

The Factor Bias of External Inputs: Implications for Substitution between Capital and Labor*

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Abstract

This paper reevaluates the longstanding debate on capital-labor substitution by examining the role of external inputs: raw materials, intermediate goods and services, imports, offshoring. Both a meta-analysis (analyzing existing estimates of substitution) and direct estimation (using U.S. data for 1963-2016) indicate that external inputs disproportionately displace labor. These findings imply (1) that the capital-labor ratio responds 40-80% more strongly to the price of labor than to the price of capital, (2) that value added cannot be modeled separably from gross output, and (3) that historical disagreements regarding substitution can be recast as an omitted variable bias involving external inputs.

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1 Introduction

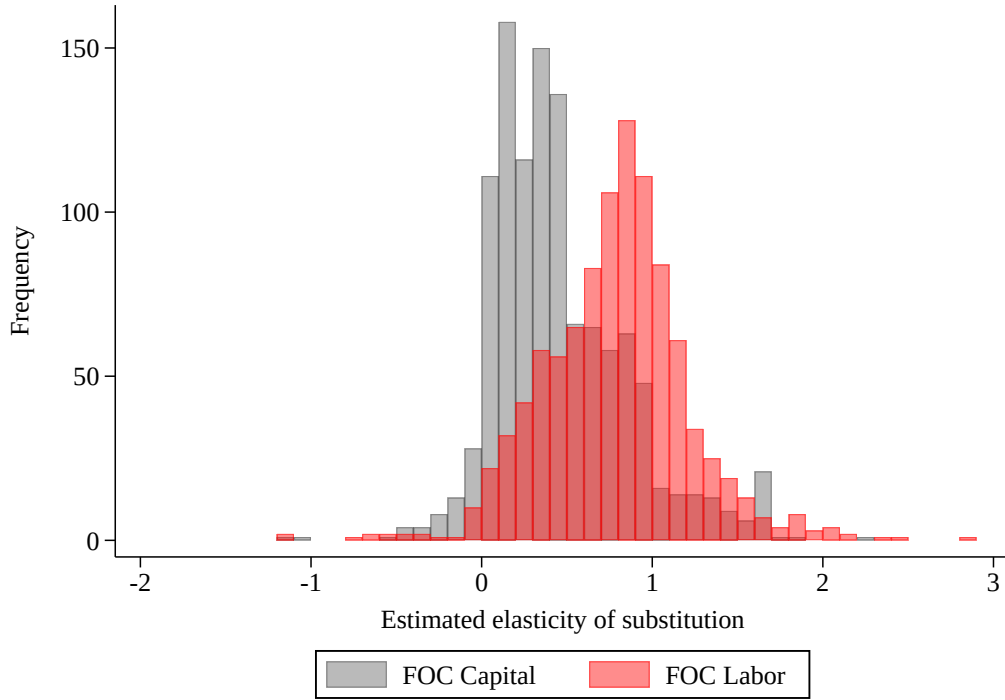
The extent of substitution between capital and labor is fundamental to a host of economic questions. And, yet, existing studies provide support for nearly any conclusion about how capital and labor could be used in production: in fixed proportion, as substitutes or as complements.¹ This paper argues that purchases of inputs external to the firm—raw materials, intermediate goods and services, imports, offshoring—help rationalize these historical disagreements because external inputs can displace capital and labor to differing degrees. For instance, imports from emerging markets like China or purchases of outsourcing services might disproportionately displace labor. At the same time, paying Dropbox for cloud storage might displace a firm’s capital investments, leading it not to purchase data servers of its own. The extent to which external inputs displace capital versus labor shapes the substitution between those two factors.

This paper links external inputs to a firm’s cost-minimizing choice of capital and labor. Under cost minimization, input demands depend solely on relative input prices. In other words, input demands for a given output level are homogeneous of degree zero. A direct implication of this homogeneity, via Euler’s theorem, is that elasticities of the capital-labor ratio with respect to each input price must jointly sum to zero. In a two-input world there are only two elasticities and they are equal in magnitude and opposite in sign: the capital-labor ratio responds symmetrically to a change in the price of labor and to a change in the price of capital. However, introducing external inputs breaks this symmetry by adding new elasticities into the zero-sum constraint, allowing the capital-labor ratio to respond differently to a change in the price of labor and to a change in the price of capital.

Viewed through this lens, the factor bias of external inputs can help rationalize a striking pattern in the historical record of capital-labor substitution: estimates of substitution tend to be larger when estimated using labor-price variation and tend to be smaller when estimated using capital-price variation. Figure 1 illustrates this pattern drawing on 121 studies published since the early 1960s. The red bars—mean 0.85, median 0.81—show the distribution of elasticities from estimating equations based on the first-order condition (FOC) for labor, which rely solely on variation in labor prices. The gray bars—mean 0.45, median 0.38—show elasticities from the FOC for capital, relying solely on variation in capital prices. The difference suggests that the capital-labor ratio is on average 40% more responsive to changes in labor prices than to changes in capital prices. This asymmetry is robust across multiple dimensions, including when focusing on long-run elasticities and when comparing within studies that estimate both specifications on the same data.

¹For an overview of estimates dating back to the 1960s see [Gechert, Havranek, Irsova and Kolcunova \(2022\)](#).

Figure 1: Estimates of Capital-Labor Substitution with Different Price Variation



Note: Data collected by [Gechert et al. \(2022\)](#). FOC capital estimates use capital-price variation. FOC labor estimates use labor-price variation.

The asymmetry in figure 1 arises naturally if external inputs are closer substitutes for labor than for capital. Intuitively, when labor becomes more expensive, firms substitute towards both capital and external inputs, making the capital-labor ratio more responsive to labor prices than to capital prices. Cost minimization—by imposing structure on input demands—suggests an additional test of this hypothesis: if external inputs are more substitutable with labor, a fall in their price should disproportionately displace labor and raise the capital-labor ratio. Moreover, the elasticity of the capital-labor ratio with respect to the price of external inputs should not only be negative, but of a magnitude comparable to the asymmetry in figure 1.

Using data from the BEA and BLS Integrated Production Accounts (IPA), 1963–2016, I document that the U.S. capital-labor ratio rises when the price of intermediate inputs falls—consistent with those inputs disproportionately displacing labor. Using the IPA price index for intermediates (energy, materials and services, both domestic and foreign), I estimate elasticities of the capital-labor ratio ranging in value from -0.4 (using ordinary least squares) to -0.8 (using an instrument based on plausibly exogenous variation in global commodity prices). These elasticities match both the expected negative sign and the ballpark magnitude of the asymmetry in figure 1.

The two sets of results—one from the meta-analysis, the other from the IPA—point in the same direction. Still, external inputs need not be the only force behind the asymmetry in figure 1. The same pattern could arise if the two first-order conditions differ in measurement quality. The user cost of capital, for example, may be measured with more error than the price of labor ([Leon-Ledesma et al., 2010](#)). Differences in modeling and specification choices across studies may also play a role. My aim is to establish factor-biased external inputs as an important channel—one grounded in cost minimization and supported by two independent bodies of evidence—not as the only explanation for the historical record.

These differential responses of the capital-labor ratio are directly policy relevant: for instance, [Chirinko \(2002\)](#) finds that moving from an elasticity of 1 to 0.5 decreases the welfare losses associated with a range of capital taxation policies by 50–79 percent. This change in elasticity is similar in magnitude to the asymmetry in figure 1: it corresponds roughly to switching from using the estimated elasticity with respect to labor prices to the—contextually more appropriate—elasticity with respect to capital prices.

More generally, the results in this paper suggest that there are quantitatively important interactions among external inputs, capital and labor—interactions inconsistent with modeling value added as separable from gross output. This non-separability matters wherever substitution plays a role—from growth accounting to evaluating policies affecting labor and capital costs (e.g., minimum wage, capital taxation, or interest-rate policy). In that sense, this paper contributes to a literature dating back to [Diewert \(1971\)](#) and [Christensen, Jorgenson and Lau \(1973\)](#), which emphasized generalized Leontief and translog specifications as more comprehensively capturing interactions among production inputs. Indeed, estimates from those more general functional forms—including the [Jorgenson, Gollop and Fraumeni \(1987\)](#) precursor to current IPA data—would have been in a position to speak to richer substitution patterns. However, elasticities of substitution were not a widely noted implication as the focus was primarily on the nature and the sources of technical change.

Through its emphasis on the factor bias of external inputs, this paper also contributes to a large literature on capital-labor substitution. On the conceptual front, [Morishima \(1967\)](#) and [Blackorby and Russell \(1989\)](#) generalized the substitutability notions from [Hicks \(1932\)](#) to multi-input settings, allowing the capital-labor ratio to respond differently to labor versus capital prices.² This paper highlights that—under cost minimization—the difference in Morishima elasticities reflects the extent to which external inputs are factor biased. These results also help rationalize disagreements about *relative-price* elasticities—the missing complement to those in figure 1—which are derived from the ratio of capital

²Appendix A provides additional historical context.

and labor FOCs. I formalize concerns about these relative-price elasticities as a form of omitted-variable bias, with external inputs playing a key role.

Prior work noting that capital and labor FOCs yield different estimates assumed that the estimates speak to the same (symmetric) measure of substitution. [Antras \(2004\)](#) notes that this pattern has been observed since at least [Berndt \(1976\)](#). [Leon-Ledesma, McAdam and Willman \(2010\)](#) highlight differential measurement error as a potential explanation, while [Gechert et al. \(2022\)](#) argue the true elasticity lies closer to the estimates from the capital FOC than to those from the labor FOC. By contrast, this paper argues that the estimates from capital and labor FOCs identify two distinct dimensions of substitution. These explanations need not compete. Measurement error, specification and publication choices, and the factor bias of external inputs can all contribute to the dispersion in figure 1. This paper identifies and quantifies the last of these.

Different literatures have focused on different subsets of external inputs. Labor economics studies the outsourcing of specific occupations (e.g., [Abraham and Taylor, 1996](#); [Katz and Krueger, 2018](#)), while international economics emphasizes imports and offshoring (e.g., [Feenstra and Hanson, 1996](#); [Grossman and Helpman, 2005](#)). [Berndt and Wood \(1975, 1981\)](#) found that energy complements capital and substitutes for labor, consistent with the findings emphasized here. This mechanism also fits into work studying the decline of the labor share ([Karabarbounis and Neiman, 2014](#)) and the rising importance of imported inputs, a relationship that is prominently featured in [Elsby, Hobijn and Sahin \(2013\)](#). More recently, [Castro-Vincenzi and Kleinman \(2026\)](#) show that material purchases shape the manufacturing labor share and offer an interpretation based on input complementarity. A key message of the present paper is that understanding substitution between capital and labor requires considering the combined impact of all external inputs.

Moving forward, section 2 draws on cost minimization to guide measurement of external-input bias. Section 3 uses two approaches—a meta-analysis and direct estimation—to quantify this bias. Section 4 discusses implications. Section 5 concludes.

2 Factor Bias of External Inputs: A Stylized Theory

This section links external inputs to capital-labor substitution through cost minimization.

2.1 Zero-Sum Constraint on the Elasticities of Input Demand

Input demands consistent with cost minimization depend only on relative prices and a given output level. In other words, conditional input demands x_i are homogeneous of degree

zero in the input price vector $\mathbf{w}$,

$$x_i(\lambda \mathbf{w}) = x_i(\mathbf{w}), \quad \forall \lambda > 0. \quad (1)$$

Applying Euler's theorem for homogeneous functions to these input demands yields the following constraint:

$$\nabla x_i(\mathbf{w}) \mathbf{w} = 0.$$

The constraint is easier to interpret after unpacking the gradient, which consists of derivatives with respect to all $j \in \mathcal{I}$ input prices w_j ,

$$\sum_{j \in \mathcal{I}} \frac{\partial x_i}{\partial w_j} w_j = 0.$$

Dividing by x_i yields a zero-sum constraint in terms of elasticities:

$$\sum_{j \in \mathcal{I}} \varepsilon_{x_i, w_j} = 0 \text{ with elasticities } \varepsilon_{x_i, w_j} = \frac{\partial x_i}{\partial w_j} \frac{w_j}{x_i}. \quad (2)$$

The zero-sum constraint applies to any input demand or to any transformation of input demands that remains homogeneous of degree zero. Thus, it also applies to the capital-labor ratio. When capital and labor demands are homogeneous of degree zero, increasing all input prices by a factor λ leaves the capital-labor ratio unchanged:

$$\frac{K}{L}(\lambda \mathbf{w}) = \frac{K(\lambda \mathbf{w})}{L(\lambda \mathbf{w})} = \frac{K}{L}(\mathbf{w}).$$

As a result, we see that cost minimization requires that the elasticities of the capital-labor ratio with respect to all input prices must collectively sum to zero:

$$\sum_{j \in \mathcal{I}} \varepsilon_{\frac{K}{L}, w_j} = 0 \text{ with elasticities } \varepsilon_{\frac{K}{L}, w_j} = \frac{\partial \frac{K}{L}}{\partial w_j} \frac{w_j}{\frac{K}{L}}. \quad (3)$$

2.2 External Inputs and Asymmetry in Capital-Labor Dynamics

The zero-sum constraint highlights an understudied relationship that can be important for capital-labor substitution: the elasticity of the capital-labor ratio with respect to the price of

external inputs. To highlight this elasticity, I rewrite the constraint in three terms:

$$\varepsilon_{\frac{K}{L},w_L} + \varepsilon_{\frac{K}{L},w_K} + \underbrace{\sum_{j \notin \{K,L\}} \varepsilon_{\frac{K}{L},w_j}}_{\varepsilon_{\frac{K}{L},w_X}} = 0. \quad (4)$$

The first two terms reflect elasticities that are more commonly discussed. First, $\varepsilon_{\frac{K}{L},w_L}$ reflects the response of the capital-labor ratio to the price of labor, which we expect to be positive. Second, $\varepsilon_{\frac{K}{L},w_K}$ reflects the response to the price of capital, which we expect to be negative. The third term reflects how the capital-labor ratio responds to a change in the price of external inputs. I denote by $\varepsilon_{\frac{K}{L},w_X}$ the net elasticity across external inputs.

Depending on how the capital-labor ratio responds to the price of external inputs, these inputs can be classified as factor neutral or factor biased. In a factor-neutral world $\varepsilon_{\frac{K}{L},w_X}$ is zero so that—if the price of external inputs w_X falls—a firm may purchase more of these inputs but it will keep unchanged its capital-labor ratio. This invariance implies that the capital-labor ratio responds symmetrically to labor and capital prices (i.e., $|\varepsilon_{\frac{K}{L},w_L}| = |\varepsilon_{\frac{K}{L},w_K}|$). Such symmetry arises automatically in two-input models but also holds in multi-input models if the additional inputs are factor neutral. For instance, in a three-input Cobb-Douglas or Constant-Elasticity-of-Substitution (CES) production function, the third input is equally substitutable with capital and labor, making it factor neutral.

By contrast, in a factor-biased world $\varepsilon_{\frac{K}{L},w_X}$ is not zero and a decline in the price w_X would cause the firm to displace capital and labor unequally. If external inputs are thus factor biased, the capital-labor ratio would respond asymmetrically to changes in labor and capital prices (i.e., $|\varepsilon_{\frac{K}{L},w_L}| \neq |\varepsilon_{\frac{K}{L},w_K}|$), providing a way to rationalize the asymmetry in figure 1. I next provide evidence of this factor bias and then return to its implications.

3 External Inputs Displace Labor More than Capital

Motivated by the zero-sum constraint, I measure factor bias using two complementary approaches. First, I compare historical estimates of substitution from studies dating back to the 1960s, showing that estimates based on labor-price variation ($\varepsilon_{\frac{K}{L},w_L}$) are systematically larger than those based on capital-price variation ($\varepsilon_{\frac{K}{L},w_K}$). Second, I estimate factor bias directly ($\varepsilon_{\frac{K}{L},w_X}$) by examining how the capital-labor ratio responds to changes in intermediate input prices.

The two approaches yield consistent results: a decline in the price of external inputs disproportionately displaces labor, increasing the capital-labor ratio ($\varepsilon_{\frac{K}{L},w_X} < 0$). While

each method has its own limitations, together they provide complementary evidence that external inputs are labor-biased in a way that can rationalize the asymmetry in figure 1.

3.1 Measurement Using Historical Estimates

The first approach draws on estimates of capital-labor substitution from 121 published studies dating back to the early 1960s. The underlying dataset, compiled by [Gechert et al. \(2022\)](#) to study publication bias in the substitution literature, contains rich metadata describing the context and specification of each estimate. Notably, the dataset records whether each estimate is derived from the FOC for labor (ε_{FOC_L}) or for capital (ε_{FOC_K}). Optimization implies that each FOC contains only a single factor price: w_L for ε_{FOC_L} and w_K for ε_{FOC_K} .

To infer factor bias, I compare substitution elasticities from ε_{FOC_K} to those from ε_{FOC_L} , using the following specification:

$$\hat{\varepsilon}_{is} = \beta \mathbb{1}(\varepsilon_{FOC_K})_{is} + \delta_s + \text{Constant} + e_{is}, \quad (5)$$

where $\hat{\varepsilon}_{is}$ is elasticity estimate i from study s , $\mathbb{1}(\varepsilon_{FOC_K})_{is}$ is an indicator equal to one for ε_{FOC_K} estimates and zero otherwise, δ_s is a potentially included study fixed effect, and e_{is} is an error term. In this sense, table 1 formalizes and tests the asymmetry visible in figure 1. Given the sample restriction, the Constant reflects the average elasticity using labor-price variation (ε_{FOC_L}), while β captures the difference between ε_{FOC_K} and ε_{FOC_L} . Under cost minimization, β quantifies the factor bias of external inputs, ε_{L,w_X}^K .

This empirical strategy mitigates concerns about the absolute quality of underlying estimates. Identification relies on relative comparisons—and thus on relative quality—of labor-price estimates (ε_{FOC_L}) and capital-price estimates (ε_{FOC_K}). To assuage concerns about relative quality, I examine specific subsets of studies and include study fixed effects, allowing comparison of elasticity estimates within the same study.

The results in table 1 indicate that external inputs are factor biased, disproportionately displacing labor relative to capital. Viewed through the lens of the zero-sum constraint from cost minimization, the estimate in column (1) implies that a 1% decrease in the real price of external inputs displaces labor and raises the aggregate capital-labor ratio by 0.484%. Column (2) applies inverse-variance weighting, giving greater weight to more precise estimates, and implies a larger elasticity of -0.632 . Columns (3)–(5) introduce study-level fixed effects to exploit within-study variation from studies reporting both ε_{FOC_L} and ε_{FOC_K} . The estimated elasticity remains strongly negative, with the point estimate in column (3) falling to -0.330 . Columns (4) and (5) restrict the sample to U.S. data and to manufacturing data, yielding similar results.

Table 1: Quantifying Factor Bias of External Inputs through Meta Analysis

Dependent Variable	Elasticity estimate from a published study (ε_{si})				
	(1)	(2)	(3)	(4)	(5)
Indicator for ε_{FOCK} ($\varepsilon_{\frac{K}{L},w_X} = \varepsilon_{FOCK} - \varepsilon_{FOCL}$)	-0.484*** (0.061)	-0.632*** (0.049)	-0.330*** (0.050)	-0.307*** (0.055)	-0.426*** (0.057)
Constant (ε_{FOCL})	0.892*** (0.127)	0.831*** (0.073)	0.573*** (0.105)	0.600*** (0.108)	0.658*** (0.022)
Study Sample	All	All	All	U.S.	Manuf.
Study FEs	No	No	Yes	Yes	Yes
Weighted	No	Yes	Yes	Yes	Yes
R ²	0.020	0.473	0.632	0.937	0.921
N	1764	1764	1760	952	967

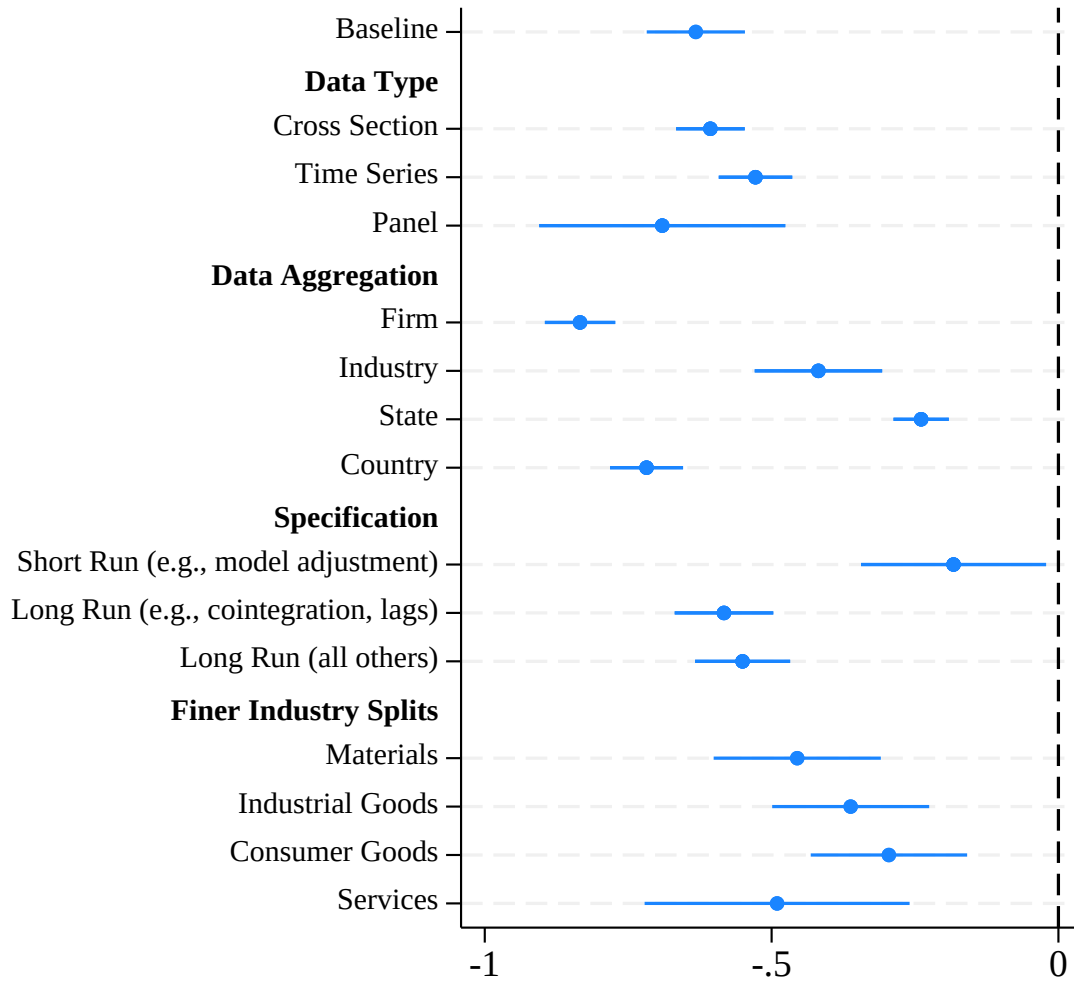
Note: An observation ε_{is} is an individual elasticity estimate i from a published study s . Standard errors are block bootstrapped at the country-by-aggregation-level (firm/industry/state/country) to account for different studies drawing on the same data. The sample includes only estimates based either on the first-order condition for labor or the first-order condition for capital. Weights are defined as the inverse of the variance of the estimate.

Figure 2 further shows that the labor-displacing effect of external inputs is robust across a wide array of study subsamples. The point estimate is negative across all subsamples, indicating that the labor-displacing character of external inputs is not an artifact of any particular data type (cross-section, time series, or panel), aggregation level (firm, industry, state, or country), coarse industry group (materials, industrial goods, consumer goods, services), or time horizon (short-run vs. long-run). The finding that long-run estimates are close to the baseline—and larger than their short-run counterparts—is consistent with substitution operating more fully once labor and capital have adjusted.

3.2 Direct Measurement Using Input Quantities and Prices

I next corroborate the earlier results by showing that changes in the capital-labor ratio are inversely related to changes in external input prices. Specifically, I use the Integrated Production Accounts from the U.S. Bureau of Economic Analysis and the U.S. Bureau of Labor Statistics (1963-2016), which distinguish prices from quantities for production

Figure 2: Estimates of Factor-Biased External Inputs by Subsample



Note: The baseline estimate of factor bias corresponds to the coefficient estimate from column (2) of table 1, where meta-analysis observations are weighted by the inverse of their variance. Subsequent estimates in the figure correspond to the same specification but on the indicated subset of meta-analysis estimates.

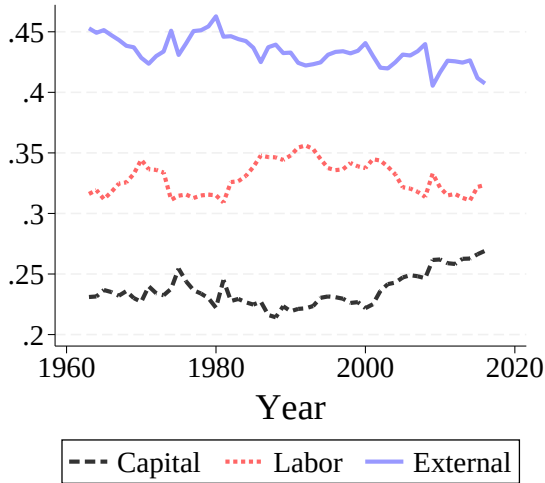
inputs.³

External inputs—defined as all inputs purchased from others—have historically been the largest input expenditure in the U.S. economy, exceeding 40% of gross output since the 1960s. Panel (a) of figure 3 shows the time series of capital, labor, and external input expenditures as shares of gross output. Panel (b) disaggregates external inputs into energy,

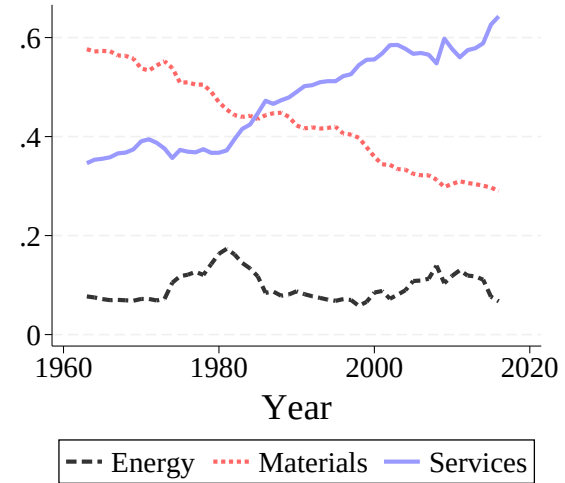
³These accounts follow the KLEMS framework of [Jorgenson, Gollop and Fraumeni \(1987\)](#), separating inputs into capital, labor, energy, materials and services. In practice, the data contain three production inputs: capital, labor, and intermediates (commingling energy, materials and services, both domestic and imported); intermediates are treated here as external inputs. These intermediates capture inter-establishment flows at the industry level and may, in principle, include transfers between establishments of the same parent company alongside arm's-length purchases from other firms.

Figure 3: U.S. Factor Shares

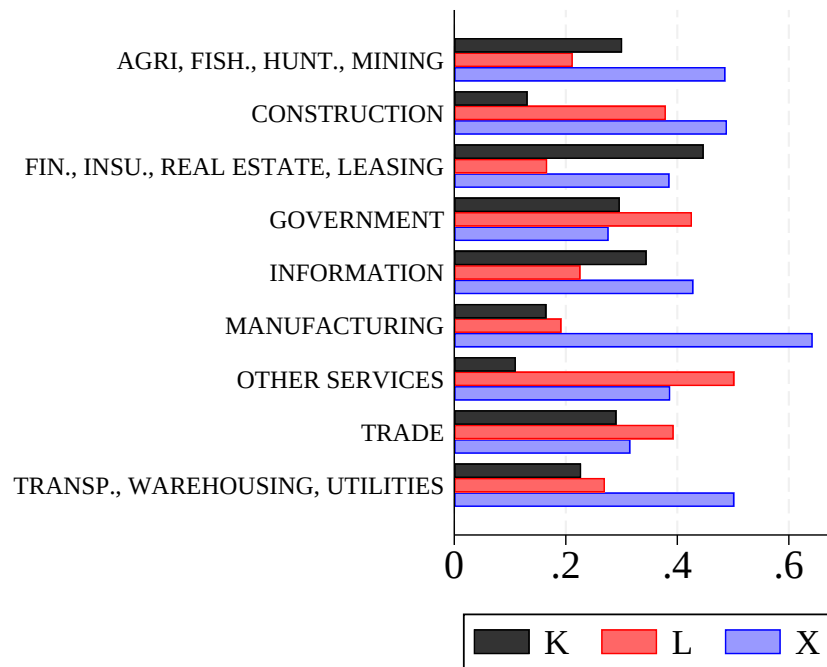
(a) of Aggregate Gross Output, 1963-2016



(b) of Aggregate External Inputs, 1963-2016



(c) of Sectoral Gross Output, 2005



Note: Panels A and C are constructed from the Integrated Production Accounts by the U.S. Bureau of Economic Analysis and the U.S. Bureau of Labor Statistics. Panel B additionally uses the BEA Make and Use tables, as detailed in Appendix C, to partition external inputs into Energy, Materials and Services.

materials, and services, showing that while energy's share has remained relatively stable, services have increased at the expense of materials.⁴ Panel (c) highlights that external input use is widespread across sectors, often exceeding direct expenditures on capital and labor combined.

A key component for directly measuring factor bias is the BEA's price index for intermediate inputs, constructed from annual input-output tables. The index combines input industry prices with weights from these tables and separately deflates domestic and imported components. Capital and labor quantities are quality-adjusted: capital services account for asset heterogeneity (equipment, structures, inventories, land), while labor services adjust hours worked for worker education and experience.

Since the data provide indexes rather than levels, I estimate factor bias in differences:

$$\Delta \ln \frac{K}{L}_{it} = \varepsilon_{\frac{K}{L}, w_X} \Delta \ln \frac{w_X}{p}_{it} + \gamma \Delta \text{Controls}_{it} + \Delta e_{it}. \quad (6)$$

Here, w_X is normalized by the price of gross output p , focusing on real input prices. The controls include other factor prices and fixed effects. Estimating factor bias via OLS requires that external-input prices are not endogenous to U.S. capital intensity. While U.S. demand may influence input prices, the requirement that external input prices are not determined by U.S. capital intensity is potentially less restrictive.

To further address endogeneity, I instrument U.S. external-input prices with an index of global commodity prices. I focus on non-energy commodities, as the United States has historically been a major energy producer; this restriction narrows the list to commodities whose prices likely—but not definitively—reflect global supply and demand rather than U.S. capital intensity. Using World Bank data, I construct the following instrument:

$$\Delta \ln p_t^{com} = \sum_j \omega_j \times \Delta \ln p_{j,t}^{com}, \quad (7)$$

where $p_{j,t}^{com}$ is the real price of commodity j at time t , and ω_j are fixed import weights from U.N. COMTRADE data.

The results in table 2, like those in table 1, suggest that external inputs are factor biased, disproportionately displacing labor. In Panel A, column (1), the elasticity of -0.529 implies that a 1% fall in the real price of external inputs raises the aggregate capital-labor ratio by 0.529%, controlling for changes in capital and labor prices. Because this is a first-difference specification, it is consistent with both Hicks-neutral and factor-biased

⁴Appendix C describes how BEA Make-Use tables were used to partition external inputs into EMS.

Table 2: Direct Estimates of Factor Bias in External Inputs for the United States

Panel A: OLS					
Dep. Variable	$\Delta \ln K/L$	$\Delta \ln K/L$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$
	(1)	(2)	(3)	(4)	(5)
$\Delta \ln w_X/p$	-0.529** (0.268)	-0.750*** (0.257)			
$\Delta \ln w_{X,i}/p_i$			-0.122* (0.071)	-0.228*** (0.074)	-0.214*** (0.075)
Data	Aggregate	Aggregate	Sectoral	Sectoral	Sectoral
Weights	None	None	None	Val. Added	Val. Added
Controls	Yes	Yes	Yes	Yes	Yes
Time Trend	No	Yes	No	No	Yes
R ²	0.240	0.341	0.183	0.238	0.266
N	53	53	477	477	477
Panel B: IV					
Dep. Variable	$\Delta \ln K/L$	$\Delta \ln K/L$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$
	(1)	(2)	(3)	(4)	(5)
$\Delta \ln w_X/p$	-0.889** (0.453)	-0.881** (0.419)			
$\Delta \ln w_{X,i}/p_i$			-0.757** (0.322)	-0.689*** (0.237)	-0.682*** (0.237)
Data	Aggregate	Aggregate	Sectoral	Sectoral	Sectoral
Weights	None	None	None	Va. Added	Va. Added
Controls	Yes	Yes	Yes	Yes	Yes
Time Trend	No	Yes	No	No	Yes
N	53	53	477	477	477
1 st stage F-stat	22.94	25.51	18.37	34.03	32.96
A.R. C.I.s	[-1.9,-.1]	[-1.8,-.3]	[-1.4,-.1]	[-1.2,-.3]	[-1.2,-.3]

Note: An observation is at the country-year level in columns (1) and (2) and at the sector-year level in columns(3)-(5). The instrument is at the country-year level. The data span 1963-2016, and controls include changes in the cost of labor and capital, as well as sector fixed effects for sectoral regressions. Sectoral regressions are either unweighted or weighted by value added (VA). Standard errors are robust to autocorrelation, and sectoral regressions allow for arbitrary clustering following Driscoll-Kraay.

technological change models.⁵ Nonetheless, to accommodate more flexibly differential growth trends in factor-biased technological change, column (2) adds time trends, yielding an even larger elasticity of -0.750 . Panel B reports IV estimates using the commodity-price instrument. The resulting elasticities of -0.889 and -0.881 further reinforce the conclusion that external inputs displace labor. Finally, sectoral regressions in columns (3)–(5) of both panels confirm that this pattern holds broadly across industries.

The online appendixes B and C provide further detail on instrument construction and the sectoral regressions; they also explore heterogeneity in factor bias across energy, materials, and services, and examine robustness to time-varying instrument weights.

4 Three Implications of Factor-Biased External Inputs

This section highlights three implications of the finding that external inputs disproportionately displace labor relative to capital.

4.1 Value Added Cannot Be Modeled Separably from Gross Output

First, the factor bias of external inputs implies that value added cannot be modeled separably from gross output. [Goldman and Uzawa \(1964\)](#) outline conditions under which capital and labor—inputs into value added—are (weakly) separable from an external factor X . These conditions require the capital-labor ratio to be independent of the price of external inputs.

While non-separability can take different forms, a stylized example illustrates the close link between non-separability and factor bias. Consider a firm producing output Y by combining capital K , labor L , and external inputs X using a nested CES technology:

$$Y = \left[K^{\frac{\sigma_{out}-1}{\sigma_{out}}} + \left(L^{\frac{\sigma_{in}-1}{\sigma_{in}}} + X^{\frac{\sigma_{in}-1}{\sigma_{in}}} \right)^{\frac{\sigma_{in}}{\sigma_{in}-1} \frac{\sigma_{out}-1}{\sigma_{out}}} \right]^{\frac{\sigma_{out}}{\sigma_{out}-1}}. \quad (8)$$

The elasticity σ_{out} governs substitution between K and the inner nest, while σ_{in} governs substitution between L and X . It does not matter whether capital or labor is placed in the inner nest. Key to the example is that external inputs are in the inner nest, so that they can potentially be differently substitutable with capital and with labor.

In this example, a value-added subfunction of K and L is separable only when external inputs are equally substitutable with capital and labor ($\sigma_{in} = \sigma_{out}$). Assuming price-taking and cost-minimizing behavior, we can derive elasticities of the capital-labor ratio with

⁵In levels, one would typically include a time trend for factor-biased technological change (e.g., [Diamond, McFadden and Rodriguez, 1978](#); [Antras, 2004](#)). In differences, this trend is absorbed by the constant.

respect to factor prices w_L , w_K , and w_X :

$$\begin{aligned}\varepsilon_{\frac{K}{L}, w_L} &= \alpha\sigma_{in} + (1 - \alpha)\sigma_{out} \\ \varepsilon_{\frac{K}{L}, w_K} &= -\sigma_{out} \\ \varepsilon_{\frac{K}{L}, w_X} &= -(\sigma_{in} - \sigma_{out})\alpha,\end{aligned}$$

where $\alpha = w_X X / (w_L L + w_X X)$ is the share of external inputs inside total inner-nest costs. Only when $\sigma_{in} = \sigma_{out}$ is the capital-labor ratio invariant to the price of external inputs ($\varepsilon_{\frac{K}{L}, w_X} = 0$), allowing capital and labor—and hence value added—to be separable from X in this production function.

However, if external inputs are differentially substitutable with capital and labor ($\sigma_{in} \neq \sigma_{out}$), then the capital-labor ratio depends on the price of external inputs ($\varepsilon_{\frac{K}{L}, w_X} \neq 0$), and a value-added term can no longer be separated from X . In this case, the capital-labor ratio responds asymmetrically to changes in labor and capital prices ($|\varepsilon_{\frac{K}{L}, w_L}| \neq |\varepsilon_{\frac{K}{L}, w_K}|$), helping to explain the asymmetry in figure 1. The results in section 3 suggest that external inputs are distinctly more substitutable with labor than with capital, making $\sigma_{in} - \sigma_{out}$ meaningfully different from zero and likely greater than one.⁶ This degree of non-separability and differential substitution is quantitatively consistent with [Mertens and Schoefer \(2024\)](#), who estimate these elasticities using firm-level German data and show that firms shift from labor to intermediates as they grow. It also echoes [Hubmer, Chan, Ozkan, Salgado and Hong \(2025\)](#), who find that Canadian firms have output elasticities with respect to intermediates that increase with firm size, while those with respect to labor decrease.

More generally, these results caution against first-order approximations of gross-output production functions, as second-order (i.e., interaction) terms with external inputs can be quantitatively important. This paper argues that such interaction terms matter for substitution between capital and labor. In a variety of contexts where this substitution matters—from growth accounting to evaluating policies that affect labor or capital costs (such as changes in the minimum wage, capital taxation, or interest-rate policy)—using non-separable gross-output production functions would align with the evidence presented here and is likely to be quantitatively important.

A concrete example of what is at stake arises in the measurement of markups. A large and active literature infers a firm’s markup—its price relative to marginal cost—as the ratio of a flexible input’s output elasticity to that input’s share in revenue ([Hall, 1988](#)). Putting this idea into practice requires specifying a production function, and a recurring choice

⁶Rearranging the above elasticities: $\sigma_{in} - \sigma_{out} = \frac{(-\varepsilon_{\frac{K}{L}, w_X})}{\alpha}$. In figure 3, α exceeds 0.5, while tables 1 and 2 report $\varepsilon_{\frac{K}{L}, w_X}$ as often -0.5 or smaller. Hence, $\sigma_{in} - \sigma_{out}$ is implied to be above one.

is whether to do so in gross output or in value added. The choice is consequential. A value-added markup is a coherent production object only when value added is separable from intermediates. This is precisely the separability that the factor bias of external inputs rejects. Infer a value-added markup nonetheless, and movements in factor shares that in truth reflect substitution between value-added factors and external inputs are recorded instead as movements in market power. The implication advocated by [Fernald et al. \(2025\)](#) is concrete: markups should be estimated from gross-output specifications and cannot be measured in a way that abstracts from intermediates.

4.2 Relative-Price Elasticities Are Frequently Misspecified

Second, the factor bias of external inputs helps explain why economists systematically disagree not only about substitution estimates from separate first-order conditions—such as those in figure 1—but also about relative-price elasticities, which are often estimated by combining those first-order conditions.

Using the zero-sum constraint (3), we can recast concerns about relative-price elasticities as a case of classical omitted-variable bias involving external inputs. By rewriting the zero-sum constraint as a total derivative that relates changes in the capital-labor ratio to changes in factor prices, and rearranging to see what is measured by the relative-price elasticity $\varepsilon_{\frac{K}{L}, \frac{w_L}{w_K}}$, we obtain:

$$d \ln \frac{K}{L} = \underbrace{\left[\varepsilon_{\frac{K}{L}, w_L} \times \frac{d \ln w_L}{d \ln \left(\frac{w_L}{w_K} \right)} + \varepsilon_{\frac{K}{L}, w_K} \times \frac{d \ln w_K}{d \ln \left(\frac{w_L}{w_K} \right)} \right]}_{\varepsilon_{\frac{K}{L}, \frac{w_L}{w_K}}} d \ln \left(\frac{w_L}{w_K} \right) + \varepsilon_{\frac{K}{L}, w_X} \times d \ln w_X. \quad (9)$$

The bracketed term shows that the relative-price elasticity $\varepsilon_{\frac{K}{L}, \frac{w_L}{w_K}}$ is a weighted average of the two underlying single-price elasticities, $\varepsilon_{\frac{K}{L}, w_L}$ and $\varepsilon_{\frac{K}{L}, w_K}$.

If we were to regress changes in the capital-labor ratio K/L on changes in the relative price w_L/w_K , the estimate will suffer from two sources of omitted-variable bias:

$$\widehat{\varepsilon_{\frac{K}{L}, \frac{w_L}{w_K}}}^{OVB} = \varepsilon_{\frac{K}{L}, w_L} + \varepsilon_{\frac{K}{L}, w_X} \times \underbrace{\left(-\beta_{w_K, \frac{w_L}{w_K}} + \beta_{w_X, \frac{w_L}{w_K}} \right)}_{\beta_{\frac{w_X}{w_K}, \frac{w_L}{w_K}}}, \quad (10)$$

where $\beta_{w_f, \frac{w_L}{w_K}}$ is the projection coefficient of $d \ln w_f$ on $d \ln(w_L/w_K)$. The first source of bias $\beta_{w_K, \frac{w_L}{w_K}}$ concerns the extent to which variation in the relative price w_L/w_K comes from changes in w_K versus changes in w_L . The second source of bias $\beta_{w_X, \frac{w_L}{w_K}}$ concerns the extent

to which the price of external inputs covaries with the relative price w_L/w_K . These biases reflect the fact that—with more than two factors of production—we must consider multiple relative prices.

As a result, estimates of relative-price elasticities can be uninformative about the underlying substitution patterns. For instance, even if the elasticities $\varepsilon_{\frac{K}{L}, w_L}$, $\varepsilon_{\frac{K}{L}, w_K}$, and $\varepsilon_{\frac{K}{L}, w_X}$ were known and constant, the estimated relative-price elasticities would still be dispersed:

$$Variance(\widehat{\varepsilon_{\frac{K}{L}, w_L}}^{OV B}) = \underbrace{(\varepsilon_{\frac{K}{L}, w_X})^2}_{\text{Factor-Biased External Inputs} \times \text{Price Variation}} \times Variance(\beta_{\frac{w_X}{w_K}, \frac{w_L}{w_K}}).$$

This dispersion increases with the magnitude of factor bias $\varepsilon_{\frac{K}{L}, w_X}$ and with the extent to which different studies use different sources of relative-price variation, $\beta_{\frac{w_X}{w_K}, \frac{w_L}{w_K}}$. In the U.S. Integrated Production Accounts, this price covariance $\beta_{\frac{w_X}{w_K}, \frac{w_L}{w_K}}$ is about 0.6 from 1963 to 2016, indicating that the two relative-price changes are positively correlated. When scaled by the labor-displacing effect of external inputs—the estimated $\varepsilon_{\frac{K}{L}, w_X}$ of about -0.5 —this omitted-variable bias would be around -0.3 . Since most estimates of capital-labor substitution tend to be close to—or often below—1, this bias represents quantitatively meaningful uncertainty about the underlying estimates.

4.3 Production Networks Can Modulate Factor Bias

Third, the results in this paper apply at any level of aggregation where capital and labor demand are homogeneous of the same degree. However, their importance at different levels of aggregation can vary and be modulated by reallocation and input-output relationships. This section shows that aggregate factor bias reflects a combination of across-firm reallocation and within-firm factor bias. The results have a parallel in the careful aggregation of substitution elasticities found in [Oberfield and Raval \(2021\)](#).

An aggregate elasticity $\varepsilon_{\frac{K}{L}, w_f}$ with respect to any factor price w_f is comprised of elasticities of relative firm size $\varepsilon_{\frac{L_i}{L}, w_f}$ (reallocation across firms) and elasticities of the capital-labor ratio $\varepsilon_{\frac{K_i}{L_i}, w_f}$ (substitution within firms). This decomposition follows from the fact that aggregate K/L is a weighted average of firms' capital-labor ratios K_i/L_i ,

$$\frac{K}{L} = \sum_i \frac{L_i}{L} \frac{K_i}{L_i},$$

where the weights are each firm's relative size in terms of labor, L_i/L . Differentiating both

sides with respect to a factor price w_f yields:

$$\varepsilon_{\frac{K}{L},w_f} = \sum_i \frac{K_i}{K} \times \varepsilon_{\frac{L_i}{L},w_f} + \sum_i \frac{K_i}{K} \times \varepsilon_{\frac{K_i}{L_i},w_f}. \quad (11)$$

so factor bias can potentially look different in the aggregate $\varepsilon_{\frac{K}{L},w_f}$ and at the firm level $\varepsilon_{\frac{K_i}{L_i},w_f}$ due to reallocation across firms $\varepsilon_{\frac{L_i}{L},w_f}$.

Reallocation can either amplify or attenuate firm-level factor bias. A knife-edge case could see the reallocation term completely offset factor bias at the firm level. For example, suppose manufacturing firms lay off janitors in response to a decline in the price of cleaning services. Within the manufacturing sector, the external input (cleaning) clearly displaces labor disproportionately. However, if cleaning firms—seeking to meet the higher demand—absorb all the displaced labor, the aggregate capital-labor ratio could remain unchanged, even though the lower price of cleaning services clearly displaced labor within manufacturing. In this case, reallocation would fully offset firm-level factor bias, leaving no factor bias at the aggregate level. However, different models of production, input-output structure, and trade—whether domestic or international—can generate different reallocation terms and produce aggregate factor bias. Appendix A provides further details.

5 Conclusion

This paper highlights the critical role external inputs—raw materials, intermediate goods and services, imports, offshoring—play in shaping substitution between capital and labor. In doing so, it provides a framework for measuring the factor bias of external inputs and reconciling historical disagreements in substitution estimates. External inputs need not be the only force at work. Differences across studies in measurement and specification may also shape the estimates in figure 1. The aim in this paper has been to show that factor-biased external inputs are an important part of the explanation.

The finding that external inputs displace labor relative to capital helps explain why firms respond asymmetrically to changes in labor and capital prices. These asymmetric responses have important implications for economic policy, suggesting that policies affecting labor costs—such as changes to the minimum wage—are likely to have more significant pass through into the economy than policies targeting capital costs, such as capital taxation. These asymmetries also suggest that traditional measures of capital-labor substitution may be incomplete or misleading if they fail to account for external inputs. In both respects, the factor bias of external inputs has broad implications for how we understand firm behavior in a globalized economy, where external inputs are playing an increasingly central role in production.

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ONLINE APPENDIX

(NOT FOR PUBLICATION)

A Capital-Labor Substitution: History and Theory

A.1 Historical Context

The study of capital-labor substitution has its roots in early neoclassical production theory, with seminal contributions by [Hicks \(1932\)](#) and [Robinson \(1933\)](#). In these early models, the economy was typically assumed to consist of just two factors—capital and labor—leading to symmetric formulations of the elasticity of substitution. In such settings, the elasticity of substitution between capital and labor captures the responsiveness of the capital-labor ratio to changes in the relative price of labor and capital, and is invariant to which price is perturbed. This framework provided an elegant and tractable way to understand technological choice, but its assumptions implicitly imposed symmetry in factor responses and did not account for more complex production settings involving additional factors or heterogeneous input structures.

Later work expanded this framework to accommodate more than two factors of production. Early efforts to generalize the notion of substitution in multi-input settings include the work of [Hicks and Allen \(1934\)](#), [Allen \(1938\)](#), and [Uzawa \(1962\)](#), who developed symmetric elasticity measures such as the Allen-Uzawa elasticity of substitution. These measures retained the appealing properties of the original two-factor models but imposed symmetry in the cross-effects between input pairs. A key conceptual advance came with [Morishima \(1967\)](#), who introduced an alternative notion of substitution that allowed for asymmetry: the responsiveness of the capital-labor ratio to a change in the price of labor need not equal its responsiveness to a change in the price of capital. These so-called Morishima elasticities of substitution were further formalized by [Blackorby and Russell \(1989\)](#), who clarified how they generalize Hicksian ideas to multi-factor environments.

The focus of the current paper is to emphasize that—under standard assumptions of cost minimization—the difference in these Morishima elasticities speaks to the extent of factor bias of external inputs. In other words, the possibility that capital-labor substitution may differ depending on which input price changes has important implications for both theoretical modeling and empirical measurement of technological change.

A.2 Dynamic input choices

Relative to the zero-sum constraint in the paper—which focuses on static input choices—this appendix explores dynamic input choices. Relative to the static case, the capital-labor ratio in the work below will depend both on the relative price W^L/W^K as well as on the path of investment. To generate asymmetry—for a given change in W^L/W^K —the path of investment would have to differ when the change in W^L/W^K comes from an increase in W^L versus an equivalent decrease in W^K . However, a firm's desire to invest more in, say, capital can arise both from a situation in which labor becomes more expensive as well as a situation in which capital becomes less expensive, suggesting asymmetry is not an immediate consequence of a generalization to dynamic input choices. The rest of the appendix develops this line of reasoning more formally.

Consider a two-factor production function $F(K, L)$ where the firm chooses to maximize the present value of current and expected future net revenues, written recursively as:

$$V_t(K_{t-1}, L_{t-1}) = P_t F_t(K_t, L_t) - W_t^K K_t - W_t^K C_t^K(I_t^K, K_t) - W_t^L L_t - W_t^L C_t^L(I_t^L, L_t) + \psi_t E_t[V_{t+1}(K_t, L_t)].$$

The inputs are hired at rental rates W^K and W^L and evolve following laws of motion:

$$\begin{aligned} K_t &= (1 - \delta^K)K_{t-1} + I_t^K \\ L_t &= (1 - \delta^L)L_{t-1} + I_t^L, \end{aligned}$$

where δ s denote exogenous rates of depreciation and I s denote gross investment/hiring. Each input is potentially subject to adjustment costs $C(\cdot, \cdot)$, expressed as financial costs above and beyond those of production. The expected value $E_t[\cdot]$ conditions on information available at time t and ψ_t is the discount factor of $t + 1$ revenue at time t .

Taking first order conditions with respect to the two state variables (K_{t-1}, L_{t-1}) and the two control variables (I_t^K, I_t^L) , the ratio of the marginal products is:

$$\frac{\frac{\partial F_t}{\partial L_t}}{\frac{\partial F_t}{\partial K_t}} = \frac{W_t^L}{W_t^K} \times \frac{1 + \frac{\partial C_t^L}{\partial I_t^L} + \frac{\partial C_t^L}{\partial L_t} - (1 - \delta^L)\psi_t E_t\left(\frac{W_{t+1}^L}{W_t^L} \frac{\partial C_{t+1}^L}{\partial I_{t+1}^L}\right)}{1 + \frac{\partial C_t^K}{\partial I_t^K} + \frac{\partial C_t^K}{\partial K_t} - (1 - \delta^K)\psi_t E_t\left(\frac{W_{t+1}^K}{W_t^K} \frac{\partial C_{t+1}^K}{\partial I_{t+1}^K}\right)}.$$

To fix ideas, consider a Cobb-Douglas technology $F(K, L) = K^{\alpha^K} L^{\alpha^L}$ and a setting where only capital faces adjustment costs, assumed to be quadratic $C^K(I^K, K) = c^K(I^K)^2/2$. Moreover, to align the dynamic case with the static elasticity concept—where, in the absence

of time, the distinction between temporary and permanent price changes is moot—consider a form of perfect foresight where factor prices can change today but will remain unchanged moving forward. This perfect foresight helps isolate substitution effects from expectations about future price paths. The capital-labor ratio can then be expressed as:

$$\frac{K_t}{L_t} = \frac{W_t^L}{W_t^K} \times \frac{\alpha^K}{\alpha^L} \times \frac{1}{1 + c^K I_t^K \left[1 - (1 - \delta^K) \psi \frac{I_{t+1}^K}{I_t^K} \right]}.$$

If $\frac{W_t^L}{W_t^K}$ increases, the firm would become more capital intensive and $\frac{K_t}{L_t}$ will go up over time. Whether the increase in $\frac{W_t^L}{W_t^K}$ came from W_t^L going up or W_t^K going down would not obviously generate asymmetry in the response of $\frac{K_t}{L_t}$. For a given change in $\frac{W_t^L}{W_t^K}$ to have an asymmetric response to labor becoming more expensive vs to capital becoming less expensive, there would have to be a differential response in capital investment I^K . However, if W_t^L goes up and labor becomes more expensive, the firm would have an incentive to invest more in capital and to shed labor; the same incentives would arise when W_t^K goes down and capital becomes less expensive: the firm would have an incentive to invest more in capital and to shed labor.

These results suggest that—under some circumstances—asymmetry could arise from dynamic input choices. Dynamic forces giving rise to an asymmetry in response to capital and labor price changes could also arise in alternative dynamic settings not examined here—perhaps also from non-convexities or irreversibility in investment—which motivated the empirical work in this paper to focus not only on the asymmetry in figure 1 but also on how the capital-labor ratio responds to changes in external input prices.

A.3 Aggregation and the Factor Bias of External Inputs

To think about the aggregation of factor bias, I start by noting that aggregate capital and labor demand can inherit the homogeneity of the underlying (cost-minimizing) firm-level input demands. Specifically, if firm-level input demands $K_i(w)$ and $L_i(w)$ are homogeneous of degree 0 for all firms i , then aggregate input demands $K(w)$ and $L(w)$ are homogeneous of the same degree. In the context of capital, we have that

$$K(\lambda \mathbf{w}) = \sum_i K_i(\lambda \mathbf{w}) = \sum_i K_i(\mathbf{w}) = K(\mathbf{w}), \quad (\text{A.1})$$

with the same implication holding for aggregate labor demand $L(w)$. As a result of capital and labor demand being homogeneous of degree zero at both the aggregate and the firm

level, the zero-sum constraint on the behavior of the capital-labor ratio from section 2 applies both to the aggregate economy and to the underlying firms.

We can use the above aggregation structure to decompose the response of an aggregate capital-labor ratio to a change in any factor price into two forces: reallocation across firms and substitution within firms. To that effect, note first that the aggregate K/L can be written as a weighted average of firms' capital-labor ratios K_i/L_i ,

$$\frac{K}{L} = \sum_i \frac{L_i}{L} \frac{K_i}{L_i},$$

with the weights being the firm's relative size in terms of labor, L_i/L . We can then differentiate both sides of the expression with respect to a factor price w_f and express the impact on the aggregate K/L ratio as a sum of w_f 's impacts on the relative size of firms L_i/L and on the within-firm capital-labor ratio K_i/L_i :

$$\varepsilon_{\frac{K}{L}, w_f} = \sum_i \frac{K_i}{K} \times \varepsilon_{\frac{L_i}{L}, w_f} + \sum_i \frac{K_i}{K} \times \varepsilon_{\frac{K_i}{L_i}, w_f}. \quad (\text{A.2})$$

The aggregate elasticity $\varepsilon_{\frac{K}{L}, w_f}$ is then comprised of two capital-weighted average elasticities, the elasticity of relative firm size $\varepsilon_{\frac{L_i}{L}, w_f}$ (reallocation across firms) and the elasticity of the capital-labor ratio $\varepsilon_{\frac{K_i}{L_i}, w_f}$ (substitution across firms). Different models of production, input-output structure, trade networks (e.g., domestic or international) would inevitably lead to different interpretations of the reallocation term.

Applied to external inputs, the decomposition suggests that factor bias can potentially look different at the aggregate and at the firm level because of reallocation across firms. For instance, we could have aggregate factor bias driven entirely by reallocation. Consider a world where external inputs are factor neutral for individual firms ($\varepsilon_{\frac{K_i}{L_i}, w_f} = 0 \forall i$) and where these external inputs advantage capital-intensive firms relative to labor-intensive firms. When the price of external inputs falls, demand will increase for the services of the capital-intensive firms, leading to an increase aggregate demand for capital relative to labor. As aggregate K/L rises following a fall in w_X , we then have aggregate factor bias even though none exists at the level of a firm.

More generally, reallocation could either accentuate or attenuate firm-level factor bias. A knife-edge case, for instance, could see reallocation completely undo factor bias at the firm or sector level. Imagine manufacturing firms firing janitors in response to a reduction in the price of cleaning services. Hence, within the manufacturing sector, the external input (cleaning) is clearly displacing labor disproportionately. However, if the cleaning

companies—in a bid to meet the increased demand for cleaning services—simply absorb all the fired factors of production, then the aggregate capital-labor ratio could remain constant even as the decline in the price of cleaning services clearly displaced labor among the manufacturing firms. This knife-edge case would be picked up by a reallocation term that perfectly offsets the labor-displacing bias of external inputs in the manufacturing sector. Conceptually, this case could represent a frictionless closed-economy, where aggregate output is ultimately produced only with capital and labor: production could be factor biased at the level of individual producers, but not for the aggregate economy.

By contrast, imagine that cleaning firms are specialized in cleaning because they can do the work in a more efficient or a more capital-intensive way (e.g., manufacturing firms fire janitors and hire services of cleaning companies employing only Roomba cleaning robots). In this case, the reallocation force could lead more capital-heavy cleaning firms to grow more quickly and reallocation would then reinforce the increase in aggregate capital demand relative to labor. A similar role is played by imports from abroad: if an economy opens to trade, the imported inputs might disproportionately displace labor within domestic companies with consequences for the aggregate capital-labor ratio.

B Data

B.1 BEA-BLS Integrated Production Accounts (IPA)

The IPA data used in the paper comes from a joint effort by the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS) to produce a historical total-economy-production account. This file can be downloaded at: <https://www.bls.gov/productivity/articles-and-research/bea-bls-integrated-production-accounts.htm>, under *Underlying detailed data*. The dataset provides the accounts required for the analysis. For instance, quantity indexes of capital and labor are calculated in the IPA using Törnqvist aggregation:

$$\frac{Q_{K,t}}{Q_{K,t-1}} = \prod_j \left(\frac{q_{K,j,t}}{q_{K,j,t-1}} \right)^{\frac{1}{2} \left(\frac{p_{K,j,t-1} * q_{K,j,t-1}}{p_{K,t-1} * q_{K,t-1}} + \frac{p_{K,j,t} * q_{K,j,t}}{p_{K,t} * q_{K,t}} \right)},$$

where j specifies the type of capital (IT, Software, R&D, Arts and Others), $p_{K,j,t} * q_{K,j,t}$ is the nominal value of input j and $q_{K,j,t}$ its quantity index (both measures provided by the BEA/BLS). The same formulas are used to compute the Törnqvist aggregation index for labor. In that case, index j specifies the type of labor (College and Non-College).

B.2 Global-Commodity Shifter of External Input Prices

The annual commodity prices come from the World Bank (<https://www.worldbank.org/en/research/commodity-markets>). The import data are compiled and published by the United Nations Comtrade database, and available at <https://comtradeplus.un.org/>. U.S. import shares by commodity are constructed based on a concordance mapping SITC codes into the World Bank commodities. Historical yearbooks (primarily from the UN's Food and Agriculture Organization, the U.S. Department of Agriculture, and the U.S. Geological Survey) provide some data on the U.S. share of global commodity production. For instance, in the 1960s and 1970s the U.S. was often one of the dominant global producers of coal, crude oil and natural gas (e.g., U.S. global production shares were often in excess of 25-30%, nearly 2-3 times the average across other commodity categories). While not providing exhaustive coverage for all commodities, this data suggest that U.S. dominance in producing energy commodities stands out, leading to the focus on non-energy commodities (metals, fertilizers, food and agriculture) in the instrument's construction.

C Additional Evidence on Factor Bias in External Inputs

C.1 Weighting of Sectoral Regressions

Table C1 presents evidence that conclusions about the labor-displacing nature of external inputs are not driven by the weighting of sectoral regressions. Both the OLS and the IV panels follow the same structure: the first column presents the baseline specification (weighting by value added), while columns (2)-(4) show estimates from sectoral regressions weighted by gross output, capital and labor. All specifications yield negative point estimates, suggesting that a fall in the price of external inputs leads to a displacement of labor, driving up the capital-labor ratio.

Table C1: Weighting of Sectoral Regressions

Panel A: OLS				
Dep. Variable	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$
	(1)	(2)	(3)	(4)
$\Delta \ln w_{X,i}/p_i$	-0.228*** (0.074)	-0.277*** (0.083)	-0.175** (0.082)	-0.264*** (0.070)
Data	Sectoral	Sectoral	Sectoral	Sectoral
Weights	VA	GO	Capital	Labor
Controls	Yes	Yes	Yes	Yes
R ²	0.238	0.249	0.231	0.244
N	477	477	477	477
Panel B: IV				
Dep. Variable	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$
	(1)	(2)	(3)	(4)
$\Delta \ln w_{X,i}/p_i$	-0.689*** (0.237)	-0.882*** (0.253)	-0.570** (0.226)	-0.777*** (0.245)
Data	Sectoral	Sectoral	Sectoral	Sectoral
Weights	VA	GO	Capital	Labor
Controls	Yes	Yes	Yes	Yes
Time Trend	No	No	No	No
R ²	0.138	0.112	0.149	0.132
N	477	477	477	477
1 st stage F-stat	34.03	38.66	32.12	35.22
A.R. C.I.s	[-1.3,-.3]	[-1.5,-.4]	[-1.1,-.1]	[-1.3,-.3]

Note: An observation is at the sector-year level. The instrument is at the country-year level. The data span 1963-2016, and controls include changes in the cost of labor and capital. Sectoral regressions are weighted by value added (VA), gross output (GO), by capital or by labor.

C.2 Robustness: Time-Varying Instrument Weights

Table C2 presents evidence that conclusions about the labor-displacing nature of external inputs are not driven by the time-invariant nature of the import shares used to construct the instrument. Replacing the fixed weights with a 3-year rolling average of lagged import shares—so that weights are predetermined and reflect recent U.S. import patterns—leaves all estimates negative and statistically significant. No point estimate differs from the corresponding fixed-weight estimate in table 2 by more than 0.13. Panel B confirms the same stability across the four regression-weighting schemes of table C1.

Table C2: Robustness to Time-Varying Instrument Weights

Panel A: IV					
Dep. Variable	$\Delta \ln K/L$	$\Delta \ln K/L$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$
	(1)	(2)	(3)	(4)	(5)
$\Delta \ln w_X/p$	-0.814*	-0.758*			
	(0.450)	(0.410)			
$\Delta \ln w_{X,i}/p_i$			-0.774**	-0.667***	-0.648**
			(0.359)	(0.253)	(0.253)
Data	Aggregate	Aggregate	Sectoral	Sectoral	Sectoral
Weights	None	None	None	Va. Added	Va. Added
Controls	Yes	Yes	Yes	Yes	Yes
Time Trend	No	Yes	No	No	Yes
N	53	53	477	477	477
1 st stage F-stat	23.21	27.36	14.82	28.64	27.45
Panel B: IV, Weighting Robustness					
Dep. Variable	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	$\Delta \ln K_i/L_i$	
	(1)	(2)	(3)	(4)	
$\Delta \ln w_{X,i}/p_i$	-0.667***	-0.868***	-0.551**	-0.751***	
	(0.253)	(0.265)	(0.240)	(0.262)	
Weights	VA	GO	Capital	Labor	
Controls	Yes	Yes	Yes	Yes	
Time Trend	No	No	No	No	
N	477	477	477	477	
1 st stage F-stat	28.64	34.07	27.26	29.64	

Note: The instrument uses a 3-year rolling average of lagged import shares, $\bar{\omega}_{j,t} = \frac{1}{3}(\omega_{j,t-1} + \omega_{j,t-2} + \omega_{j,t-3})$, in place of the fixed weights ω_j used in tables 2 and C1. Panel A replicates the specifications of Panel B of table 2. Panel B replicates Panel B of table C1. All other specification details follow the corresponding tables.

C.3 Unpacking External Inputs into Energy, Materials and Services

The IPA is a KLEMS-style dataset of production accounts that, in theory, decompose inputs into five categories: capital, labor, energy, materials and services. However, the IPA—as is the case with many KLEMS datasets—provides quantity and price indexes for only three categories: capital, labor and intermediates, where intermediates commingles energy, materials and services.

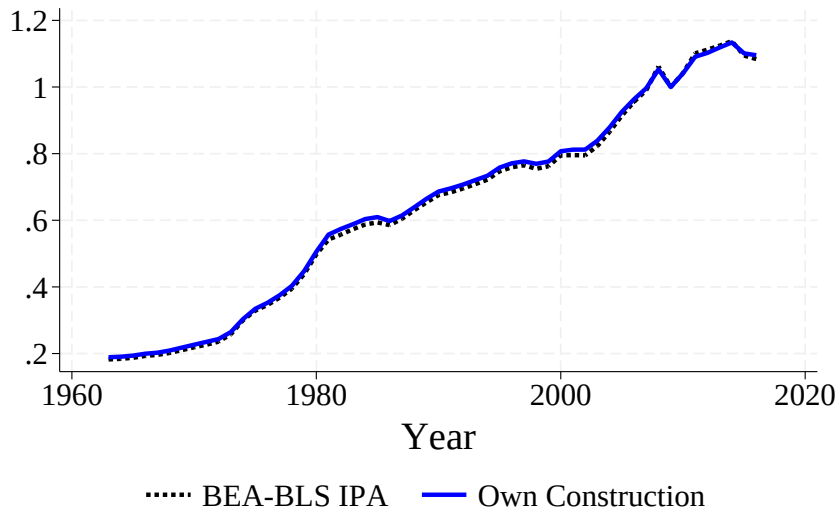
To unpack the intermediates into energy, materials and services, I follow the methodology outlined in previous work by Dale Jorgenson and coauthors (e.g., Jorgenson et al. (1987)). Key to the decomposition are the BEA's historical Make-Use tables (<https://www.bea.gov/industry/input-output-accounts-data>), describing the utilization of each commodity/industry as an input by other industries. The Jorgenson methodology partitions industries into energy, materials and services (as per table C3), making it possible to collapse the Make-Use tables and characterize the shares of energy,

Table C3: EMS Breakdown of the Make-Use Tables

Number	Industry	Sector	Number	Industry	Sector
1	Farms	Materials	32	Truck transportation	Services
2	Forestry, fishing	Materials	33	Transit and ground transportation	Services
3	Oil and gas extraction	Energy	34	Pipeline transportation	Services
4	Mining, except oil and gas	Energy	35	Other transportation	Services
5	Support activities for mining	Energy	36	Warehousing and storage	Services
6	Utilities	Energy	37	Publishing industries, except internet	Materials
7	Construction	Materials	38	Motion picture and sound	Services
8	Wood products	Materials	39	Broadcasting and telecommunications	Services
9	Nonmetallic mineral products	Materials	40	Data processing and internet	Services
10	Primary metals	Materials	41	Federal Reserve banks	Services
11	Fabricated metal products	Materials	42	Securities and investments	Services
12	Machinery	Materials	43	Insurance carriers	Services
13	Computer and electronics	Materials	44	Funds and trusts	Services
14	Electrical equipment	Materials	45	Real estate	Services
15	Motor vehicles	Materials	46	Rental and leasing	Services
16	Other transportation	Materials	47	Legal services	Services
17	Furniture	Materials	48	Computer systems design	Services
18	Miscellaneous manufacturing	Materials	49	Technical services	Services
19	Food and beverage	Materials	50	Management	Services
20	Textile mills	Materials	51	Administrative	Services
21	Apparel and leather	Materials	52	Waste management	Services
22	Paper products	Materials	53	Educational services	Services
23	Printing	Materials	54	Ambulatory health care services	Services
24	Petroleum and coal products	Energy	55	Hospitals and Nursing and residential care	Services
25	Chemical products	Materials	56	Social assistance	Services
26	Plastics and rubber products	Materials	57	Arts	Services
27	Wholesale trade	Services	58	Amusements	Services
28	Retail trade	Services	59	Accommodation	Services
29	Air transportation	Services	60	Food services and drinking places	Services
30	Rail transportation	Services	61	Other services, except government	Services
31	Water transportation	Services	62	Federal	Services
			63	State and local	Services

materials and services among intermediate inputs. Combining gross-output price indexes from IPA with the usage intensities from the Make-Use tables also allows for the construction of Törnqvist price indexes for energy, materials, and services. As a sanity check, I combine those price indexes into the Törnqvist price index for the overall intermediates price index. Figure C1 shows that the index I construct lines up with the index available directly in the BEA-BLS IPA data, providing some reassurance before looking into the EMS subcomponents of that index.

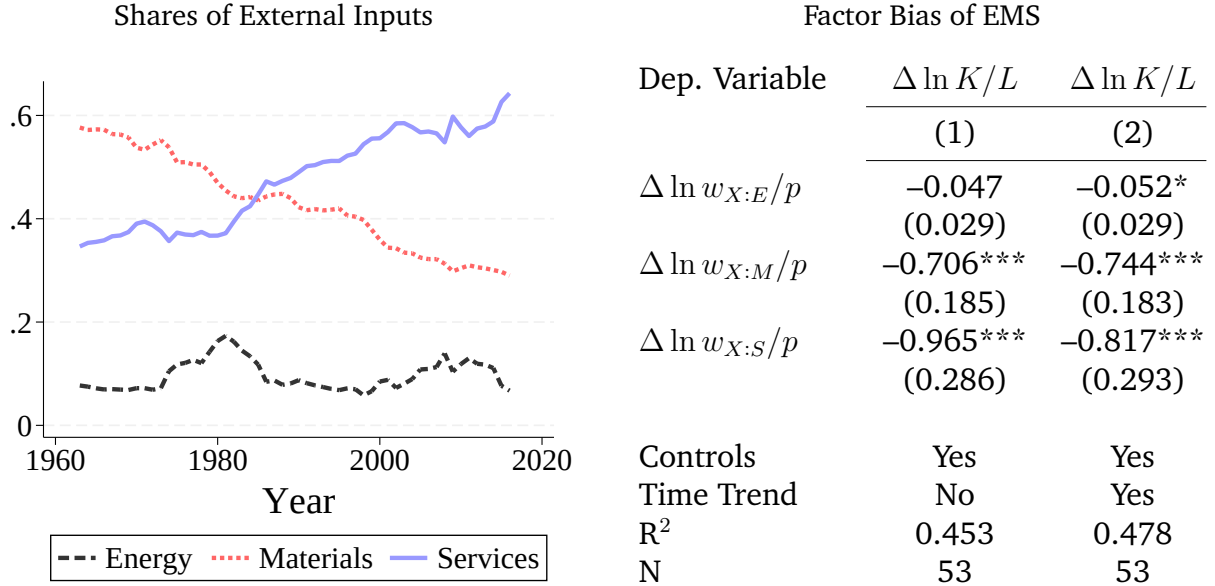
Figure C1: Comparison of (Overall) Intermediate Price Indexes



Unpacking the expenditures on intermediates in panel A of Figure C2 shows that—while the share of energy expenditures in intermediates has stayed relatively stable throughout the years—expenditures on services have risen at the expense of materials. Namely, the share of energy in intermediates has averaged about 15% since the 1960s. Meanwhile, the share of materials has halved, declining from nearly 60% in the 1960s to below 30% by 2016. As materials have fallen in importance, services have steadily risen and now exceed 60% of the overall intermediate bundle.

Panel B of Figure C2 examines the sources of labor-displacing factor bias by using the constructed Törnqvist price indexes for energy $w_{X:E}$, materials $w_{X:M}$ and services $w_{X:S}$. With varying degrees of statistical significance, all three subcomponents of external inputs are shown to be labor-displacing: the negative elasticities suggest that a decline in the price of an external input coincides with a displacement of labor that drives the capital-labor ratio upwards. That said, there is a clear difference in the estimates for the three components, with the coefficient on energy an order of magnitude smaller than the much-more-clearly labor displacing coefficients for materials and services. These patterns are in line with

Figure C2: Decomposing U.S. External Inputs: Energy, Materials and Services



prior literatures that have examined the subcomponents separately: work on factor-energy relationships (Berndt and Wood, 1975, 1981) has long documented a distinct role for energy inputs relative to capital and labor, while research on outsourcing and offshoring highlights how purchased services and imported materials can substitute for domestic labor (e.g., Abraham and Taylor, 1996; Feenstra and Hanson, 1996; Castro-Vincenzi and Kleinman, 2026).

While there is a clear compositional change over time from materials to services in panel A, the results in panel B suggest that both materials and services are labor displacing, suggesting that the overall conclusion about the labor-displacing nature of external inputs is robust within this partition of external inputs.

These results can also provide context for why the relative magnitudes of the OLS estimates from the baseline table 2 tend to be smaller than the IV estimates. To the extent that the commodities used to construct the instrument are primarily inputs into the production of materials (rather than services or energy), the IV estimates are likely to load more strongly on the on-average-larger elasticity for the price of materials $w_{X:M}$.