for capital goods, thereby stifling growth. In contrast, if capital and energy are substitutes, rising energy prices would instead stimulate the demand for capital.

Since the first oil-price shock at least fifty studies of *K-E* substitutability have appeared in the literature. As many of these studies were recently reviewed by Apostolakis (1990), and Kintis and Panas (1989), we do not intend to describe their findings in detail. The salient features are now well known:

(1) The estimates of the elasticity of substitution are highly variable between sectors and countries, and across time. For example, Anderson's (1981) estimates of the aggregate σ_{KE} for U.S. manufacturing doubled between 1960 and 1971, from -0.68 to -1.39. Denny et al. (1981) report estimates at the two-digit level for Canadian and U.S. industries. In many industries (e.g., textiles, wood, paper, rubber and metal fabricating), capital and energy are revealed to be substitutes in one country and complements in the other.[1]

(2) There appears to be a dichotomy between estimates constructed from time-series data and those obtained using cross-sectional data. In the former, a greater proportion of the estimates indicate that capital and energy are complements, while in the latter substitutability is more common.[2]

Considerable effort has been expended in attempting to explain these results. Griffin and Gregory (1976) and Apostolakis (1990) argue that time-series data reflect short-term effects, while cross-sectional studies capture equilibrium, or long-run, relationships. Other authors have focused on the possibility of misspecification and measurement errors, among them missing factors (Berndt and Wood, 1975), variations in the definitions of capital (Field and Grebenstein, 1980) and its cost (Berndt, 1976), time-varying parameters (Debertin, et al., 1990), and non-neutral technical change (Griliches, 1967). However, as Apostolakis notes "this substantial controversy has not yet been resolved" (1990, p. 55).

In virtually all of these studies conclusions have been based on estimates, derived from three- and four-input cost and production functions, of Allen partial elasticities of substitution (AES) which are defined in terms of the cost function as

$$AES_{ij}(y,w) = \frac{C(y,w)C_{ij}(y,w)}{C_i(y,w)C_j(y,w)} \tag{1}$$

where subscripts denote partial derivatives. The Allen elasticity measures the percentage change in the quantity of input i demanded given a 1% change in the price of input j, with output and the prices of all other inputs held constant. It is easy to show (see, for example, Chambers (1988), pp. 95–96) that AES_{ij} is equivalent to the cross-price elasticity of conditional factor demand, ϵ_{ij} divided by the cost share of input j, S_j.

When there are more than two inputs, of course, there is no unique measure of substitutability, and the best choice of elasticity measure depends on the pur-

Received for publication August 24, 1992. Revision accepted for publication January 10, 1994.

* Monterey Institute of International Studies and University of Florida, respectively.

We are grateful to an anonymous reviewer for very helpful suggestions.

[1] See table 1, column 5.

[2] See Apostolakis (1990), Kintis and Panas (1989), and Griffin and Gregory (1976) for a discussion of this dichotomy.

pose for which it is intended. As Samuelson (1973, p. 771) has suggested, the elasticity of substitution is "merely [a name given] to effects that need to be measured." We suggest, however, that the Allen partial elasticity does not measure the effect of greatest interest in the capital–energy substitutability debate.

We offer two reasons. The first is that energy shares of total costs tend to be very small, considerably less than 3% of total costs and less than 10% of value added in most industries (see, for example, Denny et al. (1981), p. 248 and Halvorsen and Ford (1979), p. 52). Thus, relatively small variations in energy utilization will induce sizable variations in estimates of the Allen elasticity of substitution. This has indeed been a major characteristic of estimates to date.

The second reason is that *any* elasticities of substitution are not, by themselves, sufficient statistics to predict the response of growth and employment to changes in the price of an input. Changes in output of different sectors are not analyzed, because output is held constant in the calculation of elasticities. In view of the fact that the major impetus behind the studies of capital–energy substitutability was concern about impending restrictions on the supply of energy, a more useful measure of elasticity might be one which measures the response of the K/E ratio, rather than the change in K, to changes in price. Thus, with energy supply fixed at some level, an increase [decrease] in the share of capital would indicate an increase [decrease] in the demand for capital.

A more useful measure, then, is the *Morishima* elasticity of substitution, developed independently by Morishima (1967) and Blackorby and Russell (1975). Defined in terms of the cost function as

$$MES_{ij}(y,w) = \frac{w_i C_{ij}(y,w)}{C_j(y,w)} - \frac{w_i C_{ii}(y,w)}{C_i(y,w)} \qquad (2)$$

the Morishima elasticity measures the percentage change in the ratio of input j to input i when the price of input i alters.

As Blackorby and Russell (1989) argue, the MES is a natural generalization of the two-factor elasticity of substitution function which accurately measures changes in factor shares. As a definition of K-E substitutability, it has a further advantage, because it can also be written as

$$MES_{ij}(y,w) = \epsilon_{ji}(y,w) - \epsilon_{ii}(y,w) \qquad (3)$$

and thus it is not sensitive to the small, but variable, share of energy in total cost. Furthermore, it is easy to see from (3) that while a pair of inputs which are Allen substitutes must also be Morishima substitutes, the converse does not hold.[3] One might expect, therefore, that estimates of the MES between K and E will be less variable than their corresponding AES measures, and that one is likely to see a greater proportion of estimates indicating that K and E are substitutes.

To show that this is indeed the case, we summarize in table 1 the AES estimates reported in eight major studies of energy–capital substitutability. The studies are based on a mixture of time-series and pooled cross-sectional data and are intended to capture the dichotomy analyzed by Apostolakis.[4] In total, 92 elasticity estimates are tabulated.[5] The reported AESs are indeed highly variable with a variance of 20.60, and although they range between -22.40 and 18.60, they are sufficiently scattered around zero (70% of the estimates were positive and 30% negative) that the mean AES was just 0.17. Clearly, on the basis of the AES, there is quite a need for reconciliation of the evidence.

A markedly different conclusion arises when the MESs are calculated. Column 6 of table 1 reports our calculations of the Morishima elasticity of substitution between capital and energy when the price of energy changes, and column 7 reports the MES when the price of capital changes. Note first that out of 148 estimates of the MES, only 4 are negative; that is, over 97% of the estimates point to capital–energy being *substitutes*. Second, observe that the variances of the MES estimates are 0.54 and 0.25, in both cases less than 3% of the variance for the AES estimates. We therefore find that for the MES:

(i) there is no evidence of a dichotomy between cross-sectional and time-series studies,
(ii) the perceived "excessive" variability of elasticity is no longer evident, and
(iii) the evidence indicates that capital and energy are substitutes.

Finally, note that the MES is significantly larger when the price of energy adjusts ($MES_{EK} = 1.01$) than is the case when the price of capital changes ($MES_{KE} = 0.76$). Thus, energy conservation policies designed to stimulate investment in energy-efficient machinery by altering energy prices may be more effective than those

[3] Note, however, that the MES is not invariant to which price is being altered. While this entails the calculation of two MESs, there is an interesting interpretation to differences in the two measures, as we indicate below.

[4] Table 1 includes 5 studies from Apostolakis' table 1 (studies supporting complementarity) and 4 studies from his table 2 (supporting substitutability). One study (Denny et al. (1981)) is in both tables. The choice of studies was determined by the availability of sufficient information to calculate the MES.

[5] Unfortunately, none of the studies listed in table 1 provides sufficient information to allow us to report standard errors for the MES.

TABLE 1.—AES AND MES MEASURES OF CAPITAL-ENERGY SUBSTITUTION

	Conditional Elasticities of Factor Demands				Elasticities of Substitution		
	ϵ_{KK} 1	ϵ_{EE} 2	ϵ_{KE} 3	ϵ_{EK} 4	AES_{KE} 5	MES_{EK} 6	MES_{KE} 7
Anderson (1981)[a]							
U.S. Manufacturing, 1948–71							
1948	−0.18	−0.33	−0.05	−0.06	−0.65	0.28	0.12
1960	−0.22	−0.28	−0.05	−0.06	−0.69	0.23	0.16
1971	−0.02	−0.25	−0.10	−0.09	−1.39	0.15	−0.07
Denny et al. (1981)[b]							
(i) United States, 1948–71							
Food	−0.21	−0.57	0.03		8.05	0.60	
Tobacco	−0.58	−0.01	−0.01		−2.59	0.00	
Textiles	−1.10	−0.19	−0.01		-1.06	0.18	
Apparel	−0.84	−0.36	−0.13		−22.40	0.23	
Wood	−2.18	−1.10	−0.03		−2.07	1.07	
Furniture	−1.27	−0.16	−0.07		−9.29	0.09	
Paper	−0.50	−0.73	−0.06		−2.74	0.67	
Printing	−0.42	−0.69	−0.04		−6.61	0.65	
Chemicals	−0.48	−0.15	0.00		0.00	0.15	
Rubber	−0.29	−0.51	−0.01		−1.21	0.50	
Stone, clay	−0.60	−0.38	−0.04		−1.47	0.34	
Primary metals	−0.52	−0.65	−0.06		2.43	0.59	
Metal fabricating	−1.00	−0.25	−0.09		−9.70	0.16	
Machinery, electrical	−2.15	−0.01	−0.02		−4.09	−0.01	
Machinery	−2.25	−0.16	−0.05		−8.11	0.11	
Motor vehicles	−0.55	−0.13	0.00		0.67	0.13	
Other transport	−1.64	−0.35	−0.05		−9.39	0.30	
Instruments	−0.45	−0.59	−0.01		−1.42	0.58	
(ii) Canada, 1962–75							
Food	−0.86	−0.51	0.08		6.83	0.59	
Tobacco	−0.54	−0.49	−0.00		−1.13	0.49	
Rubber	−0.80	−0.73	0.03		2.50	0.76	
Leather	−0.49	−0.46	0.02		2.45	0.48	
Textiles	−0.68	−0.07	0.01		0.61	0.08	
Knitting Mills	−4.92	−0.77	0.19		18.60	0.96	
Wood	−1.37	−0.43	0.07		3.97	0.50	
Furniture	−0.85	−0.67	−0.00		−0.04	0.67	
Paper	−0.81	−0.51	0.08		1.93	0.59	
Printing	−0.15	−0.57	−0.00		−0.16	0.57	
Primary metals	−1.59	−1.96	0.36		9.60	2.32	
Metal fabricating	−0.27	−0.09	0.00		0.29	0.09	
Machinery	−0.62	−1.47	−0.02		−4.29	1.45	
Transportation equip.	−1.66	−0.69	−0.05		−9.00	0.64	
Electrical	−0.42	−0.52	0.00		0.32	0.52	
Minerals	−0.86	0.00	−0.07		−1.30	−0.07	
Chemicals	−1.11	−2.83	0.46		13.82	3.29	
Miscellaneous	−0.33	−0.87	−0.00		−0.31	0.87	
Griffin and Gregory (1976)[c]							
Manufacturing							
Belgium	−0.38	−0.77	0.17	0.32	1.02	0.94	0.70
Denmark	−0.37	−0.79	0.08	0.39	1.04	0.87	0.76
France	−0.37	−0.80	0.11	0.27	1.05	0.91	0.64
West Germany	−0.36	−0.80	0.10	0.40	1.03	0.90	0.76
Italy	−0.38	−0.79	0.15	0.33	1.03	0.94	0.71
Netherlands	−0.38	−0.78	0.16	0.32	1.02	0.94	0.70
Norway	−0.38	−0.77	0.17	0.33	1.02	0.94	0.71
United Kingdom	−0.37	−0.80	0.12	0.27	1.04	0.92	0.64
United States	−0.18	−0.79	0.13	0.15	1.07	0.92	0.33
Hudson and Jorgenson (1974)[d]							
U.S. Manufacturing, 1947–71	−0.42	0.07	−0.02	−0.18	−1.39	−0.09	0.24
Berndt and Wood (1975)[d]							
U.S. Manufacturing, 1947–71	−0.50	−0.45	−0.14	−0.18	−3.22	0.31	0.32
Berndt and Khaled (1979)[e]							
U.S. Manufacturing, 1947–71	−0.35	−0.71	−0.11	−0.14	−2.46	0.60	0.21

TABLE 1.—(*Continued*)

	Conditional Elasticities of Factor Demands				Elasticities of Substitution		
	ϵ_{KK} 1	ϵ_{EE} 2	ϵ_{KE} 3	ϵ_{EK} 4	AES_{KE} 5	MES_{EK} 6	MES_{KE} 7
Walton (1981)[f]							
U.S. Regions Manufacturing							
(i) Electricity — 1953	−0.18	−1.20	0.00	0.18	0.36	1.20	0.36
— 1959	−0.18	−1.16	0.00	0.25	0.49	1.16	0.43
— 1965	−0.18	−1.13	0.00	0.27	0.57	1.13	0.45
— 1971	−0.15	−1.12	0.00	0.36	0.65	1.12	0.51
SIC 29 — 1953	−0.82	−1.77	0.01	1.07	2.35	1.78	1.89
— 1959	−0.86	−1.60	0.01	0.91	2.11	1.61	1.77
— 1965	−0.87	−1.53	0.01	0.85	2.00	1.54	1.72
— 1971	−0.97	−1.44	0.01	0.72	1.95	1.45	1.69
SIC 32 — 1953	−0.33	−1.09	0.01	0.40	0.76	1.10	0.73
— 1959	−0.33	−1.07	0.01	0.43	0.80	1.08	0.76
— 1965	−0.34	−1.06	0.01	0.42	0.81	1.07	0.76
— 1971	−0.32	−1.06	0.01	0.46	0.83	1.07	0.78
SIC 33 — 1953	−0.24	−3.42	0.00	0.12	0.25	3.42	0.36
— 1959	−0.24	−2.38	0.00	0.17	0.34	2.38	0.41
— 1965	−0.25	−1.98	0.00	0.22	0.47	1.98	0.47
— 1971	−0.23	−2.05	0.00	0.25	0.48	2.05	0.48
Other — 1953	−0.53	−1.12	0.00	0.30	0.99	1.12	0.83
— 1959	−0.53	−1.12	0.00	0.30	0.99	1.12	0.83
— 1965	−0.53	−1.10	0.00	0.30	0.99	1.10	0.83
— 1971	−0.52	−1.09	0.01	0.32	0.99	1.10	0.84
(ii) Fuel							
SIC 28 — 1953	−0.18	−1.20	0.01	0.28	0.57	1.21	0.46
— 1959	−0.18	−1.16	0.00	0.23	0.45	1.16	0.41
— 1965	−0.18	−1.13	0.00	0.21	0.43	1.13	0.39
— 1971	−0.15	−1.12	0.01	0.30	0.54	1.13	0.45
SIC 29 — 1953	−0.82	−1.77	0.01	1.11	2.44	1.78	1.93
— 1959	−0.86	−1.60	0.01	0.95	2.21	1.61	1.81
— 1965	−0.87	−1.53	0.01	0.89	2.10	1.54	1.76
— 1971	−0.97	−1.44	0.02	0.74	2.00	1.46	1.71
SIC 32 — 1953	−0.33	−1.09	0.58	0.58	1.09	1.67	0.91
— 1959	−0.33	−1.07	0.58	0.58	1.09	1.65	0.91
— 1965	−0.34	−1.06	0.58	0.58	1.11	1.64	0.92
— 1971	−0.32	−1.06	0.61	0.61	1.10	1.67	0.93
SIC 33 — 1953	−0.24	−3.42	0.00	0.09	0.18	3.42	0.33
— 1959	−0.24	−2.38	0.00	0.01	0.01	2.38	0.25
— 1965	−0.25	−1.98	0.00	0.04	0.09	1.98	0.29
— 1971	−0.23	−2.05	0.00	0.07	0.13	2.05	0.30
Other — 1953	−0.53	−1.12	0.00	0.40	1.31	1.12	0.93
— 1959	−0.53	−1.12	0.00	0.42	1.38	1.12	0.95
— 1965	−0.53	−1.10	0.00	0.43	1.42	1.10	0.96
— 1971	−0.52	−1.09	0.01	0.46	1.39	1.10	0.98
Turnovsky et al. (1982)[g]							
Australian Manufacturing							
1946–75	−0.94	−0.22	0.06	0.44	2.26	0.28	1.38
Mean	−0.63	−0.96	0.04	0.35	0.17	1.01	0.76
Variance	0.41	0.49	0.02	0.09	20.60	0.54	0.25
Coefficient of variation	-1.01	−0.73	3.44	0.83	26.61	0.73	0.65
Maximum	−0.02	0.07	0.61	1.11	18.60	3.42	1.93
Minimum	−4.92	−3.42	−0.14	−0.18	−22.40	−0.09	−0.07
% of estimates positive					0.70	0.96	0.98
% of estimates negative					0.30	0.04	0.02

Notes:
[a] CRTS translog cost function, KLEM model, IZEF estimation.
[b] It was not possible to calculate MES_{KE} for this study. A dynamic model was estimated to differentiate between LR and SR effects. Estimates based on quadratic cost function with 2-digit U.S. and Canadian data, with a translog submodel for Canada. We report LR estimates only; SR estimates were not available for capital inputs.
[c] Pooled cross-sectional data for 1955–69. Estimates reported for 1965 data.
[d] CRTS translog cost function.
[e] Non-homothetic production function with non-neutral technological change.
[f] Fuel and electricity separated in 5 input cost function.
[g] KLEM translog cost function.

designed to stimulate capital investment through altering the price of capital by means such as an investment tax credit. This result provides empirical support for some conventional wisdom among economists: the most effective way to reduce energy consumption is a tax on energy.

REFERENCES

Anderson, Richard, "Conditional Factor Demand Functions," in E. Berndt and B. Field (eds.), *Modeling and Measuring Natural Resource Substitution* (Cambridge, MA: MIT Press, 1981), 119–144.

Apostolakis, Bobby E. "Energy-Capital Substitutability/Complementarity," *Energy Economics* 12 (1) (1990), 48–58.

Berndt, Ernst R., "Reconciling Alternative Estimates of the Elasticity of Substitution," this REVIEW 58 (1) (1976), 59–68.

Berndt, Ernst R., and Mohammed S. Khaled, "Parametric Productivity Measurement and Choice Among Flexible Functional Forms," *Journal of Political Economy* 87 (6) (1979), 1220–1245.

Berndt, Ernst R., and David O. Wood, "Technology, Prices and the Derived Demand for Energy," this REVIEW 57 (1975), 376–384.

Blackorby, Charles, and R. Robert Russell, "The Partial Elasticity of Substitution," Discussion Paper No. 75-1, Economics Department, University of California, San Diego (1975).

______, "Will the Real Elasticity of Substitution Please Stand Up? (A Comparison of the Allen/Uzawa and Morishima Elasticities)," *American Economic Review* 79 (4) (1989), 882–888.

Chambers, Robert G., *Applied Production Analysis* (Cambridge: Cambridge University Press, 1988).

Debertin, David L., Angelos Pagoulatos, and Abdessalem Aoun, "Impacts of Technological Change on Factor Substitution between Energy and Other Inputs within U.S. Agriculture, 1950–1979," *Energy Economics* 12 (1) (1990), 2–10.

Denny, Michael, Melvyn Fuss, and Leonard Waverman, "Substitution Possibilities for Energy: Evidence from U.S. and Canadian Manufacturing Industries," in E. Berndt and B. Field (eds.), *Modeling and Measuring Natural Resource Substitution* (Cambridge, MA: MIT Press, 1981), 230–257.

Field, Barry C., and Charles Grebenstein, "Capital–Energy Substitution in U.S. Manufacturing," this REVIEW 62 (2) (1980), 207–212.

Griffin, James M., and Paul R. Gregory, "An Intercountry Translog Model of Energy Substitution Responses," *American Economic Review* 66 (1976), 845–857.

Griliches, Zvi, "Production Functions in Manufacturing: Some Preliminary Results," in M. Brown (ed.), *The Theory and Empirical Analysis of Production*, Studies in Income and Wealth 32 (New York: Columbia University Press, 1967), 275–322.

Halvorsen, Robert, and J. Ford, "Substitution among Energy, Capital and Labor Inputs in U.S. Manufacturing," in R. Pindyck (ed.), *The Structure of Energy Markets, Advances in the Economics of Energy and Resources* 1 (Greenwich, CT: JAI Press, 1979), 51–76.

Hudson, Edward A., and Dale W. Jorgenson, "U.S. Energy Policy and Economic Growth," *Bell Journal of Economics* 5 (1974), 461–514.

Kintis, Andreas, and Epaminondas E. Panas, "The Capital-Energy Controversy: Further Results," *Energy Economics* 11 (1989), 201–212.

Morishima, M., "A Few Suggestions on the Theory of Elasticity," *Keizai Hyoron (Economic Review)* 16 (1967), 145–150.

Samuelson, Paul A. "Relative Shares and Elasticities Simplified: Comment," *American Economic Review* 63 (4) (1973), 770–771.

Turnovsky, Michelle, Michael Folie, and Alistair Ulph, "Factor Substitutability in Australian Manufacturing with Emphasis on Energy Inputs," *Economic Record* 58 (1982), 61–72.

Walton, A. L., "Variations in the Substitutability of Energy and Nonenergy Inputs: The Case of the Middle Atlantic Region," *Journal of Regional Science* 21 (3) (1981), 411–420.

ERRATUM

Donald Cox and Mark R. Rank would like to make the following correction to tables 1 and 2 which appeared on pages 309 and 312 of their May 1992 article, "Inter-Vivos Transfers and Intergenerational Exchange" (volume 74, no. 2, pp. 304–314). The authors neglected to include the following footnote to the tables: The inverse Mills ratio term is generated from probit estimation that includes the vector of explanatory variables in column 1 plus median household income in county of residence. These estimations are contained in an appendix available upon request.