The Cost of Capital and The Economics of the Environment

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1. Introduction

During the past decade, the economic analysis of environmental policies has undergone a quiet revolution. Prior to the 1990's, empirical studies of environmental regulation were typically static. Many took the total cost of a given regulation in a particular year to be the sum of the regulated firms' direct expenditures on compliance. The most careful studies also included indirect welfare losses caused by changes in the markets upstream and downstream of the point of regulation. Virtually all, however, examined regulation on a year-by-year basis. During the 1990's, however, the pioneering work of Dale Jorgenson on the development and application of large-scale, intertemporal econometric general equilibrium models demonstrated that the most important costs of regulations are often due to their effects on the cost of capital and hence on economic growth. Regulations can raise the cost of new capital goods and hence slow the rate of capital formation and reduce the rate of growth.[1] At the same time, market-based environmental policies, such as emissions taxes, may raise enough new tax revenue to allow capital income taxes to be reduced, possibly lowering the cost of capital and stimulating growth.[2] On the other hand, tax reforms or policies designed stimulate growth by changing the cost of capital can have unintended effects on environmental problems.[3]

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1. Jorgenson and Wilcoxen (1990) show that much of the adverse effect of environmental policy on US economic growth in the 1970's and early 1980's was due to an increase in the price of new capital goods brought about by the regulations.
2. There is a substantial literature on the link between environmental taxes and opportunities for tax reform. We will return to this point below.
3. See Jorgenson and Wilcoxen (1997), for example.

In order to evaluate an environmental policy, therefore, it is essential to determine the effect of the policy on the cost of capital and capital formation. This requires a quantitative model that can capture environmental regulations at a detailed level, trace the effects of those regulations through the economy to determine their influence on the cost of producing new capital goods, and can also determine the effect of the policy on savings and investment. The principal analytical approach possessing these features is large-scale econometric, intertemporal general equilibrium modeling.

Large scale general equilibrium models divide the economy into many sectors in order to measure policy impacts on narrow segments of the economy. This also makes it possible to model differences among industries in responses to changes in energy prices and the imposition of pollution controls. A second dimension for disaggregation is to distinguish among households by level of wealth and demographic characteristics. This makes it possible to model differences in responses to price changes and environmental controls. It is also useful in examining the distributional effects of energy and environmental policies.

Simply having a large number of sectors or households is not sufficient to capture the effects of environment regulations, however. The behavioral parameters appearing in the optimization models used to represent each agent's behavior must be determined. Under the econometric approach to general equilibrium modeling, pioneered by Jorgenson, these parameters are econometrically estimated from painstakingly-assembled historical data. This attention to the empirical basis of each model is the distinguishing feature of Jorgenson's work; most other general equilibrium models are parameterized by "calibrating" them to very limited dataset, such as a single input-output table. Empirical evidence on substitutability among inputs is essential in analyzing the impact of environmental policies. If it is easy for industries to substitute among inputs, the effects of these policies will be very different than if substitution were limited. Although calibration avoids the burden of data collection required by econometric estimation, it also specifies the substitutability among inputs by assumption rather than relying on empirical evidence. This can easily lead to substantial distortions in estimating the effects of environmental policies.

The remainder of this paper will explore the link between environmental policy and the cost of capital. We begin by presenting an overview of the evolution of large-scale general equilibrium modeling. Following that we discuss the structure and features of one such model in detail and then examine the model's results for a particular simulation: a carbon tax designed to hold US carbon dioxide emissions at 1990 levels with revenues from the tax returned through three alternative instruments: a lump-sum rebate, a reduction in the tax rate on capital income, and a reduction in the tax rate on labor. To explore how these results depend on the estimated behavioral parameters in the model, we next examine one of these policies, the carbon tax with an accompanying cut in capital taxes in a somewhat simpler model that can be used to calculate confidence intervals for results based on the covariance matrix of the parameter estimates. We use the model to calculate the policy' s mean equivalent variation (EV) and the corresponding 95% confidence interval. Following this, we conclude with a short summary.

2. The Econometric Approach

The roots of large scale general equilibrium modeling go back to Leontief, who built the first input-output models in the early 1950's.[4] Input-output models are based on the assumption that the behavior of consumers and firms can be represented by fixed-coefficient utility and production functions. This allows technology and preference parameters to be determined from a single inter-industry input-output transactions table. In the 1960' s and 1970's the input-

4. Leontief (1951, 1953).

output approach was extended to incorporate pollution and the use of natural resources, allowing it to be used to examine environmental policy.[5]

The obvious objection to the fixed coefficients approach to modeling energy and environmental policies is that these policies induce changes in the input-output coefficients. In fact, the objective of pollution control regulations is to induce producers and consumers to substitute less polluting inputs for more polluting ones. A prime example is the substitution of low sulfur coal for high sulfur coal by electric utilities and manufacturing firms to comply with regulations on sulfur dioxide emissions. Another important example is the shift from leaded to unleaded motor fuels in order to clean up motor vehicle emissions.

The first successful implementation of an applied general equilibrium model without the fixed coefficients assumption is due to Johansen (1960). Johansen retained the fixed coefficients assumption in modeling demands for intermediate goods, but employed linear logarithmic or Cobb-Douglas production functions in modeling the substitution between capital and labor services and technical change. He replaced the fixed coefficients assumption for household behavior by a system of demand functions originated by Frisch (1959).

Linear logarithmic production functions have the obvious advantage that the capital and labor input coefficients respond to price changes. Furthermore, the relative shares of these inputs in the value of output are fixed, so that the unknown parameters characterizing substitution between capital and labor inputs can be estimated from a single data point. In describing producer behavior Johansen employed econometric methods only in estimating constant rates of technical change. Similarly, the unknown parameters of the demand system proposed by

5. See, for example, Ayres and Kneese (1969), Kneese, Ayres, and d'Arge (1970), or Leontief, Carter, and Petri (1977). Detailed surveys of fixed coefficient input-output models applied to environmental policy, including those of Leontief (1970) and Leontief and Ford (1973), are presented by Forsund (1985) and James, Jansen, and Opschoor (1978).

Frisch can be determined from a single data point, except for one parameter that must be determined econometrically.

The essential features of Johansen's approach were widely adopted in general equilibrium models built in the 1970's and 1980's.[6] Most used a mixture of fixed coefficients and linear-logarithmic functions to represent preferences and technology. The fixed coefficients approach was generally used to model the demand for intermediate goods while linear-logarithmic functions were used to model substitution between capital and labor This approach avoided some of the restrictions imposed by the input-output approach but still permitted behavioral parameters to be determined by "calibration" to a single data point. However, the oil price shocks of the 1970' s provided massive evidence directly contradicting the fixed coefficients assumption for intermediate goods: price-induced energy conservation lead to substantial changes in the ratios of energy to output.[7]

Later models relaxed the unitary substitution elasticity imposed by the linear-logarithmic form by switching to constant elasticity of substitution functions.[8] Such models were usually parameterized by taking substitution elasticities from the literature and then "calibrating" the model by choosing the remaining parameters so that the model would reproduce the given table. The obvious disadvantage of this approach is that highly restrictive assumptions on technology and preferences are required to make calibration feasible. Moreover, calibration causes a model to be affected by peculiarities of the data for the calibration point. By construction, parameters obtained by calibration are forced to absorb all the random errors present in the

6. Surveys of such models include Fullerton, Henderson, and Shoven (1984) and Bergman (1985). Johansen's approach has been used in modeling environmental policies for Norway by Forsund and Strom (1976).

7. Reductions in energy use during the 1970's and 1980's has been documented in great detail by Schipper and Meyers (1992). Reductions in energy-output ratios f or these activities average 15-20 percent. Price-induced energy conservation in the US has been analyzed in greater detail by Hogan and Jorgenson (1991), Jorgenson (1981, 1984b), Jorgenson and Fraumeni (1981), and Jorgenson and Stoker (1984).

8. The constant elasticity of substitution function was proposed by Arrow, Chenery, Minhas, and Solow (1961).

data for a single benchmark year. This poses a severe problem when the benchmark year is unusual in some respect. For example, parameters calibrated to the year 1973 would incorporate into the model all the distortions in energy markets that resulted from price controls and the rationing of energy during the first oil crisis.

Another important limitation of the Johansen approach is that changes in technology are taken to be exogenous. This rules out another important method for pollution abatement by assumption. This is the introduction of changes in technology by redesigning production methods to reduce emissions. An important example is the introduction of fluidized bed technology for combustion, which results in reduced emissions. Gollop and Roberts (1983, 1985) have constructed a detailed econometric model of electric utility firms based on a cost function that incorporates the impact of environmental regulations on the cost of producing electricity and the rate of productivity growth. They conclude that the annual productivity growth of electric utilities impacted by more restrictive emissions controls declined by .59 percentage points over the period 1974-1979. This resulted from switching technologies to meet new standards for air quality.

To represent technologies and preferences that overcome the limitations of the Johansen approach, it is essential to employ econometric methods. Berndt and Jorgenson (1973) pioneered the use of econometric models of producer behavior to generate complete systems of demand functions for inputs of capital, labor, energy, and materials inputs in each industrial sector.[9] Each system gives quantities of inputs demanded as functions of prices and output. The econometric approach was later extended to incorporate endogenous technical change by Jorgenson and Fraumeni (1981).[10] It has been used in general equilibrium modeling by Hudson

9. Surveys of functional forms used in modeling producer behavior have been presented by Fuss, McFadden and Mundlak (1978), Jorgenson (1986), and Lau (1986).

10. Alternative models of endogenous productivity growth are surveyed by Jorgenson (1984a, 1990b). A comprehensive survey of models of producer behavior constructed along the lines of Berndt and Jorgenson (1973) is presented by Jorgenson (1986).

and Jorgenson (1974), Longva and Olsen (1983), Hazilla and Kopp (1986), Jorgenson and Wilcoxen (1990b), Glomsrod, Vennemo, and Johnsen (1992), Kildegaard (1994), and McKibbin and Wilcoxen (1999).[11]

Similarly, econometric models of consumer behavior can be used to overcome the limitations of the Frisch model employed by Johansen. Models stemming from the path-breaking contribution s of Schultz (1938), Stone (1954), and Wold (1953) consist of complete systems of demand functions, giving quantities demanded as functions of prices and total expenditure. Subsequent work, including Christensen, Jorgenson and Lau (1971), has led to the development of flexible functional forms that impose no restrictions on preferences beyond those implied by economic theory.[12]

A difficult issue in modeling consumer behavior is choosing an appropriate level of aggregation. Most general equilibrium models use the representative consumer approach, in which aggregate demand functions are derived by treating the entire household sector as a single maximizing individual. This is a convenient approach but it imposes strong restrictions on the structure of the underlying optimization problems solved by individual households. For example, the simplest set of restrictions under which the representative consumer approach is appropriate is that preferences are identical and homothetic for all consumers.[13] However, there is abundant empirical evidence rejecting these restrictions. Homothetic preferences are inconsistent with well-established empirical regularities in the behavior of individual consumers, such as Engel' s Law, which states that the proportion of expenditure devoted to food is a declining proportion of total expenditure. Identical preferences are inconsistent with empirical

11. Surveys of the literature on the econometric approach to general equilibrium modeling are given by Jorgenson (1982), Bergman (1990), and Hazilla and Kopp (1990). Bergman provides detailed comparisons with alternative approaches to general equilibrium modeling.

12. See Fuss, McFadden and Mundlak (1978) for a survey of flexible functional forms.

13. This set of restrictions is implicit in the linear logarithmic demand systems employed by Stone (1954) and Wold (1953), among others.

findings that expenditure patterns depend on demographic characteristics of individual consumers.[14] Somewhat weaker sets of restrictions for the existence of a representative consumer have been developed but have not been widely used in general equilibrium modeling.[15]

An alternative approach to modeling of aggregate consumer behavior is provided by Lau's (1982) theory of exact aggregation. This approach makes it possible to dispense with the notion of a representative consumer. Under exact aggregation, systems of aggregate demand functions can be shown to depend on statistics of the joint distribution of individual total expenditures and attributes of individuals associated with differences in preferences. A very useful feature of exact aggregation is that systems of demand functions for individuals can be recovered uniquely from the system of aggregate demand functions. This makes it possible to exploit all the implications of the economic theory of the individual consumer in constructing an econometric model of aggregate consumer behavior.

The implementation of an econometric model of aggregate consumer behavior based on the theory of exact aggregation has been carried out by Jorgenson, Lau, and Stoker (1982). Their approach requires time series data on prices and aggregate quantities consumed and cross section data on individual quantities consumed, individual total expenditures, and attributes of individual households, such as demographic characteristics.[16] By contrast the non-econometric approaches of Leontief and Johansen require only a single data point for prices, aggregate quantities consumed, and aggregate expenditure. A general equilibrium model employing this approach has been constructed by Jorgenson and Wilcoxen (1990), which is discussed in detail

14. Reviews of the literature are presented by Deaton and Muellbauer (1980b) and Jorgenson (1990a).

15. See, for example, Gorman (1953), Muellbauer (1975) and Lewbel (1989). Econometric models of aggregate consumer behavior based on the theory of a representative consumer have been constructed by Berndt, Darrough, and Diewert (1977) and Deaton and Muellbauer (1980a, 1980b).

16. The theory of exact aggregation is discussed by Jorgenson, Lau, and Stoker (1982) and Lau (1982). Econometric models based on the theory of exact aggregation are surveyed by Jorgenson (1990a) and Stoker (1993).

in the next section.

3. An Econometric General Equilibrium Model

To show how environmental and energy policy are linked to the cost of capital, we now present a brief discussion of the intertemporal general equilibrium model of the US economy constructed by Jorgenson and Wilcoxen (1990). The production portion of the model is based on the approach originated by Jorgenson and Fraumeni (1981). It includes systems of demand functions for capital, labor, energy, and materials inputs and a model of endogenous productivity growth for each of thirty-five sectors of the US economy. The household portion of the model is based on exact aggregation, rather than the representative agent approach, and includes a system of demand functions for five commodity groups–energy, food, nondurable goods, capital services, and other services.

The empirical foundation of the model is a set of US national accounts data developed and refined over many years by Dale Jorgenson and his colleagues.[17] The critical feature of this data is that it includes fully integrated accounts for capital, including investment, capital accumulation, and capital service flows. Unlike conventional national accounts, this approach links the current flow of capital services to the accumulated stock of capital from all past investments. At the same time, the accounts also link the price of investment goods to expected future prices of capital services.

17. Conventional systems of national accounts, such as the United Nations (1968) System of National Accounts and the US National Income and Product Accounts are unsatisfactory for modeling purposes, since they do not success fully integrate capital accounts with income and production accounts. An aggregate set of fully integrated accounts for the US was constructed by Christensen and Jorgenson (1973). Disaggregation to the industry level was done by Fraumeni and Jorgenson (1980). For more information, see Jorgenson (1980) and Jorgenson (1990b).

The dataset contains annual time-series data on transactions in the US economy over the period from 1947 to 1985. It includes data on sales of intermediate goods between industries at approximately the two-digit SIC level of aggregation (derived from tables produced by the Bureau of Economic Analysis); data on capital and labor income by industry (from the National Income and Product Accounts produced by the Bureau of Economic Analysis) extended as described in Jorgenson, Gollop, and Fraumeni (1987); and integrates the capital accounts described by Jorgenson (1990b) with an accounting system based on the United Nations (1968) System of National Accounts.[18] This extensive dataset allows the parameters of the producer and consumer models to be estimated econometrically.

3.1. Producers

Production is disaggregated into thirty-five industries. Each industry's behavior is modeled as a two-stage cost minimization problem.[19] The first stage determines the industry' s factor demands for each of four aggregate inputs: capital, labor, energy, and materials. The industry's unit cost is taken to be a transcendental logarithmic function of the prices of each of the aggregates.[20] Each unit cost function must be homogeneous of degree one, non-decreasing, and concave in the input prices. These restrictions are incorporated into the system of input demand functions for each industry.[21] The second stage of each cost minimization problem allocates expenditures on aggregate energy and materials to individual commodities.[22] All parameters in each industry' s cost function are estimated using the dataset described above.

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18. Details are given in Wilcoxen (1988), Appendix C.
19. Two-stage allocation in the context of producer behavior is discussed in more detail by Jorgenson (1986) and Blackorby, Primont, and Russell (1978).
20. This approach was introduced by Christensen, Jorgenson, and Lau (1971, 1973).
21. A more detailed discussion of our econometric methodology is presented by Jorgenson (1984a, 1986).
22. The tier structure used for modeling producer behavior is described by Wilcoxen (1988), Appendix A.

An important feature of the production model is that each industry's productivity growth can be biased toward some first stage inputs and away from others. Biased productivity growth is a common feature of historical data but is often excluded from models of production. By allowing for biased productivity growth, the model provides a separation between price-induced reductions in energy utilization and those resulting from changes in technology. In addition, the overall rate of productivity growth for each industry in the model is determined endogenously as a function of input prices.[23]

Overall, the key features of the production portion of the model for the purposes of studying environmental and energy policy are that it is disaggregated, econometrically estimated, and includes a model of endogenous technical change. This allows it to capture the effects of regulations falling on narrow segments of the economy and to follow those effects through to changes in key variables: the cost of capital, the rate of investment, and the rate of productivity growth.

3.2. Households

To evaluate the effects of a policy on growth and welfare, however, it is also important to account for the effects of the policy on households. Households determine savings, investment in housing and consumer durables, labor supply, and the demand for goods and services, all of which influence overall economic growth.

The econometric approach to modeling consumer behavior has similar advantages over the calibration approach to those described for modeling producer behavior. Moreover, the

23. This approach follows Hudson and Jorgenson (1974), and Jorgenson and Fraumeni (1980). Other econometric models for analyzing energy and environmental policies, for example, Hazilla and Kopp (1990) and Longva, Lorentsen, and Olsen (1983), exclude biases in productivity growth and take the rate of productivity growth to be exogenous.

exact aggregation approach allows the model to incorporate detailed cross section data on the impact of demographic differences among households and levels of total expenditure on household expenditure patterns. The model takes advantage of this by dividing households into 672 demographic groups.[24] Consumer demands are not required to be homothetic, so that patterns of individual expenditure change as total expenditure varies, even in the absence of price changes. This captures an important characteristic of cross section observations on household expenditure patterns that is usually ignored in general equilibrium modeling.

The model' s specification of consumer demand behavior is based on two-stage allocation.[25] At the first stage, households allocate total expenditure among five broad aggregates: energy, food, nondurable goods, capital services, and other services. At the second stage, expenditure on each aggregate is allocated among labor and capital services and the individual commodities. Preferences are represented by a nested transcendental logarithmic indirect utility function.[26] Exact aggregation requires that the indirect utility function be homothetically separable in the prices of the commodities within the second stage. It must also be homogeneous of degree zero in prices and total expenditure on all commodities. Finally, it must be non-increasing in the prices, non-decreasing in total expenditure, and quasi-convex in prices and expenditure. These restrictions are incorporated into a separate system of demand equations constructed for each of the 672 different household types.[27] All behavioral parameters are estimated using the dataset described above.

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24. There are seven categories for family size, six categories for age of head, four categories for region of residence, two categories for race, and two categories for urban versus rural location. For further details, see Jorgenson and Slesnick (1987).

25. Two-stage allocation in the context of consumer behavior is discussed in more detail by Jorgenson, Slesnick, and Stoker (1987, 1988) and Blackorby, Primont, and Russell (1978). The tier structure for our model of consumer behavior is described by Wilcoxen (1988), Appendix A.

26. The translog indirect utility function was introduced by Christensen, Jorgenson, and Lau (1975). Surveys of functional forms employed in modeling consumer behavior have been presented by Blundell (1988), Deaton (1986), and Lau (1986).

27. The particular form of the model follows Jorgenson and Slesnick (1987). For further discussion of our econometric methodology, see Jorgenson (1984a, 1990a).

To determine the level of total expenditure within each period, this system is embedded in a higher-level model that represents consumer preferences between goods and leisure and between saving and consumption. At the highest level, each household allocates "full wealth", defined as the sum of human and non-human wealth, across time periods. This decision is formalized by introducing a representative agent who maximizes an additive intertemporal utility function, subject to an intertemporal budget constraint. The conditions for optimality of the household's intertemporal optimization problem can be expressed in the form of an Euler equation. This equation gives the value of full consumption in one period in terms of the value of full consumption in the next period, the interest rate, the time preference rate, the intertemporal elasticity of substitution and the rate of population growth.[28] The Euler equation is forward-looking, so that the current level of full consumption incorporates expectations about all future prices and discount rates.

The allocation of full wealth to the current time period is "full consumption" , defined as an aggregate of goods and leisure. Given this allocation, each household proceeds to a second stage of the optimization process–choosing the mix of leisure and goods. Household preferences at this stage are represented by means of a representative agent with an indirect utility function that depends on the prices of leisure and goods.[29] Demands for leisure and goods are derived as functions of these prices and the wealth allocated to the current period. This implies an allocation of the household's exogenously given time endowment between leisure time and the labor market, so that this stage of the optimization process determines labor supply.[30] In addition, by determining the value of personal consumption expenditures it completes

28. The Euler equation approach to modeling intertemporal consumer behavior was originated by Hall (1978). Our application of this approach to full consumption follows Jorgenson and Yun (1990).

29. The price index for consumption goods follows the approach of Jorgenson and Slesnick (1990) and is given by the cost of living index generated from the first stage of the model of consumer behavior. The price of leisure time is the wage rate less the marginal tax rate on labor income.

30. Jorgenson and Wilcoxen assume the household has a single exogenous endowment of time which can be used for either labor or leisure. The time endowment is adjusted by educational attainment to reflect changes in the quality of the labor force.

the model for household final demand. Finally, saving is determined by the difference between current income from the supply of capital and labor services and personal consumption expenditures.

In summary, the model of household behavior consists of three stages. First, it includes a system of expenditure share equations derived from maximization of a household utility function and satisfying conditions for exact aggregation. Second, it includes a higher level representative agent model that determines the intertemporal allocation of consumption through an Euler equation derived from maximization of an intertemporal utility function. Third, the representative agent model also allocates full consumption between goods and leisure, determining personal consumption expenditures, labor supply, and saving.

3.3. Investment

The model' s treatment of investment is based on perfect foresight or rational expectations. Under this assumption the price of investment goods in every time period is based on expectations of future capital service prices and discount rates that are fulfilled by the solution of the model. In particular, the equilibrium price of new investment goods is always equal to the present value of future capital services.[31] The price of investment goods and the discounted value of future rental prices are brought into equilibrium by adjustments in future prices and rates of return. This incorporates the forward-looking dynamics of asset pricing into the model of intertemporal equilibrium.

For tractability, Jorgenson and Wilcoxen assume there is a single capital stock in the economy which is perfectly malleable and mobile among sectors, so that it can be reallocated

31. The relationship between the price of investment goods and the rental price of capital services is discussed in greater detail by Jorgenson (1989).

among industries and final demand categories at zero cost. Under this assumption changes in energy and environmental policy can affect the distribution of capital and labor supplies among sectors, even in the short run. However, the total supply of capital in the model in each time period is perfectly inelastic, since the available stock of capital is determined by past investments. An accumulation equation relates capital stock to investments in all past time periods and incorporates the backward-looking dynamics of capital formation into our model of intertemporal equilibrium.

Since capital is perfectly malleable, the price of capital services in each sector is proportional to a single price of capital services for the economy as a whole. This rental price balances each period's supply with the sum of demands by all thirty-five industrial sectors together with the demand for personal consumption. The model gives the price of capital services in terms of the price of investment goods at the beginning and end of each period, the rate of return to capital for the economy as a whole, the rate of depreciation, and variables describing the tax structure for income from capital. The income from capital in each period is equal to the value of capital services.

New capital goods are produced from the individual commodities included in the model. Each new unit of capital is an aggregate of commodities purchased for investment in producers' and consumers' durables, residential and nonresidential structures, and inventories. The technology for production of new capital goods is represented by means of a price function for investment goods. The parameters of this function were estimated from time series data on gross private domestic investment in the dataset discussed above. As with the model of producer behavior, a nested tier structure is used to capture substitution among different inputs in the construction of new capital.[32]

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32. The tier structure for our model of production for new capital goods is presented by Wilcoxen (1988), Appendix A.

Finally, the total value of investment is constrained to equal the sum of: private savings by households, the government surplus, the capital account surplus, and any revaluation of wealth as the result of inflation.

3.4. Government

Final demands for government consumption are determined from the income-expenditure identity for the government sector. The first step is to compute total tax revenue by applying exogenous tax rates to all taxable transactions in the economy. To this is added the capital income of government enterprises and non-tax receipts to obtain total government revenue. Total government spending is equal to total government revenue plus the government budget deficit, which Jorgenson and Wilcoxen take to be exogenous. Spending on government purchases of goods and services, is equal to total spending less interest paid to domestic and foreign holders of government bonds together with government transfer payments to domestic and foreign recipients. Government purchases are allocated among goods and services according to fixed shares constructed from historical data.

4. Foreign Trade

Jorgenson and Wilcoxen assume that imports are imperfect substitutes for similar domestic commodities.[33] The goods actually purchased by households and firms reflect substitutions between domestic and imported products. The price responsiveness of these purchases is estimated from historical data. Import prices are assumed to be exogenous. Exports, on the other hand, are modeled by a set of explicit foreign demand equations, one for each commodity, that depend on exogenously given foreign income and the foreign price of US exports.

33. This approach was originated by Armington (1969). See Wilcoxen (1988) and Ho (1989) for further details on our implementation of this approach.

Foreign prices are computed from domestic prices by adjusting for subsidies and the exchange rate. The demand elasticities in these equations are estimated from historical data.

The model incorporates the income-expenditure identity of the rest of the world sector. The current account surplus is equal to the value of exports less the value of imports, plus interest received on domestic holdings of foreign bonds, less private and government transfers abroad, and less interest on government bonds paid to foreigners. The current account is taken to be exogenous and the exchange rate is endogenous.

4.1. Constructing a Base Case

The first step in analyzing a change in environmental policy is to establish a point of reference by generating a "base case" simulation *without* any changes in policy. Constructing a base case is not trivial because it requires the values of all exogenous variables in every time period. During the historical period, this is straightforward as the variables can easily be obtained from the dataset. Beyond that, however, the exogenous variables must be projected. The most important projections are those associated with US population growth and the corresponding change in the time endowment of the US economy. For the years following 1986, Jorgenson and Wilcoxen project population by age, sex and educational attainment through the year 2050, using demographic assumptions consistent with Bureau of the Census projections.[34] After 2050 they hold population constant, which is roughly consistent with Census Bureau projections. They project educational attainment by assuming that future demographic cohorts will have the same level of attainment as the cohort reaching age 35 in the year 1985. They then transform our population projection into a projection of the time

34. The breakdown of the US population by age, educational attainment, and sex is based on the system of demographic accounts compiled by Jorgenson and Fraumeni (1989). The population projections are discussed in detail by Wilcoxen (1988), Appendix B.

endowment used in our model of the labor market by assuming that relative wages across all categories of workers are constant at 1985 levels. Since capital accumulation is endogenous, these population projections effectively determine the size of the economy in the more distant future.

Also important are tax rates and other exogenous components of the government model. Jorgenson and Wilcoxen set all projected tax rates to their values in 1985, the last year in the sample period. The government deficit is projected to decline through the year 2025, after which it is held at four percent of the nominal value of the government debt. This has the effect of maintaining a constant ratio of the value of the government debt to the value of the national product when the inflation rate is four percent, as it is in the model’ s steady state.

Exogenous international variables include import prices and the current account deficit. Jorgenson and Wilcoxen assume that prices of imports in foreign currency and before tariffs remain constant in real terms at 1985 levels. Projections of the current account deficit fall gradually to zero by the year 2000. After that a small current account surplus is projected sufficient to produce a stock of net claims on foreigners by the year 2050 equal to the same proportion of US national wealth as in 1982.

Given projections of the exogenous variables, the model then is solved for a full intertemporal equilibrium through the year 2050 under the assumption of perfect foresight. The solution provides annual results for a large number of variables: the prices and outputs of each of the thirty-five industries; labor supply; saving; investment; and capital accumulation. The design of the model guarantees that income-expenditure identities for all thirty-five industries and the household, government, and the rest of the world sectors are satisfied. These identities imply that gross private domestic investment is equal to private savings plus the current account deficit less the government budget deficit. Since the government and current account deficits are taken to be exogenous, changes in gross private domestic investment are driven by changes in private savings. Thus, changes in the rate of capital accumulation depend on changes in private savings and the price of investment goods.

5. Estimating the Effects of Environmental Regulation

The tight link between environmental regulation, the cost of capital, and economic growth can be seen in an application of the model to the analysis of a carbon tax, as discussed in Jorgenson and Wilcoxen (1992). A carbon tax has often proposed as a method for reducing carbon dioxide emissions and thereby slowing global warming.[35] It would be applied to fossil fuels used for combustion in proportion to the carbon dioxide the fuels emit when burned, which is shown in Table 1. From the standpoint of economic efficiency, a carbon tax is an attractive way to reduce carbon dioxide emissions because it is very close to a tax on the externality itself: if firms and individuals must pay to emit carbon dioxide, they will emit less. A carbon tax would stimulate users to substitute other inputs for fossil fuels and to substitute fuels with lower carbon content, such as natural gas, for high–carbon fuels such as coal.

The carbon tax policy which has been debated most widely would impose a tax large enough to limit emissions to 1990 rates. To measure the effect of such a policy on the United States Jorgenson and Wilcoxen constructed a simulation in which the carbon tax rate was allowed to vary from year to year but was always chosen to be exactly enough to hold U.S. carbon dioxide emissions at their 1990 value of 1576 million tons.[36] As shown in Table 2, the tax produces significant reductions in carbon emissions relative to what would have happened in the absence of the policy. By 2020, for example, emissions are sixteen percent lower than

35. A carbon tax was first proposed by Nordhaus (1979).

36. A tax which varies from one year to the next in order to keep carbon emissions absolutely constant is a useful analytical device but is not a likely policy. The tax could not be adjusted quickly enough to keep emissions constant in every year.

they would have been without the tax. The tax also produces considerable revenue: $31 billion annually by 2020.[37]

The principal direct effect of the tax is to increase purchasers' prices of coal and crude oil. By 2020, for example, the tax reaches $22.71 per ton of carbon, which is equivalent to a tax of $14.75 per ton of coal, $3.10 per barrel of oil or $0.37 per thousand cubic feet of gas. The tax would increase the prices of fuels but leave other prices relatively unaffected. The price of coal would rise by forty-seven percent, the price of electricity would rise by almost seven percent (coal accounts for about thirteen percent of the cost of electricity), and the price of crude oil would rise by around four percent. The prices of refined petroleum and natural gas utilities would rise because of the tax on the carbon content of oil and natural gas.

Changes in the relative prices for fuels would affect demands for each good and lead to changes in industry outputs. Most sectors show only small changes in output. Coal mining is an exception: its output falls by almost thirty percent. Coal is affected strongly for three reasons. First, coal emits more carbon dioxide than oil or natural gas per unit of energy produced. Thus, the absolute level of the tax per unit of energy content is higher on coal than other fuels. Second, the tax is very large relative to the base case price of coal for purchasers: at the mine mouth, the tax would increase coal prices by around fifty percent. (In contrast, oil is far more expensive per unit of energy so in percentage terms its price is less affected by the tax. The price of crude oil rises only about ten percent.) Third, the demand for coal is relatively elastic. Most coal is purchased by electric utilities, which can substitute other fuels for coal when the price rises. Moreover, the demand for electricity itself is relatively elastic, so when the price of electricity rises, demand for electricity (and hence demand for coal) falls substantially.

37. In this simulation, the revenue was returned to households as a lump sum rebate. All dollar amounts are in 1990 prices.

From the point of view of firms outside the energy sector, the main result of the tax is to increase the prices of electricity, refined petroleum and natural gas, each by a few percent. This would have two effects. First, higher energy prices would mean that capital goods (which are produced using energy) would become more expensive. Higher prices for capital goods mean a slower rate of capital accumulation and lower GNP in the future. Second, higher energy prices discourage technical change in industries in which technical change is energy-using. Together, these two effects cause the capital stock to drop by 0.7 percent and GNP to fall by 0.5 percent by 2020 (relative to the base case). Average annual GNP growth over the period 1990-2020 is 0.02 percentage points lower than in the base case. About half of this is due to slower productivity growth and half due to reduced capital formation. Thus, the link between environmental regulation and the cost of capital is absolutely fundamental to understanding the effects of the policy.

Because the tax produces 30 to 80 billion dollars of revenue a year, precisely how this revenue is used will have a large effect of the overall economic cost of slowing global warming. In particular, if the revenue were used to reduce distortionary taxes elsewhere in the economy, or if it were used to lower government budget deficits, there would be large welfare gains which would offset some or all of the welfare losses associated with the carbon tax itself.

To determine how large this welfare improvement might be Jorgenson and Wilcoxen constructed three additional simulations in which the revenue from a carbon tax was used to reduce different taxes. In each simulation they imposed a carbon tax of $15 per ton in 1990 with the rate rising by 5% annually in subsequent years. In the first simulation the revenue was returned to households by a lump sum rebate; in the second it was used to lower taxes on labor, such as social security taxes; and in the third it was used to lower taxes on capital, such as corporate income taxes.

Their results, shown in Table 3, indicate that the disposition of revenue from a carbon tax has a very significant effect on its overall impact on GNP. In the lump sum case, output in 2020 drops by 1.70 percent relative to the base case. When the revenue is returned by lowering the tax on labor the loss of GNP is less than half as much: only 0.69 percent. The improvement is due to an increase in employment brought about by the drop in the difference between before- and after-tax wages. If the revenue were returned as a reduction in taxes on capital, GNP would actually increase above its base case level by 1.10 percent. In this case, the gain is due to accelerated capital formation generated by an increase in the after-tax rate of return on investment. These results suggest that a carbon tax would provide an opportunity for significant tax reform and further emphasize the importance of the cost of capital for understanding the impacts of environmental policies.

6. Confidence Intervals

An important benefit of the economic approach to general equilibrium modeling is that it allows the precision and reliability of model results to be quantified and expressed in the form of confidence intervals. An example is Tuladhar and Wilcoxen (1998), who examined the "double dividend hypothesis" using a small econometric general equilibrium model.

Many market-based policies for controlling environmental problems, such as the carbon taxes discussed above, have the potential to raise large amounts of revenue. The idea that this revenue could be used to lower distorting taxes elsewhere in the economy, hence producing a welfare gain beyond the environmental benefits of the policy, has become known as the "double dividend hypothesis". The hypothesis has appeared in the literature in several forms.[38] The weakest form simply states that using the revenue to lower a distorting tax would be superior

38. For a clear description of the different forms the hypothesis has taken, see Goulder (1995).

to returning the revenue as a lump sum rebate. In this form, the hypothesis is true by construction and generates little controversy.

The strongest form of the hypothesis has been far more controversial. It states that taxing goods that produce externalities (such as fossil fuels) and using the revenue to reduce other taxes (particular those on primary factors) can improve economic welfare even before environmental benefits are considered. In other words, the strong form is really an assertion that the economy would benefit from tax reform.[39] Advocates of stronger environmental regulation have used the strong form to argue that both the economy and the environment would benefit from shifting the tax system toward environmental taxes.[40] The extreme version of this view is that tighter regulations can be a "no regrets" policy–one that can be justified even if its environmental benefits are modest or impossible to quantify. At the same time, however, a large theoretical literature has sprung up challenging the hypothesis and arguing that environmental taxes often exacerbate existing distortions, particularly in the labor market.[41]

Although this theoretical work has made a number of important contributions, it will never completely resolve the debate over the strong double dividend hypothesis because the hypothesis itself is fundamentally empirical rather than theoretical.[42] A simple example makes it clear why. Suppose an economy has two primary factors: capital and labor, and that the supply of capital is elastic while the supply of labor is perfectly inelastic. Now consider what happens under a revenue-neutral shift in taxation that reduces income taxes, which fall on both

39. To put the double dividend debate into terms familiar to tax policy analysts, the strong form asserts that the excess burden of taxation is relatively low on externality-producing goods.

40. Prominent examples include Repetto, et. al (1992) and Hammond, et al. (1997).

41. See, for example, Bovenberg and de Mooij (1994).

42. A few studies have attempted to test the strong double dividend hypothesis using computational general equilibrium models; see Jorgenson and Wilcoxen (1993), Ballard and Medema (1993), or Bovenberg and Goulder (1996), for example. These papers have calculated point estimates of the effect of revenue neutral shifts of taxation from primary factors to energy goods. Our work builds on this approach but extends it to allow confidence intervals to be calculated instead of point estimates.

labor and capital, and increases the tax on energy. Much of the burden of the energy tax will be passed back to the primary factors used in energy production. If energy is more labor-intensive than the rest of the economy, therefore, the shift in taxes would be equivalent to a policy that reduced taxes on capital income while raising taxes on labor income. Since capital is supplied elastically while labor is not, this would stimulate capital formation, raising GDP and producing a strong double dividend. On the other hand, if energy production is more capital-intensive than average, the effect would work in the other direction: the shift would increase the effective tax burden on capital which would reduce capital formation, lower GDP and would fail to generate a double dividend. Finally, if energy production used the two factors in the same proportions they are used in the overall economy, the shift in taxes would have no effect on GDP.

Because the strong form of the hypothesis is an empirical question it must be tested econometrically. In order to do so it is necessary to estimate the mean equivalent variation (EV) for the tax shift *and* its standard error. This would allow the hypothesis to be subjected to standard statistical tests. We could reject the strong double dividend hypothesis if the mean EV is negative and its 95% confidence interval does not include zero. On the other hand, if the estimated EV is positive and its confidence interval again does not include zero we could reject the hypothesis that there is *not* a double dividend. Finally, if the confidence interval includes zero it would be clear why different authors have come to different conclusions: the data simply does not allow us to reject either hypothesis. In that situation, different but equally reasonable choices of parameters would lead to different double dividend results.

Tuladhar and Wilcoxen use a small econometric general equilibrium model of the United States to demonstrate how the mean equivalent variation and its standard error can be calculated for a representative shift from income to energy taxes.[43] They construct a confidence

43. Many general equilibrium studies include some degree of sensitivity analysis but only a few studies have gone beyond examining the effects of fairly arbitrary perturbations a handful of parameters. Pagan and Shannon (1985) suggest one approach for systematic sensitivity analysis when the covariance matrix of parameter esti-

interval for the equivalent variation, which they then use to test the strong form of the double dividend hypothesis. In the remainder of this section we discuss their results.

Tuladhar and Wilcoxen represent the U.S. economy using the smallest possible general equilibrium model that still has enough detail to capture the important features of the double-dividend hypothesis. The production side of the economy is divided into three industries: energy, E, materials, M, and new capital goods, G. Each industry produces its output according to a constant elasticity of substitution (CES) production function which takes inputs of capital services, labor, energy and materials. Under this specification there are six technology parameters per industry for a total of eighteen in the production model overall.

Household behavior is represented using two-stage budgeting and a single infinitely-lived representative agent. The household supplies all of the economy's labor and capital services. In addition, it demands labor, capital services, energy and materials. The top tier of the household' s optimization problem follows Jorgenson and Wilcoxen: the household allocates its wealth over time in order to maximize a logarithmic intertemporal utility function. This stage of the model determines the savings rate. At the second tier Tuladhar and Wilcoxen represent preferences over labor, capital services, energy and materials using a Stone-Geary utility function. The total number of parameters in the household model is eight.

The model' s parameters were estimated using the US dataset discussed above. The complete production model–all three sectors–was estimated as a single system of simultaneous equations. The resulting estimates are showing in Table 4 along with standard errors. On the household side, the values of the time preference rate and the depreciation rate were taken

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mates is unavailable. Harrison, et. al (1993), propose using a Monte Carlo approach based on drawing parameters from a prior (but not estimated) distribution. Arndt (1996) and Arndt and Pearson (1998) propose a method of sensitivity analysis based on gaussian quadrature that has much in common with this approach.

from Jorgenson and Wilcoxen (1990). The remaining household parameters were obtained by estimating the household demand functions as system of simultaneous equations. The results shown in Table 5.

Using the estimates in Table 4 and Table 5, Tuladhar and Wilcoxen solved the model for its steady state equilibrium. They then calculated confidence intervals for the model's endogenous variables using two techniques: the delta method and Monte Carlo simulation.[44] The results for the two techniques were essentially identical and are shown in Table 6, which gives 95% confidence intervals expressed as percentages of the corresponding variable's base case value.[45] Some of the confidence intervals are quite narrow: the capital stock, for example, is determined within 0.5%.[46] Many of the variables are less precisely determined. The rental price of capital and the price of new capital goods, for example, have confidence intervals of 6.5%. The quantity of energy is the least precise of all with a confidence interval of 11.2%.

In order to examine the double dividend hypothesis Tuladhar and Wilcoxen simulated a shift in tax policy that increased the tax on energy to 10% from an initial value of zero. Simultaneously, the tax rate on capital was reduced (from an initial value of 10%) by exactly enough to leave the lump sum subsidy unchanged.[47]

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44. These techniques are necessary because the endogenous variables are, in general, nonlinear functions of the parameters. In the delta method, confidence intervals are calculated from the covariance matrix of the parameter estimates using a linear approximation to the nonlinear system of equations. This approach is commonly used by econometric software packages. In the Monte Carlo simulation the model was solved for 10,000 draws from the joint distribution of the parameter estimates.
45. These confidence intervals take into account the standard errors of the parameter estimates but not the residual variance of the estimated equations. Including the latter would make the confidence intervals considerably larger.
46. This is an interesting result but it should not be taken too literally since the time preference rate was imposed and thus did not appear in the covariance matrix. Had it been estimated, the confidence interval for K would be considerably larger.
47. These are only very rough approximations to the actual tax rates.

Figure 1 shows the distribution of new capital tax rates resulting from a Monte Carlo simulation using 10,000 draws from the distribution of parameter estimates. The mean of the distribution is 8.46% and the 95% confidence interval runs from 8.11% to 8.81%. Raising the energy tax to 10%, in other words, would allow the capital tax rate to be cut by about 1 to 2 percentage points, with 1.5 being the most likely.

More interesting is the distribution of equivalent variations, shown in Figure 2. The mean equivalent variation is 0.24% and the 95% confidence interval runs from 0.14% to 0.33%. The key result is that the confidence interval does not include zero . Conditional on the assumptions underlying the model, therefore, it is possible to reject the hypothesis that shifting to energy taxes would not produce a double dividend.

These results are suggestive but should be regarded as preliminary in several respects. First, the model only represents the economy at the steady state. To the extent that the change in policy causes welfare losses along the transition to the new steady state, this equivalent variation will overstate the benefit of the reform. Second, labor supply is fixed. If the energy tax significantly exacerbates distortions in the labor market, these results will also overstate the equivalent variation of the policy. Third, the utility function imposes a unitary intertemporal elasticity of substitution. This will have little effect on the steady state but would have important effects during the transition period in a full intertemporal solution. Finally, Tuladhar and Wilcoxen have examined only the effect of uncertainty in the parameter estimates; it would be useful and straightforward to extend the approach to examine the effect of the residual uncertainty in the estimated equations.

7. Conclusion

The shift to intertemporal analysis of environmental policies has emphasized the crucial role played by the cost of capital, which links environmental regulations to overall economic growth. Regulations can raise the cost of new capital goods and hence slow the rate of capital formation and reduce the rate of growth. At the same time, revenue from market-based environmental policies, such as emissions taxes, may raise enough new tax revenue to allow capital income taxes to be reduced, possibly lowering the cost of capital and stimulating growth.

In order to evaluate an environmental policy, therefore, it is essential to determine the effect of the policy on the cost of capital and capital formation. This requires a quantitative model that can capture environmental regulations at a detailed level, trace the effects of those regulations through the economy to determine their influence on the cost of producing new capital goods, and can also determine the effect of the policy on savings and investment.

The principal analytical approach possessing these features is large-scale econometric, intertemporal general equilibrium modeling. The pioneering work of Dale Jorgenson has shown that it is possible to construct large, detailed models without compromising on parameterization. Indeed, intertemporal general equilibrium models can be constructed using econometrically-estimated flexible functional forms, a detailed disaggregation of industries, commodities and households, endogenous technical change, and nonhomothetic consumption. Moreover, the econometric approach allows a further methodological refinement by permitting confidence intervals to be constructed for estimates of the costs and benefits of environmental policies.

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Table 1: Relative Carbon Content of Fossil Fuels

Characteristic	Fuel		
	Coal (ton)	Oil (bbl)	Gas (mcf)
Million BTU per unit	21.94	5.80	1.03
Tons of carbon per unit	0.649	0.137	0.016
Carbon per million BTU:			
Tons	0.030	0.024	0.016
Relative to coal	100%	80%	54%
Approximate price before tax:			
Per unit of fuel	$22	$21	$2.4
Per million BTU	$1.00	$3.62	$1.36
Tax equal to $10/ton of carbon			
Per unit	$6.49	$1.36	$0.16
Per million BTU	$0.30	$0.24	$0.16
Percentage increase per unit	29.50%	6.48%	6.67%

Table 2: Selected 2020 Results for the Stabilization Scenario

Variable	Unit	Value
Carbon Emissions	%Δ	-16.12
Carbon Tax	$/ton	22.71
Tax on Coal	$/ton	14.75
Tax on Oil	$/bbl	3.10
Tax on Gas	$/mcf	0.37
Price of Capital	%Δ	0.40
Capital Stock	%Δ	-0.83
Tax Revenue	$B	31.41
Real GNP	%Δ	-0.55
Coal Price	%Δ	46.99
Coal Output	%Δ	-29.28
Electricity Price	%Δ	6.60
Electricity Output	%Δ	-6.17
Oil Price	%Δ	4.45
Oil Output	%Δ	-3.90

Table 3: Selected Results for Revenue Experiments in 2020

Variable	Unit	Revenue Policy		
		Lump Sum	Labor Rebate	Capital Rebate
Carbon Emissions	%Δ	-32.24	-32.09	-31.65
Carbon Tax	$/ton	64.83	64.83	64.83
Price of Capital	%Δ	0.97	-1.86	0.23
Capital Stock	%Δ	-2.13	-1.36	1.89
Tax Revenue	$B	79.65	79.82	80.35
Real GNP	%Δ	-1.70	-0.69	1.10
Coal Price	%Δ	143.49	140.57	142.06
Coal Output	%Δ	-54.14	-54.19	-53.45
Electricity Price	%Δ	18.57	15.97	16.99
Electricity Output	%Δ	-15.93	-15.37	-14.66
Oil Price	%Δ	14.20	12.28	14.55
Oil Output	%Δ	-11.92	-11.54	-11.39

Table 4: Production Parameter Estimates with Standard Errors

Parameter	Estimate	Std Error
σ_E	1.048	0.0031
A_E	1.187	0.0183
γ_{KE}	0.285	0.0040
γ_{LE}	0.160	0.0024
γ_{EE}	0.393	0.0081
γ_{ME}	0.159	0.0020
σ_M	0.764	0.0048
A_M	0.999	0.0010
γ_{KM}	0.176	0.0012
γ_{LM}	0.356	0.0013
γ_{EM}	0.025	0.0008
γ_{MM}	0.441	0.0016
σ_I	0.990	0.0029
A_I	0.871	0.0199
γ_{KI}	0.041	0.0011
γ_{LI}	0.179	0.0028
γ_{EI}	0.012	0.0013
γ_{MI}	0.767	0.0029

Table 5: Household Parameter Estimates with Standard Errors

Parameter	Estimate	Std Error	Parameter	Estimate	Std Error
μ_K	55430	20469	α_K	0.205	0.0043
μ_L	110104	20174	α_L	0.125	0.0046
μ_E	52760	23259	α_E	0.044	0.0111
μ_M	670442	79937	α_M	0.623	0.0073

Table 6: Base Case Confidence Intervals as Percentages

Variable	%	Variable	%	Variable	%
q	6.5	K	0.5	c_K	6.1
P_G	6.5	Q_E	11.2	c_L	2.1
P_E	4.2	Q_M	1.1	c_E	17.5
P_M	2.2	I	0.5	c_M	1.3

Figure 1: Distribution of Capital Tax Rates

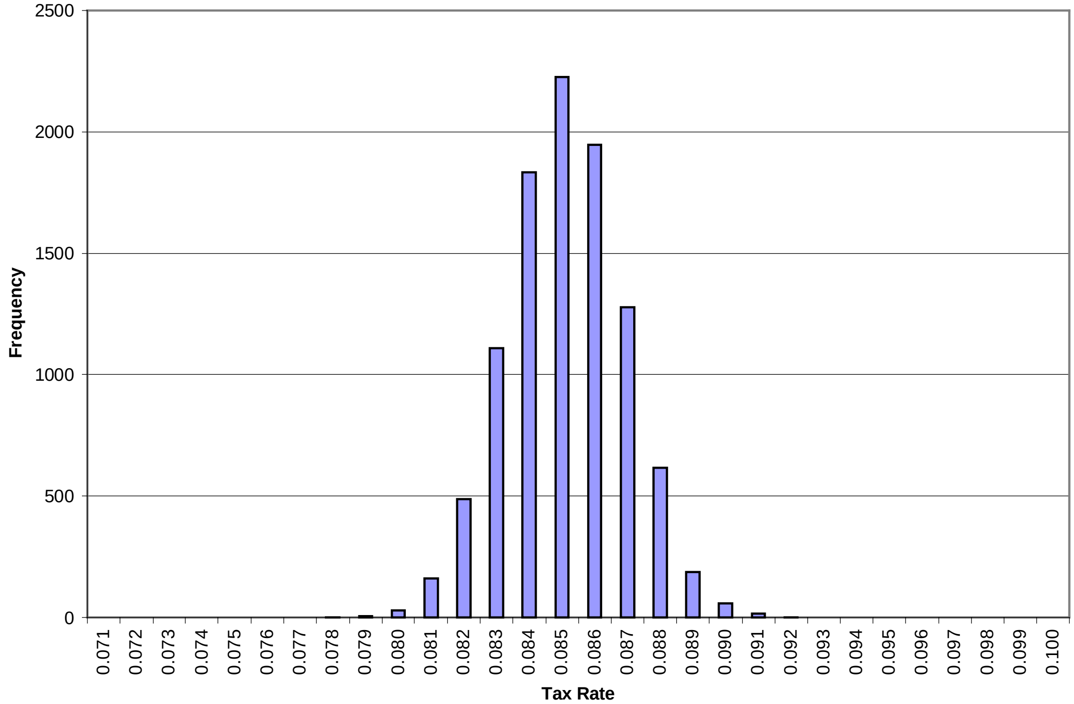

Figure 2: Distribution of Equivalent Variations