Substitution in Energy-Economy Models: Using a Hybrid Simulation Model to Estimate U.S. Energy Elasticities

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RESEARCH REPORT

Measuring Substitutability: Elasticity of Substitution

Within economics, "elasticity" refers to how changes in one variable impact another. More specifically, elasticity refers to a measure of the relationship between price and demand for two variables.[3] Economists commonly use elasticity values as a representation of the degree of responsiveness amongst various inputs to production, such as capital, labour, materials, energy, and amongst various forms of energy in response to changes in their prices. Thus, elasticities play a key role within production analysis and various economic models, since they determine the size and direction of demand adjustments that come about from price changes in a given market.

An elasticity of substitution (ESUB) in particular refers to the ratio of relative price changes to relative quantity changes for two inputs. Most relevant for understanding our ability to reduce greenhouse gas emissions are substitution between capital and energy, and between various fuels. Introduced by Hicks[4] and further developed by Allen[5], ESUBs have become fundamental, and highly debated economic parameters. They are useful in various capacities for production analysis, as inputs to economic models, as well as being informative stand-alone indicators of the relationships between pairs of economic inputs. ESUBs indicate the responsiveness of a quantity to a change in price. "Own" price elasticities describe the responsiveness of a quantity of a variable to changes in its price. "Cross" price elasticities on the other hand describe the change in quantity of one variable as a result of changes to the price of another.

ESUBs can be short-run or long-run in nature. Short-run ESUBs indicate responsiveness to price changes over a time horizon that is in general less than a 5-year period. These changes include near-term adaptive responses such as turning off lights more frequently, and changing habits about driving. On the other hand, long-run parameters involve changes in an economy or sector's infrastructure in response to prices, which occur over time spans that allow for the turnover of capital stock, such as the replacement of used equipment and retrofits.[6]

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[3] Ramskov, J., & Munksgaard, J. (2001, February). Elasticities – a Theoretical Introduction. Retrieved December 2010 from Balmorel Project: www.balmorel.com/Doc/B-ElastTheory0201.pdf

[4] Hicks, J. (1932). Theory of Wages. London: Macmillan.

[5] Allen, R. (1938). Mathematical Analysis for Economics. London: Macmillan.

[6] Wade, S. (2003). Price Responsiveness in the AEO2003 NEMS Residential and Commercial Buildings Sector Models. Energy Information Administration .

Energy Substitution: Introduction and Background

The responsiveness of the economy to changes in energy prices is a key concern of policy makers for assessing the ability of price-related policies to reduce greenhouse gas emissions or reduce reliability on certain forms of energy.

Substitution among productive inputs plays an important role in understanding the costs of climate change policy, since substitution possibilities underlie resilience and adaptability in an economy.[1] Assumptions about substitution between forms of energy and other inputs have a large influence on the results of economic models used to study costs. Rigidity in a model tends to magnify economic costs, whereas flexibility tends to reduce them.[2] Jorgenson et al. (2000) outline ways in which producers can substitute among the inputs to production (they note that similar opportunities exist for consumers):

- less carbon-intensive fuels for more carbon-intensive fuels (for example, gas for coal);
- non-fossil energy sources for fossil fuels (nuclear, hydropower, geothermal, solar, and wind for coal, oil, and gas);
- non-energy inputs (materials, labor, and capital) for energy inputs (installing automation and process control equipment);
- energy conserving inputs for highly energy-using inputs (more energy-efficient vehicles, lighting, cooling, heating, production and computing equipment);
- less energy-intensive goods for more energy-intensive goods (greater use of high strength plastics and products made from recycled aluminum and steel);
- more competitive imported goods and services for the now more expensive domestic ones.

[1] Jorgenson, D., Goettle, R., Wilcoxen, P., & Ho, M. (2000). The Role of Substitution in Understanding the Costs of Climate Change Policy. *Pew Center Report* .

[2] There are exceptions, however. For example, substitution rigidity would obscure the increasing energy demands with the depletion of more readily accessible forms of a resource.

Measuring Substitutability: Elasticity of Substitution

Within economics, "elasticity" refers to how changes in one variable impact another. More specifically, elasticity refers to a measure of the relationship between price and demand for two variables.[3] Economists commonly use elasticity values as a representation of the degree of responsiveness amongst various inputs to production, such as capital, labour, materials, energy, and amongst various forms of energy in response to changes in their prices. Thus, elasticities play a key role within production analysis and various economic models, since they determine the size and direction of demand adjustments that come about from price changes in a given market.

An elasticity of substitution (ESUB) in particular refers to the ratio of relative price changes to relative quantity changes for two inputs. Most relevant for understanding our ability to reduce greenhouse gas emissions are substitution between capital and energy, and between various fuels. Introduced by Hicks[4] and further developed by Allen,[5] ESUBs have become fundamental, and highly debated economic parameters. They are useful in various capacities for production analysis, as inputs to economic models, as well as being informative stand-alone indicators of the relationships between pairs of economic inputs. ESUBs indicate the responsiveness of a quantity to a change in price. "Own" price elasticities describe the responsiveness of a quantity of a variable to changes in its price. "Cross" price elasticities on the other hand describe the change in quantity of one variable as a result of changes to the price of another.

ESUBs can be short-run or long-run in nature. Short-run ESUBs indicate responsiveness to price changes over a time horizon that is in general less than a 5-year period. These changes include near-term adaptive responses such as turning off lights more frequently, and changing habits about driving. On the other hand, long-run parameters involve changes in an economy or sector's infrastructure in response to prices, which occur over time spans that allow for the turnover of capital stock, such as the replacement of used equipment and retrofits.[6]

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Interpreting ESUB values is fairly straightforward. Negative values suggest that input pairs are compliments, while positive values suggest that pairs are substitutes. A value of 1 for a pair of inputs (or for an own-price elasticity), for example, indicates that a 1% rise in the relative price of one, will yield a 1% rise in the relative demand for the other—and vice versa. An own-price value of -1, means that a 1% rise in the own-price of an input will lead to a 1% decrease in consumption of that input. Values between 0 and 1, or between 0 and -1 indicate an inelastic relationship and values greater than 1 or less than -1 indicate an elastic relationship. Note that special cases are 0 (perfectly inelastic - a fixed proportion, 'Leontief' relationship), 1 or -1 (unit elastic), and positive or negative infinity (perfectly elastic – indicating perfect compliments/substitutes). Table 1 below offers a useful guide to interpreting quantitative ESUB results qualitatively:

Table 1 – Interpretation of Elasticities

Substitutes	or	***Complements***	***ESUB Value***
0 to 0.3		0 to -0.3	**Highly inelastic**
0.3 to 0.9		-0.3 to -0.9	**Fairly inelastic**
0.9 to 1.1		-0.9 to -1.1	**(Roughly) unit elastic**
1.1 to 2.0		-1.1 to -2.0	**Fairly elastic**
2.0 and above		-2.0 and below	**Highly elastic**

ESUB values are key parameters in 'top-down' general equilibrium models—and in particular in the computable general equilibrium (CGE) class of models. They help to simulate price-dependant energy use responses that relate to changes in technology. Since, in response to price changes, ESUB values indicate the degree of substitutability between any two pairs of production inputs, as well as between different forms of energy/fuels, ESUB values govern how demand adjusts to price changes within these economic models. For example, they indicate how easily one can buy energy-efficient equipment when energy prices rise. Calibrating these parameters is vital to the accuracy of model simulations, and is thus an important part of model design.

The ESUB between energy and capital (E-K) pertains to a particularly important and highly debated relationship, which is indicative of the potential of energy efficiency measures to reduce energy consumption. The idea that we can substitute capital (for example, in the form of the monetary value of more efficient equipment) for energy is widespread, and the debate over the extent to which we can substitute the two inputs is a very complicated—and divisive—topic.[7] Engineers and environmentalists often argue that we can make considerable reductions in energy consumption while maintaining economic output levels, even with possible economic benefits.[8] However, by employing more energy-efficient capital, economists note several possible complicating factors. These include rebound effects such as purchasing a more efficient, but larger television, driving more in light of a more efficient vehicle, or using energy cost savings from energy efficiency improvements to acquire additional goods or services that in themselves use energy.

Seminal papers on the subject of the E-K relationship found conflicting results. Given the importance of accurately portraying substitution in CGE models, determining elasticity of substitution values is very important, and there is little agreement. The brief survey of energy-capital substitution values in a few key studies/models in Table 2 below shows the variation and lack of consensus over the values. A recent comprehensive review[9] of E-K relationships in past literature reinforces that the debate on E-K complementarity/substitutability has not been resolved.

[7] Jaccard, M. (2008). Modeling Energy Use and Technological Change for Policy Makers: Campbell Watkins' Contribution as a Researcher-Practitioner. *The Energy Journal , Special Issue*, 31-42.
[8] Lovins, A. (1977). Soft Energy Paths: Toward a Durable Peace. Friends of the Earth International, San Francisco and Ballinger Publishing, Cambridge, USA.; McKinsey&Company. (2009). Unlocking Energy Efficiency in the US Economy.
[9] Broadstock, D., Hunt, L., & Sorrell, S. (2007). UKERC Review of Evidence for the Rebound Effect - Technical Report 3: Elasticity of substitution studies. *UK Energy Research Center Working Paper* .

Table 2 - Energy-Capital ESUBs

Model/Survey[10]	Sector	Elasticity of Substitution
Time series data (Berndt & Wood, 1975)	U.S. Manufacturing	-3.25
Pooled data (Griffin & Gregory, 1976)	U.S. National	1.07
Time series data (Fuss, 1977)	CAN Manufacturing	-0.10
Pooled data (Pindyck, 1979)	U.S. National	1.77
Time series data (Hunt, 1984)	U.K. Industrial	-1.6
MIT-EPPA (Paltsev, et al., 2005)	U.S. National	0.4 to 0.5
Generated from CIMS-CANADA (Bataille, 2005)	CAN National	0.13
Comprehensive review (Broadstock, Hunt, & Sorrell, 2007)	National	-0.39
	Industrial	-0.23

[10] Berndt, E., & Wood, D. (1975). Technology, Prices, and the Derived Demand for Energy. Review of Economics & Statistics , 57, 259-268.; Griffin, J., & Gregory, P. (1976). An Intercountry Translog Model of Energy Substitution Responses. *The American Economic Review* , 65 (5), 845-857.; Fuss, M. (1977). The Demand for Energy in Candian Manufacturing. *Journal of Econometrics* , 5, 89-116.; Pindyck, R. (1979). Interfuel Substitution and the Industrial Demand for Energy: An International Comparison. *The Review of Economics and Statistics* , 61 (2).; Hunt, L. (1984). Energy and capital: substitutes or complements? Some results for the UK industrial sector. *Applied Economics* , 16 (5), 783-790.; Paltsev, S., Reilly, J., Jacoby, H., Eckaus, R., McFarland, J., Sarofim, M., et al. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. MIT Joint Program on the Science and Policy of Global Change , Technical Report 125.; Bataille, C. (2005). Application of a Technologically Explicit Hybrid Energy-Economy Policy Model with Micro and Macro Economic Dynamics (Vol. PhD Dissertation). Vancouver: Simon Fraser University.;

Estimating Elasticity of Substitution – An Innovative Approach

Traditionally, ESUB values are estimated from time-series data—modellers analyze historical data using econometric techniques to estimate the key parameters that drive their models. While the historic record is the best (because it is the only) true data that a modeller has upon which to base parameters, does historical data carry enough information to accurately portray *future* substitution potential? The future—with different technologies and fuels—may differ from the past in terms of price response. For example, ESUB values between electricity and gasoline, or between ethanol and electricity in personal vehicles are important for understanding future substitution possibilities, however those possibilities were non-existent in the past (and there was not a clear incentive for low-emission technologies). Relying solely on revealed preferences from past markets is dubious when we know that market options are changing. There is a lack of empirical evidence concerning our behaviour when faced with emission reduction issues. As well, in the short-run, external economic shocks such as disruptions to fuel supplies, can lead to confounding effects on prices and quantities of productive inputs used that are difficult to filter out. Thus, the data may be obscuring true future price induced energy responses.

In a recent study, building on previous research by Griffin, Bataille, Jaccard and others,[11] I used the CIMS[12] technology simulation model to produce a set of future 'pseudo-data' reflecting a series of energy-economy simulations under varying fuel prices. CIMS is an integrated simulation/optimization model and policy analysis tool developed by the Energy and Materials Research Group at Simon Fraser University, which is technologically explicit and behaviourally realistic. The model's primary use is to evaluate energy and climate policies and to determine the cost of reducing GHG emissions. CIMS has a detailed representation of technologies that produce goods and services throughout the economy and attempts to simulate capital stock turnover and choice between these technologies in a realistic way. This is accomplished by incorporating stated preferences (via discrete choice surveying techniques) as well as revealed preferences (via analysis of historical market data). It also includes a representation of equilibrium feedbacks, such that supply and demand for energy intensive goods and services adjust to reflect policy.

[11] Bataille, C. (2005). Application of a Technologically Explicit Hybrid Energy-Economy Policy Model with Micro and Macro Economic Dynamics (Vol. PhD Dissertation). Vancouver: Simon Fraser University.; Griffin, J. (1977). The Econometrics of Joint Production: Another Approach. *The Review of Economics and Statistics* , 59 (4), 389-397.
[12] Jaccard, M., Nyboer, J., Bataille, C., & Sadownik, B. (2003). Modeling the Cost of Climate Policy: Distinguishing between Alternative Cost Definitions and Long-Run Cost Dynamics. *The Energy Journal* , *24* (1), 49-73.

This reflects the importance of considering how the macroeconomic evolution of the economy proceeds in terms of structural composition and total output.

By shocking CIMS with a wide range of energy and capital prices, and observing the resulting shifts in use of individual energy inputs and capital, it is possible to gauge the responsiveness of productive inputs to shifts in the input prices. From the resulting model output—a set of 'pseudo data', I used the same econometric techniques that researchers typically apply to time-series data to estimate elasticities of substitution.[13] The methodology that I used is beneficial since it removes issues of confounding data that are often present (and difficult to filter out of) time-series data, and incorporates modern technology options that are not present in time-series or cross-sectional historical data.

Given the particular interest in, and importance of climate policy developments within the U.S., using a U.S. application of CIMS to estimate elasticity of substitution values can provide a check on the values emanating from conventional econometric estimation of historical data.

[13] I estimated transcendental logarithmic (translog) production functions. (Christensen, L., Jorgenson, D., & Lau, L. (1975). Transendental logarithmic utility functions. *American Economic Review* , 65, 367-383.) Translog is the common choice among researchers wishing to look at substitution elasticities. From the translog parameter estimates I calculated a suite ESUB values at national and sectoral scales.

Select Results from the Study and Discussion

My results involve an extensive set of estimated values – one which would be impossible to present in a meaningful way in a research report such as this. I have decided to focus in on a few key and/or interesting results that I found at the **national** scale (though note the CIMS model has detailed sectoral disaggregation, and I investigated relationships at both sector and national scales).

Capital for energy (K for E) ESUB calculations resulted in a fairly inelastic measure of 0.21, indicating only modest potential for long-term substitution from more to less energy-intensive production. While initial work by Berndt and Wood (1975) found complementarity between energy and capital, Griffin and Gregory (1976) found divergent evidence of substitutability (see Table 2 above for the values), and argued that the time-series data used by Berndt and Wood could only elicit short-run elasticities. Following this, in 1979, Berndt and Wood wrote that early contradictory results on E-K substitution were the result of differing data sets, treatments of excluded inputs, and distinctions between short-run and long-run elasticities. Thus, without sufficient time for adjustment to price changes deducible from time-series data sets, findings of complementarity might make sense. Nevertheless, Griffin and Gregory's seminal findings of E-K substitutability reflected their use of data that represented greater variation in prices, and which they argued could, as such, better elicit long-run E-K relationships. My calculations indicated substitutability, however with only a slight opportunity for the long-term substitution between capital and energy. This shows that increases in price-induced energy-efficiency have less potential for the reduction of energy consumption and GHG emissions than some claim (and in particular, less then many engineers and environmentalists believe).

At the national scale, inter-fuel ESUBs exhibited a wide range of values. Natural gas and coal own-price values in both cases were highly elastic, each with a value of -3. According to the result, at the national scale, a 1% rise in the relative price of either input will result in in a 3% decline in its relative demand.

Between individual fuels, I found the electricity for refined petroleum product (RPP) relationship to be moderately inelastic (0.36), and electricity for NG to be close to unit elastic. Electricity's more elastic relationship with natural gas (NG) (1.27) reflects the many instances across the U.S. economy in which electricity and NG can offer similar services—for example for space heating, and providing heat for industrial processes—instances in which RPPs have limited applicability. A result that is somewhat surprising, and seemingly counterintuitive are the complementary relationships that I found between coal and electricity (-0.73), and coal and RPPs (-0.16). These results remain somewhat puzzling, though I speculate that the coal-electricity result is strongly influenced by the predominance of coal in the U.S. electric generation sector, which, consuming nearly the entire share of coal in the economy, may experience a rise in electricity output price and/or decline in output in response to higher coal input prices.

The ESUB experiments revealed some interesting results about energy substitutability in the U.S., about the U.S. version of CIMS, and about the methodology that I used to elicit the elasticities of substitution. While I found modest potential for energy-efficiency changes as a response to varied energy costs, in general, potential for inter-fuel switching seems to be more significant.

Conclusions and Future Research

Energy-economy modeling has played, and continues to play an important role in helping to understand the dynamics of energy substitution in worldwide economies. The methodology which I applied in my research offers a unique, and potentially beneficial, approach to estimating elasticity of substitution parameters for production analysis and for informing top-down models. This overcomes some of the shortcomings of the standard use of parameters estimated from time-series data. While the methodology yielded interesting parameter results, it also serves to assist in CIMS model improvement and diagnostics, exposing potential areas for improvement via unexpected and outlying parameter estimates.

The debate over ESUB parameter values for the United States remains unresolved, with a notable lack of consensus in the literature. In estimating parameters for top-down models, there is always a degree of subjectivity at play, and despite the uncertainty involved with the technique presented in this paper, traditionally estimated top-down model parameters are perhaps at times more arbitrary and less informative than the numbers such as I produced from the CIMS simulation model. It seems that the price-shocking ‘pseudo-data’ methodology manages to overcome some of the shortcomings of the more common time-series and cross-sectional methods for estimating ESUBs, and is certainly worthy of further study.