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Essays on the Resource Sector, International Finance, and Environmental Policy

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ESSAYS ON THE RESOURCE SECTOR, INTERNATIONAL FINANCE, AND ENVIRONMENTAL POLICY

by

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ABSTRACT

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Possession and production of energy resources affects the host country's wealth. This dissertation considers the effects of technological and policy shocks that originate in the energy sector and the implications they create for the host country's international financial flows, environment, and wealth of population groups.

In Chapter 1, I model how the decisions made upon an oil discovery by the country's firms and households impact the current account. I use a small open economy DSGE model with an oil sector to express the current account as a function of oil discoveries. In this model, an oil discovery creates a realistic long-term borrowing-repayment-saving cycle. Three characteristics of the economy affect oil-related decisions: the presence of an oil fund, the equity home bias, and technological rigidity of the oil industry. I estimate the effects of these characteristics as structural parameters in the model using the North Sea data for Norway and the United Kingdom. I find that the presence of an oil fund amplifies the current account surpluses. The equity home bias determines how quickly the country consumes its international savings. Rigidity of the oil firms delays the accumulation of international savings and prolongs the country's time in debt.

In Chapter 2, I explore the environmental implications of the energy sector. How will a carbon tax affect construction of electricity generators and carbon emissions in the US? I model the construction choice in two parts: the decision to build and the capacity size. Because a carbon tax has yet to be implemented in the US, I proxy for the tax using variation of fuel prices. I simultaneously estimate the two-part construction outcomes for each state. I find that a hypothetical state-level tax of $10 slows the state's construction of new, dirty gas capacity by 3 percent, relative to the business-as-usual growth of gas generation. As hypothesized, other estimates indicate that a tax would have a null effect on clean wind capacity in the near-term. For policy perspective, I predict the effects of carbon taxes ranging from $10 to $100 per ton CO_2. In an average state, a tax could reduce average emissions from newly built generators by 3 to 33 percent.

Development of shale technology made available large quantities of oil and gas in the US that were previously too costly to recover. In Chapter 3, I develop an approach for examining wealth implications of shale oil and gas. This approach focuses on how the benefits from shale oil are distributed across different economic groups: landowners, oil firms, and state and local, national, and international population. To help find the speed with which the benefits spread from the oil and gas sector to the general economy, I develop a method to obtain the responses of incomes and other key macroeconomic indicators to the production of oil and gas in a multi-state DSGE model with an oil sector.

To my parents

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Chapter I. Long-term implications of oil discoveries for international saving in a DSGE model

1 Introduction

Developments in the oil and gas sector change the country's economy in a number of ways. Typically, consumption grows, work hours shorten, some of the oil wealth is being saved for the future. Often, oil-rich countries save by running a current account surplus.

I analyze the extent to which policy and technological factors determine how the current account responds to an oil discovery. First, oil-producing countries often establish savings funds, such as Norway's pension fund, to prevent squandering of the national oil wealth. Second, countries maintain long positions in international asset markets and take steps to ensure the profitability of their investments. Third, countries ensure efficient production of oil by licensing oilfields to international oil companies that possess adequate oilfield technology. To evaluate the effect of these initiatives on the international savings of an oil-producing country, I express the current account as a function of oil reserves and single out the implementation of an oil fund, the home country bias, and rigidity of oil production as the factors that shape the relationship. This is in contrast to current open-economy macroeconomic literature that focuses on the effects of prices shocks on countries' international finance.

I interpret an oil fund as a manifestation of the country's intertemporal preferences. A simple guiding principle of many oil funds is to save the oil export revenue and consume only the interest accrued on the savings. In terms of intertemporal choice, this implies that consuming today is no more preferable than tomorrow. Such an oil fund puts downward pressure on the overall intertemporal discount rate of the economy. Then, the country's population can offset this pressure to an extent by dissaving privately in the Ricardo-Barro effect. To see if this happens, I estimate and compare the intertemporal discount rate in a country with an oil fund (Norway) to a country that produces a comparable amount of oil, but does not have an oil fund (The United Kingdom).

Equity home bias reflects the tendency of asset managers to weigh their portfolios toward assets located in their home country. I estimate the home bias for Norway, a country that produces and exports oil and runs current account surplus, and for the UK, which produces a similar amount of oil, but mostly for domestic use, and does not maintain a current account surplus. Further, I check if the home bias recedes over time by allowing it to change at a fixed rate over the 43 years of the North Sea oil history and estimating that rate. I determine whether the equity home bias is the reason why Norway had been producing and exporting oil since the late 1970s, but began accumulating claims on foreign assets only in the 1990s.

Alternatively to the home bias, the lag between the discovery and the current account response observed in Norway can be due to the failure of the oil firms to instantly begin producing the discovered oil. To see how this affects the current account, I model a Calvo-style process of oil production in which only a fraction of firms is able to increase oil production in response to a discovery shock at any given time period.

Estimating the effects of policy and technological factors responsible for the formation of net international investment position (NIIP) surplus is instructive for predicting which set of policies to adopt for a desired effect: to maximize the size of the surplus, maximize its longevity, or achieve the benefits of resource wealth sooner.

This is the first paper that estimates the effect of an oil discovery within a dynamic stochastic general equilibrium (DSGE) framework. By contrast, macroeconomic literature regularly covers macroeconomic effects of oil price shocks (Kilian, Rebucci, and Spatafora (2009), Backus and Crucini (2000), Bodenstein, Erceg, and Guerrieri (2011)). In a small open economy (SOE) DSGE model with resources, discovery shocks create a long-term cycle of external borrowing, repayment, and savings. Typically, analysis employing DSGE focuses on the business cycle, and the horizon is short or medium term. By contrast, an oil discovery can change macroeconomic behavior for decades. Implementation of an endogenous oil-producing industry allows an otherwise basic DSGE model to reproduce the direction, timing, and magnitude of the current account response to a discovery. This is radically different from an oil price spike, which creates an uptick in export revenue and only has short-term implications for the general economy.

Both the oil price shocks and discoveries continue to influence major economies. The ongoing US tight ("shale") oil boom and the Canadian tar sands in 2000s are the recent examples. The case of the North Sea oil discoveries starting in the 1970s makes available forty-three years of annual oil sector and macroeconomic data for Norway and the UK, which split the bulk of the discovery roughly equally. The North Sea oil has had starkly contrasting effects on the two countries: Norway has accumulated an oil fund of claims on foreign assets, while the UK's international investment is roughly balanced. However, I show that both of these outcomes are consistent with the predictions of a SOE DSGE model with a resource sector. The difference is primarily due to Norway exporting most of its oil during the period of high oil prices, in contrast to the UK using most of its oil in domestic production.

2 Approach and literature

The theoretical literature on optimal resource management almost exclusively relies on partial equilibrium frameworks. The work of Pindyck (1978), Heal (1993), and Sweeney (1992) established the conventions of optimal resource use in the partial equilibrium setup. The advantage is the relative simplicity and tractability of the models.

External economic variables such as foreign debt, however, are easier to work with in the general equilibrium context. Kim and Loungani (1992) is the first example, to my knowledge, of the adaptation of Hansen's (1985) baseline real business cycle model to include the resource sector. Backus and Crucini (2000) calibrated a two-country model with an OPEC exporter of oil to measure the effect of oil price shocks on terms of trade. Their two-country model was augmented with the financial sector by Bodenstein, Erceg, and Guerrieri (2011), to see if incomplete financial markets lead to worsening terms of trade.[1] A New Keynesian perspective is provided by Dib (2008) in a study of the response of the Canadian dollar exchange rate to energy prices. Aside from following the Keynesian conventions, such as Calvo–Yun (Yun 1996) pricing, Dib models non-tradable sector.

DSGE models with resources are applied to study a diverse set of questions. Bems and Carvalho Filho (2011) establish the role of the precautionary savings motive for excess external reserves in the countries whose income depends on production of a stochastically-priced resource. Bohn and Deacon (2000) show that resource appropriation risk leads to

[1] A majority of models, e.g. Backus and Crucini (2000), employ real rigidities in the response of an economy to resource shocks. Cost of capital adjustment is one example. The putty-clay nature of nonoil capital, as in Atkeson and Kehoe (1999) is another avenue. This paper focuses on the role of the oil sector, thus the remainder of the model is kept as basic and close to the Hansen (1985) RBC framework as possible.

overproduction and underinvestment in exploration. Lama and Medina Guzman (2012) propose a monetary policy to combat the Dutch disease (draining of production factors from the non-resource sectors following development of the resource sector). To my knowledge, the outcomes for the external economies of Norway and the UK have not been considered in the context of DSGE models and optimal resource use.

Five of the above six examples of DSGE models treat the resource sector as exogenous. Bohn and Deacon (2000) model production and discoveries along the optimality principles as in Pindyck (1978), but in a general equilibrium. Oil is exogenously supplied in an autoregressive process. This approach is justified when the focus is on an OECD country that receives oil from OPEC. The exogeneity assumption may be less applicable if an OECD country produces a significant amount of oil of its own.

The problem with oil production in DSGE is shock propagation. In the majority of examples in the literature it is solved by allowing autoregressive shock. The problem with that approach, aside from the lack of theoretical foundation, is that the autoregression coefficient is quite high. Gross and Hansen (2013) find that resource prices follow an AR(1) process with the slope parameter equal to 0.9.

Gross and Hansen (2013) is, to my knowledge, the first work to fully endogenize resource discovery and production in an open-economy DSGE. The authors examine Australia as a small open economy to see if it will significantly change the response of macroeconomic price variables to the resource price shock. The authors conclude that while the prices are largely unaffected, the effects of the price shock on the resource sector itself are likely to be underestimated in the exogenous resource setup.

Similarly to Gross and Hansen (2013) production of oil is endogenous in this model.

However, I assume the discoveries to be an exogenous process. There is little argument against exploration being more active when the prices are high. Furthermore, some of the discoveries are nothing more than requalifications of the reserves previously deemed uneconomic. However, for the 43-year scope of the North Sea case, improvements in technology are the key driver of the discoveries, especially the developments in natural gas in the 1990s. Modeling changes in technology can be problematic and is beyond the scope of this research. Instead, I assume that the figures reported by the oil authorities in the UK and Norway represent the best current understanding of how much oil the country has in reserve in the ground.

Similarly to Gross and Hansen (2013), this research introduces optimal resource use into the DSGE framework, building on achievements in both strands of literature. The choice of a resource-rich OECD economy is also similar: Australia in Gross and Hansen (2013), and Norway and the UK in this paper. The areas of focus, however, are different. Gross and Hansen compare the performance of the endogenous-resources model to the baseline model with exogenous resources. I answer the question of how countries' external borrowing and lending responds discoveries of oil in terms of magnitude, direction, and reversal rate of the current account impulse response.

3 Theory and estimation

I model the behavior of the current account in response to a discovery shock and an oil price shock. In a structural model, the shape of this response depends on the structural parameters of the general equilibrium model and the values of main macroeconomic variables.

Some parameters represent actual economic phenomena: the intertemporal discount rate is affected by presence of the oil fund, the cost of moving resources across the border is a measure of the equity home bias, and real rigidities represent the technological obstacles to be overcome in the resource reallocation process. Macroeconomic input values of interest chiefly include the country's oil surplus (how oil produced compares to the amount used domestically as a production factor), which critically alters the effect of oil reserves and oil prices on the current account.

I estimate a dynamic stochastic general equilibrium (DSGE) model of a small open economy (SOE) with a resource sector. I use a version of Hansen's (1985) real business cycle (RBC) model and add three features: (1) oil is a production factor in the general economy, following Kim and Loungani (1992), and can be exported, (2) the country is a small open economy, as in Mendoza and Uribe (2000) and Schmitt-Grohé and Uribe (2001), and (3) oil is produced endogenously and optimally along the principles in Pindyck (1978). Appendix 2 provides detail on the work that sets the foundation for and inspires this research.

In the literature (Backus and Crucini (2000) and Bodenstein, Erceg, and Guerrieri (2011), among others), oil arrives to the economy in an exogenous stochastic process. It is assumed to be autoregressive to resemble the gradual optimal production of oil that takes place in practice. By contrast, I explain the behavior of the current account as the response to the protracted dynamics of the oil sector. The operations of the oil sector provide the long term dimension to the DSGE model and are central to justifying the causality in the oil reserve—current account relationship.

I distinguish between the stock of oil in the ground, "proven oil reserves", and the flow of oil extracted from the ground and subtracted from the reserve in the process of "production of oil". I model an oil sector where the amount of oil produced is determined by the quantity of oil-specific capital and the remaining reserve in the ground, similarly to Pindyck (1978). The oil sector optimizes by equating the marginal present value of oil output to the cost of oil-specific capital, such as pipes and rigs. In such an oil sector, a discovery prompts an initial oil capital investment, and the production of oil takes place in the years that follow.

In Section 3.1, I set up the structural objectives and conditions for the oil sector firms, households, nonoil firms, and international markets. In Section 3.2, I transform the structural conditions into a system of linear first-difference equations (reduced-form model) and outline the estimation strategy.

3.1 Model setup

The model establishes causality between the current account and the oil reserve, z_t, that is subject to discovery shocks, ϵ_{zt}. I define current account as change in the net international investment position (NIIP), which itself is the difference between a country's total assets and its domestically employed capital, $a_t - k_t$. Thus, my goal is to justify causality in

$$a_t - k_t = R \begin{bmatrix} a_t \\ z_t \end{bmatrix}. \tag{1}$$

Production of oil, v_t connects the reserves to the general economy. I add the production to the system of conditions and express it as first-order difference equations. The system is now

$$\begin{bmatrix} k_{t+1} \\ a_{t+1} \\ z_{t+1} \\ v_{t+1} \end{bmatrix} = P \begin{bmatrix} k_t \\ a_t \\ z_t \\ v_t \end{bmatrix} + Q\epsilon_t \tag{2}$$

This recursive model, once estimated, shows how $a_t - k_t$ responds to a change to z_t, introduced by the shock, ϵ_{zt}, which is an element in the shock vector, ϵ_t.

I estimate parameter matrices P and Q by maximum likelihood with the standard distributional assumptions. However, to argue for causality, I provide a theoretical justification for the relationships between a, k, and z. I adopt a theoretical model that (1) centers on the variables in question, (2) is based on the neoclassical microfoundations of agent rationality, and (3) is the simplest possible.

The world consists of a small open economy (SOE) and the rest of the world (ROW). The SOE is populated by economic agents: households, nonoil firms, oil firms, and the oil licensing authority. There is no distinction between the public and private sectors. Four production factors exist in the economy: nonoil capital, oil-specific capital, oil, and labor. Bertrand-competitive nonoil firms employ inputs of nonoil capital, oil, and labor to produce goods which can be used for consumption or capital investment. Households own all the production factors in the economy and receive factor payments which they can spend on consumption of domestic goods and imports. Households can save resources as nonoil capital, oil capital, or claims on foreign assets. Oil firms borrow nonoil capital and convert it into non-retractable oil capital in order to produce oil. Capital, oil, and goods are freely mobile across national borders, while labor is country-specific.

The ROW enters the model as a price system. Prices of goods in the home economy and ROW goods prices are equal. The interest rate on capital and the oil price are elastic with respect to international imbalances. The incompleteness of production factor markets ensures the uniqueness of the steady state, as in Mendoza and Uribe (2000). Wages are redundant under the Walras law.

3.1.1 Oil sector

The oil sector competes for household savings with the nonoil economy by offering households a factor payment. Once households turn over their savings to oil sector firms, those resources turn into oil sector-specific capital, $K_{V,t}$, which cannot be reallocated. Intuitively, once an oil well is drilled, and the oil, V_t, is gushing, the investment cannot be withdrawn (i.e. the oil well remains in place), and even stopping the extraction of oil is not always technologically possible. Production is Bertrand-competitive, so that oil producers have to start operations immediately upon discovery of the stock of reserve in the ground, Z_t, as opposed to having an opportunity to stake an oilfield and sit on it until the price of oil, q_t, increases or price of capital, r_t, decreases.[2] All the investment has to happen in the period that follows the discovery. Thus, if the discovery takes place at $t = 0$, the firms' only chance to drill will be at $t = 1$.

The volume of oil-specific capital that is invested in the first year, $K_{V,1}$, is determined by the condition that its instantaneous marginal product is equal to the price of capital.

[2]The licensing authorities, the UK Department for Business, Energy and Industrial Strategy (BEIS) and Norwegian Petroleum Directorate grant licenses for exploration and production in licensing rounds. If an oil company does not meet the minimum license obligations within limited time, the license is relinquished (Norwegian Petroleum Directorate 1997).

Since the capital is sunk into the oil sector and cannot be reallocated, in absence of new shocks, in the period that follows, oil capital (minus depreciation) will have less oil to work with, $Z_{t-1} - V_{t-1}$, and the marginal product of capital will fall below the market price of capital. Oil-specific capital is the asset of households; therefore, the oil sector's profits are transferred to them.

Production of oil is described by a Cobb–Douglas function:

$$V_t = K_{v,t}^{\gamma} Z_t^{\eta} D \tag{3}$$

Oil production volume, V_t, increases with oil-specific capital, $K_{V,t}$, and the current stock of reserve in the ground, Z_t. The contributions of the oil production factors are measured by their respective elasticities, γ and η, which sum to unity. The time-invariant element, D, is a scale parameter.

I model technology as an invariable total factor product (TFP) D because of its relative constancy over the last 45 years in Norway and the UK. Labor is not a major factor in oil production, and I omit it for simplicity. To get a sense of magnitude, in 2012 the oilfield industry accounted for roughly 40% of the total Norwegian capital bill, but only employed 60 thousand workers, whose wages composed 3.5% of all wages earned in Norway that year (Statistics Norway - National Accounts data).[3]

Practically, changes in what is known about oil reserves are reflected in the annual reports of a national energy authority, the Norwegian Petroleum Directorate (NPD) in Norway

[3] An alternative to the Cobb-Douglas functional form of oil production as a function of the single factor capital is the CES production function of oil as a function of both capital and labor. The weight of labor is around 6.5% and constant over the timeframe examined. The constructed series of oil production using CES do not offer any improvement compared to a much simpler capital-only Cobb-Douglas function.

and the Department for Business, Energy and Industrial Strategy (BEIS, formerly DECC) in the UK. Proven reserves represent the engineers' best idea of how much oil, gas, and related commodities are economically recoverable. Changes to the size of oil reserves may occur because of new geological knowledge, extraction technology, or long-term commodity price outlook. For brevity, I refer to any changes to the reported proven reserves as discoveries, positive and negative.

The oil reserves are extracted in the production process,

$$Z_{t+1} = (-V_t + Z_t)\, af\epsilon_{z,t} \tag{4}$$

The stock of reserve in the ground, Z_t, is depleted by the oil production and is increased by the discovery shock, $\epsilon_{z,t}$, which is demeaned by the average find, af.

I convert the oil sector into intensive terms by dividing every variable by the labor force, L_t, and the technology level, A_t. For brevity, I refer to variables in intensive terms as "per effective worker" to note that the value of a macroeconomic variable is divided by that year's labor force and technology level. In the intensive form the law of motion shows that, without further discoveries, resources per effective worker will be diluted in a geometric series process

$$z_{t+1}(1+g) = \left(-DK_{v,t}^{\gamma} Z_t^{\eta} / \, A_t L_t\right) \tag{5}$$

I assume the exogenous growth rate of labor force and technology, g, to be constant, equal for home and foreign economies, and include the population and technology components. The growth rate is found as a ratio of effective workers of tomorrow to effective workers of today:

$$1 + g = \frac{A_{t+1}L_{t+1}}{A_t L_t} \tag{6}$$

The exogenous growth rate is assumed to be identical at home and abroad. If the production process is converted to the intensive terms, it becomes evident that oil-specific capital is diluted among the growing number of effective workers during the gestation period.

$$v_t = Dk_{v,t}^{\gamma} z_t^{\eta} (1 + g)^{-\gamma} \tag{7}$$

At any time period, only a fraction ϕ of oil firms can change their production volume:

$$v_{t+1} = \phi Dk_{v,t+1}^{\gamma} z_{t+1}^{\eta} (1 + g)^{-\gamma} + (1 - \phi) v_t. \tag{8}$$

Oil-specific capital begins to depreciate at the rate δ_v as soon as the oil starts flowing, but not when it is committed:

$$k_{v,t} = k_{v,t-1} (1 - \delta_v) \tag{9}$$

The oil sector contributes two stochastic state variables to the two model variables: home oil production, v_t, and home reserves, z_t. The oil sector supplies two conditions of the model, embodied by Equations (5) and (78). The first one describes the law of motion for reserves, the second one expresses home oil production as a function of oil-specific capital.

Oil sector firms solve a static profit-maximization problem. They keep investing capital into oil-specific capital (the well) until the static marginal product is equal to the price of capital. In the following period, the oil reserves decrease by the volume of oil produced, and the static marginal product of the well drops. To prevent overdrilling, the government issues production licenses to maximize the difference between the present value of the revenue stream and the capital sunk into the oil sector in the licensing that takes place upon a discovery.

I formalize the licensing authority's goal of prevention of overdrilling as the maximization of the discounted net present value of the cash flow from oil sales, V_t, at the price q_t, subject to the initial capital investment, $K_{v,0}$. While the firms maximize static profits, licensing authority maximizes the net present value of the cash flows from operations.

$$\max_{K_{v,0}} E_{t=0}\left[\sum_{t=l+1}^{\infty}\frac{q_t V_t}{\prod_{i=t}^{t} 1+r_i-\delta}\right]-K_{v,0} \tag{10}$$

This multi-period problem can be reduced to a static one. Following the steps in Part III Section 2.4, I derive a static formulation of the problem:

$$\max_{K_{v,0}} q_{ss}V_{l+1} \Bigg/ \left(1-\frac{\left(1+\gamma\ln\left(1-\delta_v\right)+\eta D K_{v,1}^{\gamma} Z_0^{\eta-1}\left(1-\delta_v\right)^{-l\gamma}\right)^{-1}}{\left(1+r_{ss}-\delta\right)^{l+1}}\right)-K_{v,0} \tag{11}$$

Differentiation with respect to initial investment yields the profit maximization condition. It has no algebraic intuition in it, but can be solved numerically.

This model of the oil sector follows the literature in that it maximizes the net present value of the lifetime cash flows associated with an oil discovery. To my knowledge, this paper is the only example of a first-period maximization in the dynamic general equilibrium literature, which is dominated by recursive problems. This approach is possibly the simplest representation of an exhaustible resource sector in the DSGE context.

3.1.2 Households

There are L_t households in the economy at time t. They maximize utility by consuming domestic goods, c_t, and imports, m_t. As in Hansen (1985), the utility of households is reduced by supplying labor, n_t, as a nonoil sector production factor. The households prefer to consume domestic and imported goods, as well as avoiding work, in the current period, agreeing to wait only if compensated at the constant rate β.

$$\max_{c} E\left[\sum_{t=0}^{\infty} U\left(c,m,n\right)\beta^{t}\right] \tag{12}$$

The budget of a household is given by the sum of factor incomes: rent on capital, $r_t k_t$, interest on foreign bonds, $\left(r_t-\delta\right)b_t$, which is lower than rent on capital to compensate for depreciation, wages, $\omega_t n_t$, and oil sales windfall. The country produces the quantity of oil, v_t, uses quantity, o_t, as a production input, and sells the difference abroad at the price q_t.[4] Total household income from supplying oil is $q_t v_t$, of which the income from domestic firms' oil purchases is $q_t o_t$.

$$\begin{aligned} r_t k_t+\omega_t n_t+q_t v_t = {} & c_t+p_t m_t+\left(k_{t+1}+k_{v,t+1}\right)\left(1+g\right)-k_t\left(1-\delta\right) \\ & -k_{v,t}\left(1-\delta_v\right)+b_{t+1}\left(1+g\right)-b_t\left(1+r_t-\delta\right) \end{aligned} \tag{13}$$

A household spends its budget on consumption of domestic (c_t) and imported (m_t) goods, net increase of nonoil (k_t) and oil capital, $k_{v,t}$, and net increase of claims on foreign

[4]There are examples in the literature (Bodenstein, Erceg, and Guerrieri 2011) where oil is also a final good, consumed by the households. With the focus of this paper on the upstream industry, crude oil is considered a production factor, whereas downstream oil products are considered consumer goods.

assets, b_t. In intensive terms, the budget outlays are diluted among the increasing numbers of workers and technology that together grow at the constant rate g. A household's budget constraint (13) puts together the sources and outlays of the budget.

In addition to the standard conditions (127 – 129), derived in Appendix A, the households' problem supplies the model definition of the current account as a function of other variables in the model.

$$q_t \epsilon_{q,t} (v_t - o_t) + x_t - m_t + b_t (r_t - \delta) = b_{t+1} - b_t \tag{14}$$

The left hand side represents the current account (pluses are credits) and is composed of net oil exports, $q_t \epsilon_{q,t} (v_t - o_t)$, net nonoil exports, x_t, and net payments of interest on capital $b_t (r_t - \delta)$. The shock term in the oil exports, $\epsilon_{q,t}$, represents the fluctuations of the spot market oil price, which affects the oil export revenue, but does not affect the technology and the oil bill in the national accounts. The right hand side represents the financial account (minuses are credits) and is limited to the net change of the NIIP.

3.1.3 Nonoil sector firms

Nonoil sector firms maximize profits as the difference between revenues from the sale of output, y_t, and production factor costs: rent on capital, $r_t k_t$, payments for oil inputs, $q_t o_t$, and wages for endogenous labor supply, $\omega_t n_t$.

$$\max_{k,o,n} y_t - r_t k_t^* - q_t o_t - \omega_t n_t \tag{15}$$

At any given time period, only a fraction of firms λ can change the amount of capital they borrow from households:

$$k_{t+1} = \lambda k^*_{t+1} + (1 - \lambda)\, k_t. \tag{16}$$

3.1.4 International markets

International markets complete the set of the conditions for the model. The conditions arise from identities in oil trade, trade of nonoil goods, and international price identities. Oil that is used in the production of consumption/investment goods at home, o_t, comes from domestic production at home, v_t. The implication is that oil cannot be stored into the next period. The oil supply that can be imported from the ROW is unlimited, but the cost of the commodity crossing the border increases in the imbalance of trade.

$$q_t = q_{ROW} \left(\frac{o_t}{v_t}\right)^{\zeta} \tag{17}$$

The elasticity of the cross-border premium with respect to the trade imbalance, $\zeta > 0$, establishes the increasing cost of securing additional shipments of oil across the border. The world oil price, q_{ROW}, is time-invariant, however, an exogenous stochastic oil price shock, $\epsilon_{q,t}$, affects the country's oil export revenue as in (14). The condition implies that the price of domestic oil is determined by the ROW price adjusted by the cross-border premium.

Capital investment is subject to a similar constraint. The total stock of nonoil assets is a sum of claims on domestic capital and foreign investment

$$b_t + k_t = a_t \tag{18}$$

Capital is mobile across borders at the end of a time period, but the premium on the foreign investment increases in the net international investment position.

$$r_t = r_{ROW} \left(\frac{k_t}{a_t} \right)^{\chi} \tag{19}$$

The elasticity of the cross-border interest premium with respect to the investment imbalance, $\chi > 0$, ensures the increasing marginal price of foreign capital.

There are no terms of trade implications for exports of goods. The relative price of the SOE and ROW goods is permanently set to unity, which reduces the household decision to simply importing a fixed part of consumption from the ROW. The share of imports in consumption is determined by the parameters of the utility function. The ability of the SOE firms to export their output is determined by the fixed demand for them in the ROW.

3.1.5 Structural model summary

This section defines the variables and motivates the choices of agents and conditions on the markets. The model in its steady state rests on 14 variables and 14 conditions. Endogenous variables include c_t, k_t, $k_{v,t}$, b_t, n_t, y_t, r_t, q_t, o_t, m_t and the oil sector variables v_t and z_t. The set of exogenous stochastic variables that are bound by the distributions, rather than conditions, is $\epsilon_{z,t}$ and $\epsilon_{q,t}$. The set of conditions consists of oil sector optimality equations (5) and (78), the budget constraint (13), household optimality equations (127)–(129), the current account equation (14), firm optimality equations (130)–(132), the international market conditions (17)–(108), and the solution for the oil capital, $K_{V,t+1}(Z_t)$ in Part III 2.4. The Calvo rigidity conditions, (64) and (16), add two dynamic variables and two dynamic conditions to the system.

3.2 Solution

System of equations (2) defines the relationship of interest that is oil discovery —current account. The rest of Section 3.1 produces the structural conditions based on the theory. I connect the structural model to the estimable linear system (2) by consecutively applying three techniques. The first step is to convert the theoretical conditions to a system of nonlinear differential equations. That is achieved by algebraically eliminating the static variables by substitution (Ruge-Murcia 2007). At that point the system only includes endogenous (state and non-state) and exogenous dynamic variables. The second step is the solution of the log-linearized system of dynamic equations. I use Uhlig's (1999) method of undetermined coefficients. The result is a system of first-order difference equations. In the third step, I estimate parameters in the system with maximum likelihood using the Nelder–Mead simplex search method and the Newton derivative-based method.

3.2.1 Functional forms, eliminations, and the reduced form

Most of the 14 variables of the model are static, i.e. are not conditioned on their values in the past periods. These static variables can be eliminated from the system by using up some of the conditions of the model. In order to carry out algebraic transformations, I make functional form assumptions about the utility and production functions. I adopt the neoclassical constant elasticity of substitution functions and follow the conventions established in Backus and Crucini (2000) and more recently employed in Bodenstein, Erceg, and Guerrieri (2011).

Utility of a household is a Cobb-Douglas function of final consumption (a combination of domestic goods, c_t, and imports, m_t) of households and leisure time, $1 - n_t$, which is a proportion of total time endowment that is not supplied as labor. The preferences between final consumption and leisure are regulated by the elasticity of utility with respect to consumption, ϕ.

$$U_t = \left[w_c^{\frac{\mu}{1+\mu}} c_t^{\frac{1}{1+\mu}} + w_m^{\frac{\mu}{1+\mu}} m_t^{\frac{1}{1+\mu}} \right]^{(1+\mu)\phi} n_t^{1-\phi} \tag{20}$$

Final consumption is aggregated from domestic goods and imports with a CES function. The goods are assigned their respective weights in the utility function, w_c and w_m. Elasticity of substitution between domestic goods and imports can be inferred from the respective parameter, μ (specification from Bodenstein, Erceg, and Guerrieri 2011):

$$e_{c,m} = \frac{1+\mu}{\mu} \tag{21}$$

The production function is a Cobb-Douglas combination of a capital good and endogenous labor, as in Backus and Crucini (2000). The contributions between the Cobb–Douglas inputs are regulated by the elasticity of the non-labor inputs α,

$$y_t = B \left[w_k^{\frac{\rho}{1+\rho}} k_t^{\frac{1}{1+\rho}} + w_0^{\frac{\rho}{1+\rho}} o_t^{\frac{1}{1+\rho}} \right]^{(1+\rho)\alpha} n_t^{1-\alpha}, \tag{22}$$

where B is a scale parameter. The capital good is obtained by combining nonoil capital and domestically used oil in a CES function with the aggregation weights w_k and w_o, where the elasticity of substitution is inferred from the parameter ρ.

Once specific functional forms are adopted, it is possible to perform stepwise elimination of static variables. I perform one of the many possible algebraic eliminations in Appendix

A to arrive at the system of three first-order difference equations for three variables, k_t, a_t, and z_t that also include shock variables for discoveries, $\epsilon_{z,t}$, oil production, $\epsilon_{v,t}$, and oil price, $\epsilon_{q,t}$.

The first three equations are the reductions of the Euler equation, the law of motion for assets, and the law of motion for oil reserves. The fourth and fifth equations in the system reflect Calvo rigidities in oil production, v_t, and nonoil capital investment, k_t^*. The stochastic variables follow an AR(1) process. In Part III, Section 3.1, I apply the solution techniques developed by Blanchard and Kahn (1980), Uhlig (1999), and Sims (2001) to obtain the reduced-form model of linear first-order difference equations in (23).

$$\begin{bmatrix} \ln \frac{k^*_{t+1}}{k_{ss}} \\ \ln \frac{a_{t+1}}{a_{ss}} \\ \ln \frac{z_{t+1}}{z_{ss}} \\ \ln \frac{v_{t+1}}{v_{ss}} \\ \ln \frac{k_{t+1}}{k_{ss}} \end{bmatrix} = \mathrm{P} \begin{bmatrix} \ln \frac{k^*_{t}}{k_{ss}} \\ \ln \frac{a_{t}}{a_{ss}} \\ \ln \frac{z_{t}}{z_{ss}} \\ \ln \frac{v_{t}}{v_{ss}} \\ \ln \frac{k_{t}}{k_{ss}} \end{bmatrix} + \mathrm{Q} \begin{bmatrix} \epsilon_{z,t} \\ \epsilon_{q,t} \\ \epsilon_{v,t} \end{bmatrix} \tag{23}$$

4 Data and estimation results

The goal of estimation is to establish the direction, magnitude, and duration of the current account response to a discovery shock and show how an oil fund, the equity home bias, and oilfield technology affect the country's ability to save oil revenues internationally. In terms of the estimated model, the current account and oil discoveries are variables, while home bias, oil fund, and technology are represented by structural parameters.

The system of first-difference linear equations (2) is sensitive to a large number of structural parameters of the underlying theoretical model. Where feasible, I obtain the values of the parameters from commonly accepted theoretical conditions. For example, in a production function of the form

$$y = k^{\alpha} n^{1-\alpha},$$

capital gets α share of factor payments, and labor gets $1 - \alpha$. Thus, it is possible to infer the value of α by comparing the operating surplus to the wage bill in the national accounts data.

Table 1: Structural parameters

Parameter	Notation	Value for Norway	Value for the UK	Source/Method
Parameters inferred from data				
Aggregation weight of imports	w_m	0.52	0.32	Inferred from ratio of imports to total consumption. National accounts (NOS, ONS Pinkbook).
Elasticity of substitution imports/domestic	μ	—	—	Irrelevant because of fixed relative prices of foreign and domestic goods.
Elasticity of nonoil production wrt non-labor inputs	α	0.29	0.33	Obtained by factor payment method from national accounts
Aggregation weight of capital	w_k	0.95	0.94	Obtained by the factor payment method. National accounts (NOS d426, ONS). Oil data: NOS, tables 09170, 09174, ONS series LRXB, O&G UK Economic Report 2014 Figure 13.
Aggregation weight of oil	w_o	0.05	0.06	
Scale parameter in nonoil production	B	54.27	4.8	A ratio of the mean observed output and mean result of plugging the values for the production factors into the chosen production function
Scale parameter for oil production	D	0.12	0.53	A ratio of mean observed oil production and mean result of plugging the values for the capital and reserve into the chosen oil production function.
Growth rate in the steady state	g	0.02	0.025	Population: NOS, table 06913, ONS population estimates. Technology obtained as Solow residual (technology is Harrod-neutral). Series for Y, C, K from respective national accounts.
Steady state level of oil reserve	z_{ss}	251	2.6	The average of the lowest values of z_t in the observed series
Rate of nonoil capital depreciation	δ	0.04	0.04	Adopted as a standard literature value (Mankiw, Romer, and Weil 1992).
Rate of oil capital depreciation	δ_v	0.06	0.06	Established by the permanent inventory method between the investment into the oil industry and capital stocks.
Estimated parameters				
Elasticity of substitution capital/ oil	ρ	-2.31 (0.32)	-2.74 (2.49)	Estimated by maximum likelihood. Translates into elasticity of substitution as $e = (1+\rho)/\rho$. Values are consistent with the Backus and Crucini (2000) calibration.
Intertemporal preference rate	β	0.983 (0.003)	0.976 (2E-4)	Here and below: estimated by maximum likelihood.
Elasticity of oil output wrt oil capital	γ	0.59 (0.04)	0.64 (0.11)	—
Elasticity of utility wrt total consumption	ϕ	0.39 (0.04)	0.42 (0.05)	—
Interest rate premium on borrowing from abroad	χ	1.5E-5 (3.1E-6)	0.013 (0.003)	—
Rate of decay of the interest rate premium	$\chi_1/\chi_0 - 1$	0.004 (0.023)	0.009 (0.01)	—
Cost premium on importing oil	ζ	0.005 (0.001)	0.002 (0.011)	—
AR coefficient for oil discovery shocks	ar_z	-0.45 (7.62)	-0.13 (2.15)	—
AR coefficient for oil price shocks	ar_q	0.35 (0.15)	0.12 (0.04)	—
AR coefficient for oil production shocks	ar_v	0.68 (0.39)	0.55 (0.56)	—
Calvo-style stickiness in oil production	η	0.56 (0.03)	0.29 (0.06)	The greater the η, the more flexible the oil production is.
Calvo-style stickiness in nonoil capital employed	λ	0.001 (1.6E-4)	0.007 (0.002)	The greater the λ, the easier it is to adjust capital employed.

I estimate only the parameters that are difficult to access by applying theoretical conditions to the data: intertemporal discount rate, β, elasticity of substitution between oil and capital in the production function, ρ, elasticity of oil production with respect to oil-specific capital (as opposed to the remaining reserve), γ, elasticity of utility with respect to consumption (as opposed to leisure), ϕ, premiums of moving capital and oil across the border, and χ and ζ respectively. I allow the interest rate premium χ to decay over time as a geometric series and estimate $\chi_{t-1}/\chi_t - 1$, the rate at which it happens. Parameters η and λ measure Calvo-style rigidities in the production of oil and its usage as a production factor in the nonoil economy. Finally, I estimate the autoregressive coefficients of the shock variables. Table 1 summarizes the estimated and inferred parameters of the model.

The estimation algorithm is as follows: first, obtain the system of first difference equations of the form of equation 23 (Uhlig 1999), second, evaluate the joint density of the observed values of k_t, a_t, z_t, and third, iteratively choose parameter values in a search for the vector that maximizes the likelihood of the observations using the Nelder–Mead simplex and Newton–Raphson derivative-based search methods. To report errors, I obtain the covariance matrix as the inverse of the negative of the Hessian matrix in the Newton–Raphson method:

$$\Sigma_P = \left[-\frac{\partial^2 \ln L(X|\theta)}{\partial\theta\partial\theta^{\mathsf{T}}} \right]^{-1}, \tag{24}$$

where θ is the parameter vector, and $L(X|\theta)$ is the likelihood function for normal distribution. I compute the Hessian matrix numerically as the marginal change of the likelihood gradient.

The data come from five sources: British Office of National Statistics (ONS), UK Department for Business, Energy, and Industrial Strategy, BEIS (formerly Department of Energy

Table 2: Summary of the data inputs

Input Data	Notation	Value Norway	Value UK	Source/Method
Model inputs				
Nonoil capital (thousands of 2005 NOK/GBP per effective worker)	k_t	563.48 (32.57)	33.26 (1.52)	$k_t = K_t\,/(A_t L_t)$
Assets in the home economy (thousands of 2005 NOK/GBP per effective worker)	a_t	525.99 (137.25)	33.30 (1.56)	$a_t = (K_t + B_t)\,/(A_t L_t)$
Reserves of oil (sm3 o.e. per effective worker)	z_t	682.87 (263.43)	15.65 (8.98)	Norway: 1997–2012: NPD resource account. Prior to 1997: NPD annual reports. UK: 1995–2012: ONS Estimates of remaining recoverable oil & gas reserves and resources. Prior to 1995:DECC.
Series used to infer structural parameters and to construct model inputs				
Capital	K_t			NOS: National Accounts b048 / Statistics Norway table 09181; Starting 1997: Gross Capital Stock: S.13: TOTAL: Ind TOTAL: CVM NSA CONS Prior to 1997: OECD stan CPGK Gross capital stock, volumes.
Population	L_t			Statistics Norway table 09174; ONS Population Estimates for UK, England and Wales, Scotland and Northern Ireland, Population Estimates Timeseries 1971 to Current Year.
Consumption	C_t			IMF IFS; Statistics Norway; Household final consumption expenditure by purpose ABJQ; General Government: Final consumption expenditure (P3): CPSA £m, NMRP.
NIIP	B_t			Statistics Norway table 08291; UK: BoP IIP Net NSA £m HBQC.
Consumption of oil as a production input	O_t			BP Statistical Review (2015), adjusted by technology and labor.
Oil production	V_t			Statistics Norway table 10256; DECC UK PPRS monthly production data.
Proven reserve	Z_t			Norway: 1997–2012: NPD resource account. Prior to 1997: NPD annual reports; UK: 1995–2012: ONS Estimates of remaining recoverable oil & gas reserves and resources. Prior to 1995:DECC.
Imports	M_t			Statistics Norway table 09401/ National Accounts b048, b934; Balance of Payments: Trade in Goods & Services: Total imports: CP SA.
Output (GDP)	Y_t			IMF IFS; Statistics Norway; ONS QNA Q3 2013 Gross domestic product: expenditure at current market prices.
Capital bill	$r_t K_t$			NOS: National Accounts d426; ONS Blue Book Gross Operating Surplus: Total: CP NSA ABNF Price CURR.
Wage bill	$\omega_t L_t$			Norway Quarterly national accounts, 4. quarter 2013, Table 46. Compensation of employees; ONS Blue Book Income based:UK: Uses:Total compensation of employees:D.1: CP NSA.
Oil bill	$q_t O_t$			NOS: National Accounts table 09170, 09174; Starting 1997 ONS DIOP: 06:Extraction Of Crude Petroleum And Natural Gas: CVMNSA; ONS BB CDID CoE D.1 Production A2 CP SA, and ONS IOP 05 Output of the Production Industries.

* The table reports mean values for stationary series only. Standard errors are in parentheses.

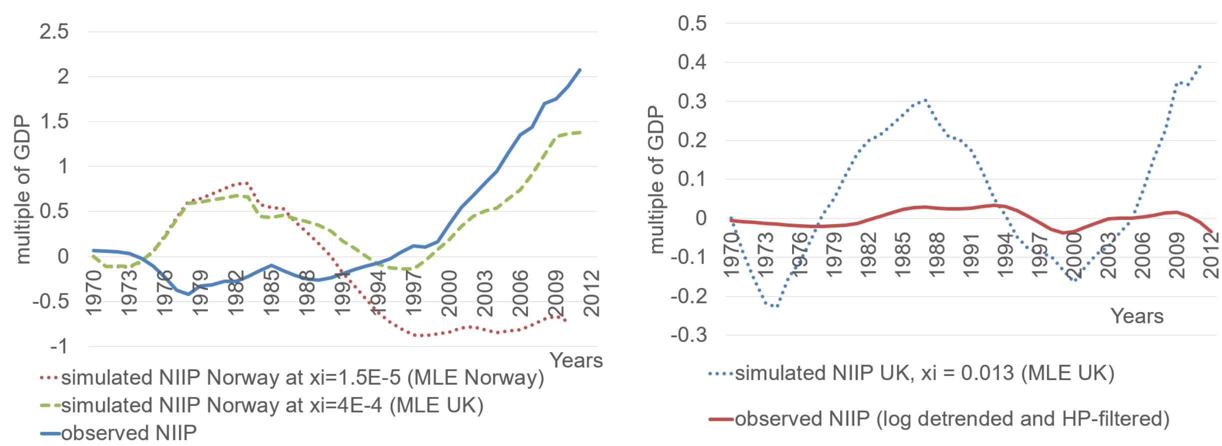

Figure 1: Overlay of simulations of the current account responses and the observed series for Norway (left) and the UK (right). When the UK's value for χ is applied to Norway, the simulation produces a realistic current account response.

and Climate Change, DECC), Norwegian Bureau of Statistics (NOS), Norwegian Petroleum Directorate (NPD), and the BP Statistical Yearbook. The series run from 1970 to 2012 with annual frequency, unless specifically noted otherwise. All the series are converted into 2005 Norwegian krones and British pounds respectively, using the GDP deflator. Additional information on parameter and input data is available in Appendix B.

Table 2 lists all the data series used in the analysis, both to construct the intensive-form (divided by labor force and the technology level in order to achieve stationarity) model inputs and to infer structural parameters. Since the input data are stationary, I provide units and descriptive statistics for them, as well as their formulas. All the values are divided by the technology level (1970 is equal to one) and labor force in order to be in intensive form.

4.1 Simulation of the current account using the estimated model

Figure 1 is a simulation of the current account behavior in response to the actual shocks using the theory in Section 3 and the estimated parameters. Overall, the simulation reproduces the surplus NIIP for Norway and lack thereof for the UK. Notable deviations include: Norway forming a moderate surplus on the wave of initial production coupled with high oil prices in the late 1970s, Norway going into deficits during the oil glut of 1980s and spending prompted by the gas discoveries of the early 1990s, and the UK assets being unrealistically sensitive to oil price fluctuations.

By 1980, the Norwegian oil production increased from 0 to 10 million standard cubic meters of oil equivalent (sm3 o.e.). Combined with the high oil prices resulting from the 1979 oil shock, Norway's annual oil export revenue reached 15% of the country's GDP. With the estimate of the home bias as low as $\chi_{NO} = 1.5E - 5$, the simulation proceeds to form international savings. In the case of Norway, adopting values for χ and its rate of decay so that the home bias is initially large and decreases at a high rate, helps eliminate the large NIIP balances of the late 1970s and early 1980s in Figure 1, created by the simulation but not present in the data.

The Norwegian χ is lower than the UK one. Taken at face value, this result suggests that the UK suffers from a higher equity home bias which inhibits large current account surpluses. However, as is evident in Figure 1, assigning the British home bias value to Norway does not inhibit Norway's ability to accumulate the NIIP as large as observed in the data. In fact, given the parameter values that maximize likelihood, Norway fails to accumulate any claims on foreign assets in the simulation. However, when assigned the UK's home bias value, the simulation for Norway produces a very close match to the observed current account[5].

[5]Norway keeps roughly two of its GDP, or 40% (4 out of 10 trillion NOK) of its total assets abroad, while the UK's adjusted NIIP is around 8% of its GDP ($100 billion out of 5 trillion GBP of assets). This costs them $1 - ((10-4)/10)^{1E-5} = 0.0005\%$ and $1 - ((5-0.1)/5)^{0.0127} = 0.02\%$ premium on the capital cost. Increasing σ_{NO} to 4E-4 brings up Norway's capital cost premium to being on par with the UK's.

Norway fails to develop a NIIP surplus with its likelihood-maximizing parameters because with the home bias as low as 2E-5, mechanically there is very little force to bring the system back to the steady state after

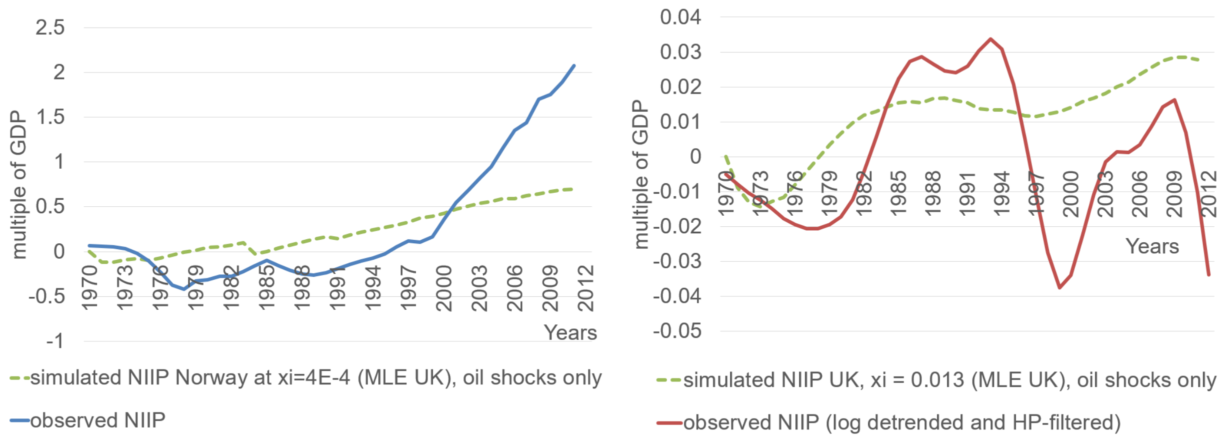

Figure 2: Simulations of the current account responses to oil discovery shocks only, compared to the observed series for Norway (left) and the UK (right).

The model overestimates the UK current account's sensitivity to oil price. This is because the British steady state oil production is much smaller than its oil consumption. When oil prices are high, the model suggests the UK will compensate its oil costs by the rent from a surplus NIIP. As oil price drops, the UK spends the surplus position. A simulation without price shocks in Figure 2 produces a roughly balanced current account, with modest surpluses during the periods when the UK is a net oil exporter.

It is informative to separate the effects of discoveries from those of oil price shocks, as in Figure 2. Stripped of the oil price shocks, the current account surplus is much more gradual for Norway, whereas the UK's modest oil exports barely register in its current account. Therefore, the rapid Norwegian buildup of a massive international oil fund is due to a lucky combination of large oil exports and high oil prices in the 2000s.

The breakdown in Figure 2 also gives the true reason why the UK did not form its own oil fund. While the North Sea oil allows it to balance its oil trade, the UK only maintains

the losses from low oil prices in the late 1980s and 1990s. The model exhibits unit root dynamics, and subsequent Norwegian oil revenues take longer to bring NIIP into the surplus territory.

modest net export in 1980s and 2000s, which, proportionately to the size of its economy, are an order of magnitude smaller than the Norwegian exports. Even the oil price shocks have the opposite effects: while Norway, being the net exporter, gets a current account boost from the improved terms of oil trade, the UK, a net importer around the steady state, has to build up international savings, the rent on which will offset the losses from the worsening terms of oil trade. The circumstances, timing, and the relative magnitudes of oil production and exports explain the difference in the two countries current accounts, while their structural parameter estimates are practically similar.

4.2 Sensitivity of the current account to parameters

System of equations 2 describes the current account response to shocks to the oil reserve (a discovery) and to the oil price. The equation relies on matrices P and Q, which themselves are functions of the structural parameters of the theoretical model (Table 1). Three of them, the intertemporal discount rate, β, the equity home bias, χ, and rigidity of the oil sector, η, are the major factors that determine the current account response to a discovery.

The intertemporal discount rate, β, is the price a person charges for waiting to consume until the next year, rather than now. With so many similarities between the economies of Norway and the UK, such as similar institutions, levels of income, culture, and international positions at the fringes of the European Union, there is little reason to expect an inherent difference in patience between the two peoples. The estimates, $\beta_{NO} = 0.983$ and $\beta_{UK} = 0.976$, suggest that the British charge a third more than Norwegians for waiting to consume.

The coincidence of having an oil fund and a high patience, β, can mean either of two things. First, it is possible that, given that the Norwegian oil fund arbitrarily saves the entire oil export revenue and only allows consumption of interest, it made the Norwegian fiscal policy more conservative than the population's patience would dictate otherwise. The second possibility is that the Ricardo-Barro effect is incomplete, if present at all. It implies that the Norwegian population is not highly patient, but once the arbitrary oil fund rule is adopted by the public sector policymakers, private households fail to adjust their consumption to counteract the impact of such a fiscal contraction. In both of these interpretations, the oil fund implies a fiscally conservative public sector for Norway, inconsistent with intertemporal preferences of the population, if comparison with the otherwise similar UK is any indication.

An oil discovery leads to a buildup of NIIP regardless of the value of β. The intertemporal discount rate just slightly amplifies the current account response. In Figure 3, I simulate the two countries' current account responses to a one-time discovery commensurate with the actual figures, 5 and 3.5 billion sm3 o.e. for Norway and the UK, respectively. A one percentage point reduction of β from the estimated values results in a 40% smaller NIIP for Norway and a 20% smaller NIIP for the UK.

The interest rate premium on borrowing/lending abroad, χ, and its rate of change, $\chi_{t+1}/\chi_t - 1$, represent the ability of the country's asset managers to borrow and invest abroad profitably. The estimates of $\chi_{NO} = 1.5E - 5$ and $\chi_{UK} = 0.013$ point to a low equity home bias. A high χ points to equity home bias and leads to a larger difference between the domestic and ROW interest rate. Figure 3 demonstrates how a higher equity home bias leads to a faster reversal of the NIIP to the steady state. While Norway uses oil export revenues to build up a surplus position, the rent from the international savings continues to support the surplus long after the oil is gone. With the UK's higher home bias estimate, the NIIP peaks

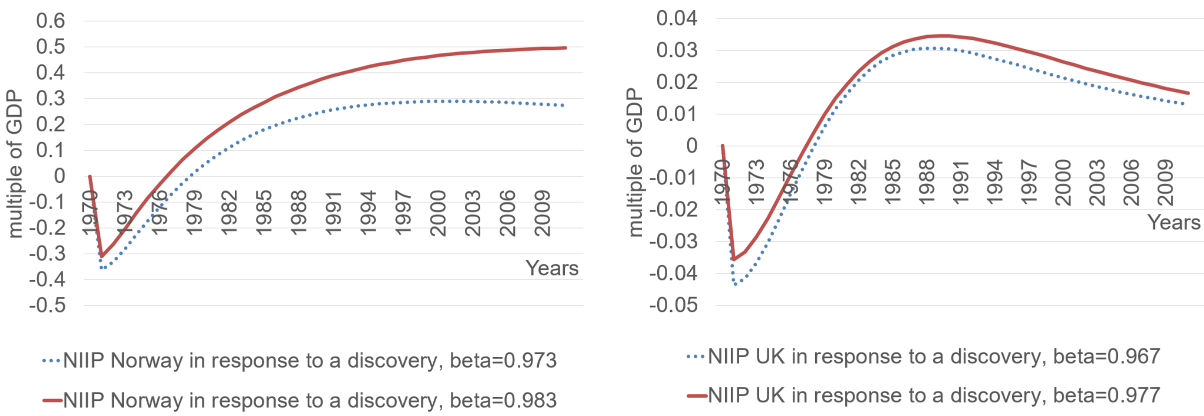

Figure 3: Simulations of the current account responses to a major oil discovery for Norway (left) and the UK (right). Decreasing β by one percentage point slightly amplifies the magnitude of the impulse responses.

out in the immediate aftermath of the oil exports and begins to gradually decline. The home bias estimates are so low that even in the UK's case half-life of the current account reversal is two decades. The North Sea oil is an ongoing case. The validity of these low estimates is to be verified once Norway runs out of oil, and new data clearly show the rate of the NIIP reversal.

Rigidity of oil production, η, reflects the difficulties that the oil sector faces with licensing and development of new fields. Although large reserves are immediately available in 1970 in both countries, production struggles to pick up to optimal levels for another decade. Accordingly, the model produces low estimates for the Calvo-style stickiness in oil production: only $\eta_{NO} = 0.56$ and $\eta_{UK} = 0.29$ of firms can change their oil production to the optimal level at any given year. Figure 4 compares the current account impulse responses with the estimated parameters to the ones with zero oil sector rigidity. Difficulties within the oil sector result in one to three year lag in repayment of the initial deficit and accumulation of international savings.

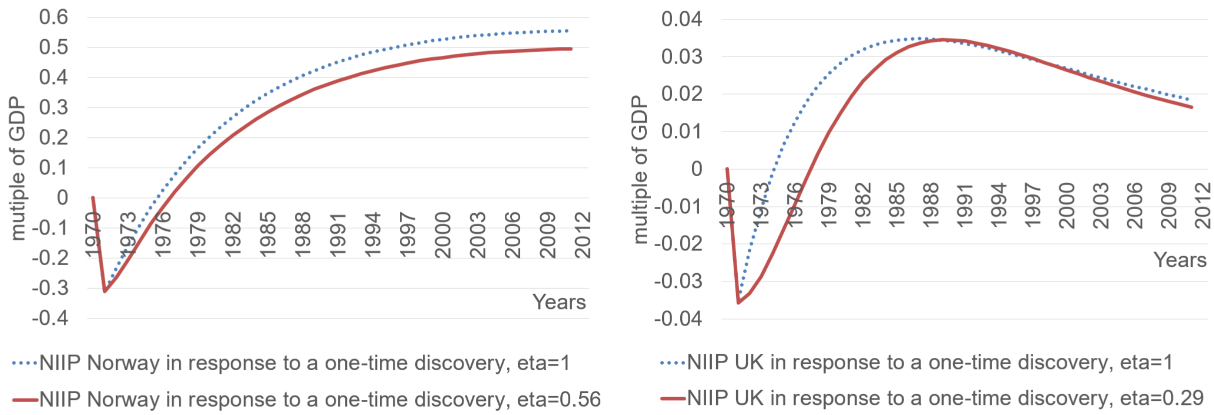

Figure 4: Simulations of the current account responses to a major oil discovery for Norway (left) and the UK (right). Allowing all oil firms to instantly adjust production to optimal volumes eliminates a one- to three-year lag in the accumulation of international savings.

The parameters that represent the main policy and technological factors of the current account response to an oil discovery, the intertemporal discount rate, β, the equity home bias, χ, and rigidity of the oil sector, η, affect the magnitude, duration, and lag of the current account response. Most of the remaining estimates are similar for the two countries. Cost of moving oil across the border (the oil market's counterpart for equity home bias) is $\zeta_{NO} = 0.005$ and $\zeta_{UK} = 0.002$, implying that it is easier to export oil than invest capital abroad for the UK, and the opposite for Norway. Capital and oil are poor substitutes in both countries, with $\rho_{NO} = -2.31$ and $\rho_{UK} = -2.74$. Poor substitutability is consistent with Backus and Crucini (2000) and Miyazawa (2009) and contradicts Kim and Loungani (1992). In both countries, elasticities of oil output with respect to oil capital, $\gamma_{NO} = 0.59$ and $\gamma_{UK} = 0.64$, suggest that investment is slightly more important for oil production than the oil reserve. Shock autoregressive coefficients are insignificant for discoveries, $ar_{z,NO} = -0.45$ and $ar_{z,UK} = -0.13$, but are consistent and statistically significant for oil prices, $ar_{q,NO} = 0.35$ and $ar_{q,UK} = 0.12$. The opposite would have been surprising, given that both countries are in the same fairly frictionless oil market. The elasticity of utility with respect to consumption at $\phi_{NO} = 0.39$ and $\phi_{UK} = 0.42$ suggests that consumption is more responsive to shocks than the production factors.

Structural parameters affect the shape of the current account response to the oil sector shocks but do not cause a country to save or borrow internationally. Between 1970 and 2012, Norway discovered 11 billion sm3 o.e. and produced 6 billion. In the same time, the UK discovered 6.6 billion sm3 o.e. and produced 6.1 billion. If all else, including structural parameters, was equal, the countries would have generated similar-sized international savings. Although the two countries found and produced similar volumes of oil, Norway exported 92% of its, whereas the UK merely broke even. Further, Norwegian export revenues were enhanced by high oil prices in the 2000s. While structural parameters affect international savings, the ability to export oil and terms of oil trade cause them.

5 Conclusion

Upon oil discoveries, countries take steps to manage the windfall of wealth optimally. The common areas of attention are public management of resource wealth (oil funds), effectiveness at international asset management, and securing adequate oilfield technology. To assess the effects of potential initiatives in these areas, I construct a theoretical model of the relationship between oil discoveries and the current account, estimate it and check its credibility by simulating the outcomes observed in the data.

A SOE RBC model with a resource sector, parameterized by MLE, succeeds at reproducing the key elements of the North Sea oil history. Most importantly, both in practice and simulation, Norway uses its oil export revenues to create international savings, whereas the UK does not. The three key reasons for the discrepancy are that (1) while Norway benefited handsomely from the 2000s oil price spike while the country's oil and gas exports were at their peak, (2) the UK discovered less oil relative to the size of its economy and (3) was never truly in the position to export it. The structural parameters suggest that Norway's public oil fund puts downward pressure on the overall intertemporal discount rate of the population, which modestly promotes savings. The overall similarity of the estimates for the two countries means that the two countries made the same decisions in the wake of the North Sea oil discovery. However, the decisions were made under different circumstances, and therefore impacted the current accounts differently.

Estimates of the structural parameters allow to make inferences about the effects of the initiatives in the three areas of resource wealth management. Initiatives to increase patience amplify the size of international savings of oil wealth. It is likely that an oil fund causes a change in the country's intertemporal preferences. Equity home bias determines the duration of the country's international savings. Low home bias, as in the case of Norway, facilitates extremely long-lived surplus net international investment position. The rigidity of oil-producing technology determines the lag between the discovery of oil and the formation of international savings. Difficulties producing the reserves imply losses from financing initial borrowing and delayed revenues.

The conclusions obtained here are case-specific and may not hold for other technologies (traditional oil vs. shale oil and gas) and types of resources (oil and gas vs. rare earth elements). However, this is likely the simplest and most flexible adaptation of modern macroeconomic general equilibrium theory to the question of natural resources in an open economy. This framework can easily be adapted to support decisions in particular cases of resource wealth management.

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Chapter II. The effects of a carbon tax on new electricity generators in the US

1 Emissions and carbon tax policy

Modern society emits vast amounts of greenhouse gases that are causing rapid and potentially destructive climate change. The largest and fastest growing emitter of anthropogenic greenhouse gases is the energy sector (IEA, 2011). In the United States, electricity generation emits 40% of the carbon dioxide (CO_2) because most power plants still burn coal or natural gas, and therefore, are considered 'dirty' (EIA, 2011). A small but growing segment of US electricity generation is carbon-neutral, using 'clean' energy sources such as wind and solar. To reduce emissions, a common suggestion is to price carbon, through a tax or a cap-and-trade policy. These policies discourage dirty generation by raising the cost of burning fossil fuels and potentially shift the market toward alternative, clean sources. I estimate the effects of a carbon tax on construction of new generating capacity for natural gas and wind turbines. These are the only two types of generators built in significant numbers in most states during my 25-year study period.[6] I ask three main questions: If adopted, how does a carbon tax affect construction of capacity that uses natural gas? Does a carbon tax affect new wind-powered capacity construction? And finally, how do different sizes of the tax, from $10 to $100 per ton of carbon, affect total emissions and carbon intensity of a megawatt-hour (MWh)?

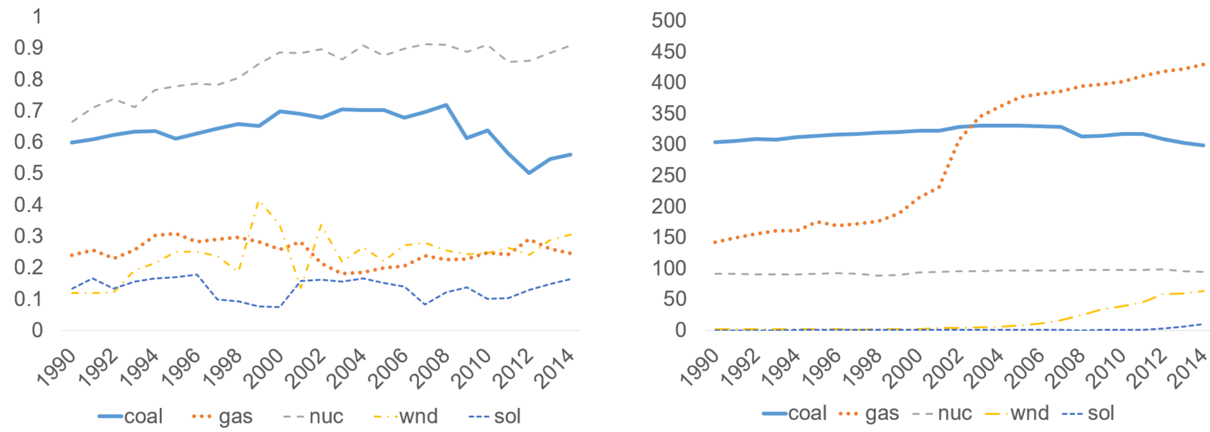
[6]Construction of coal and nuclear generators nearly ceased after the early 1990s. Solar gained in 2010s but only four states currently have large-scale generation (CA, AZ, NV, and NC).

While no actual carbon tax is imposed on US electricity generation, I proxy for the tax using variation in fuel cost as in (Cullen and Mansur 2017), for a number of reasons: First, fuel cost for electricity generation is observable. Second, the cost varies across geography and through time. Fuel cost comprises the largest component of the marginal cost. Further, both fuel costs and carbon taxes add per-unit to the marginal cost of generation. That is, a $10 per ton carbon tax simply increases the marginal cost per MWh by the carbon intensity of a megawatt-hour in tons of CO_2 per MWh. Therefore, the historical variation in fuel costs simulates a carbon tax.

Taxes raise the price of carbon emissions. Electricity firms may reduce emissions from generation in two ways: fuel switching or construction of new capacity. Fuel switching replaces the fuel a power plant burns to a less dirty one, typically from coal to natural gas. Recent literature studies how fuel prices affect fuel switching, and thus emissions. Cullen and Mansur (2017) estimate how the ratio of coal to gas prices influences an electricity firm's switching from coal to gas inputs. Fell and Kaffine (2018) show that the interaction of falling natural gas prices after 2007 and cheaper wind turbines led to a large reduction of coal generation. Linn and Muehlenbachs (2018) find that the decrease in natural gas prices over the same time period caused either reductions in CO_2 emissions or decreases in the retail electricity price across the US. Knittel, Metaxoglou, and Trindade (2016) compare firms in regulated and deregulated electricity markets, finding that deregulated firms are less responsive to effect of the cheaper natural gas on switching from coal to gas.

The potential for fuel switching is limited because (1) few fuels are viable as substitutes and (2) the current capacity of power plants with substitutable fuels is fixed in the short-run. Currently, fuel switching can reduce approximately 15% of emissions (Macmillan, Antonyuk,

Figure 5: Twenty-five year trends by fuel type.



(a) (b)

(a) Mean capacity factor by fuel type, on left, and (b) installed capacity by fuel type in gigawatts, on right. Panel (a) shows that in the 25 years analyzed, generation from fuels were run at more or less constant capacity factor, the only exception being the slowdown of use of coal generators in 2008 in response to cheaper gas. By contrast, Panel (b) shows that new capacity construction changed the makeup of the US electricity generation in 2002 through gas construction and 2010s via wind.

and Schwind 2013). Construction of new capacity is more flexible than fuel switching, but is a long-term response to a change in fuel cost. The novelty of my research is estimating the effect of a carbon tax on building of electricity capacity, rather than fuel switching.

Figure 5 compares two channels over 25 years: (a) fuel usage measured as the percentage of time used, known as capacity factor, and (b) total capacity by generation type. Panel (a) is the intensive margin: capacity factor remains stable for dispatchable generation.[7] A notable example of fuel switching is a 15-percentage-point drop in usage of coal in the late 2000s, as a reaction to cheaper natural gas. By contrast, in Panel (b) of Figure 5, new construction and plant closures have three lasting effects on electricity generation: Introduction of combined-cycle gas turbines (CCGT) in the late 1990s led to a 200% increase in gas generators. Forty

[7]sources that are subject to weather and climate variations fluctuate, such as wind and solar.

percent of coal capacity closed due to cheap natural gas in the late 2000s and 2010s. Recently, wind (and solar) generators reached seven percent of generating capacity. As the result of these changes, electricity today is generated from different fuels than 25 years ago. The amount of coal generation peaked in the mid-2000s and then returned to the level of 1990. In addition, natural gas has replaced nuclear as second-to-coal.

I estimate the extent that a carbon tax inhibits construction of new gas generators and promotes renewables. In 1990, a MWh of electricity, on average, emitted 0.67 tons of CO_2. By 2014, a MWh released 0.61 tons of CO_2. The average carbon intensity of new capacity is 0.3 tons CO_2/MWh — half as dirty as legacy capacity. The reduced emissions and carbon intensity per MWh are due to proliferation of CCGT and cheap natural gas, along with construction of renewables, wind and some solar. I use the fuel costs and megawatts of newly built capacity over the last 25 years in the 48 contiguous states. A methodological challenge is that most of the time firms build zero new capacity in a given state-year. These corner outcomes point to using Heckman's two-part model. I test robustness of the Heckman approach by also estimating outcomes with a linear fixed effects model. I then use the estimates of the tax effect to make inferences about the carbon intensity of new generating capacity for a given size of the tax.

To my knowledge, this is the first measurement of a carbon tax effect on the construction of clean and dirty electricity generators. However, this idea has a precursor in the paper industry: Gray and Shadbegian (1998) relate the prevalence of environmentally-friendly legislation and the choice of clean or dirty technology for new paper mills. The authors find that mills in states with more environment-friendly legislative votes are less likely to use the dirtiest technologies, though impact on plant size is small and not always significant.

I obtain state-level carbon tax effects separately for gas and wind generating capacity. Overall I find that fuel cost, and by extension a state-level carbon tax, discourages construction of carbon-intensive gas generators relative to business-as-usual, but does not directly promote carbon-neutral wind capacity. If a state adopts a \$10 per ton of CO_2 tax, the state sees a 3% reduction in the size of new capacity commitments relative to the counterfactual growth in these power plants. The effect is statistically significant and robust across the two approaches, the Heckman two-part model and a linear fixed effects model.

The effect of a carbon tax on new wind capacity is statistically insignificant: a tax policy will not likely encourage or discourage wind generation in the near term. However, other environmental regulation directly encourages renewable generating capacity. The dominant policy is called renewable portfolio standards (RPS), which are set and enforced at the state level. These standards typically require that power providing firms generate a certain share of their electricity from the renewable fuels by a specific date in the future. Thus I also include each state's RPS stringency as an explanatory variable. I find that one percentage point of unfulfilled RPS increases the size of new wind capacity by 10%.[8]

The consensus is that carbon emissions are global negative externalities, but the ideal policy depends on perspective. Economists prefer efficiency, which sets a tax at the marginal external cost of the emissions or sets a cap at the socially optimal level of emissions. An accurate carbon tax corrects the inefficient market outcome by tacking on the social cost of carbon (SCC). The Interagency Working Group on Social Cost of Carbon, United States Government (2010) produces estimates of the social cost of carbon ranging from \$7 to \$81

[8] I also perform limited analysis for solar in Appendix G, finding that solar generators have been present in too small a number of states and for too short amount of time for any statistically significant relationship between the fuel cost and new solar capacity.

per ton of CO_2. Moore and Diaz (2015) obtain larger estimates, placing the cost at $220 per ton of CO_2.

Political feasibility reveals another perspective. In Canada, British Columbia implemented a carbon tax in July 2008 that as of 2016 stands at 35 Canadian dollars per ton of CO_2. The US experience with carbon tax policy has stagnated at proposals which tend to fall short of the SCC. An example, from February 2016, is President Obama's "$10 a barrel" carbon tax proposal. Later the same year, Washington State voted down Measure I-732, a $15 per ton of carbon emission tax on fossil fuels in electricity generation. However, in the intervening year, nine other states introduced bills that propose studying or using financial penalties to discourage the use of fossil fuels and to encourage the growth of alternative fuel sources (Daigneau 2018).

When considering such proposals, policymakers have strong motivation to understand the effect of the tax on the electricity industry. Therefore, I calculate outcomes for several sizes of carbon tax on construction, providing estimates of generation, emissions, carbon intensity, and then aggregate these to projections of ten-year emission reductions. I consider three scenarios, state-level carbon taxes of $10, $35, and $100. Respectively, the average carbon intensity of new capacity is 0.296, 0.277, and 0.199 tons per MWh — making the new generators three to thirty-three percent cleaner on average.

New capacity built in a given year is 1% of existing capacity. In 2014, 370 MW of new generating capacity was built in an average state. Of that, 186 MW were gas and 170 were wind. A $10 tax reduces the figure for gas to 175 and a $100 tax to 70 MW of new capacity. For an average US state, this translates into emission reductions of 600, 2000, and 5700 tons of CO_2 over ten years.

2 Model of new generating capacity

I identify the effect of carbon price on megawatts of new capacity by modeling a Heckman two-part decision: first, I estimate if new electricity generating capacity is built, and if yes, I estimate how much. The proxy variable for carbon tax is markup, the difference between the retail price of electricity and the cost of fuel required to produce a MWh. The unit of analysis is state and year. I check the robustness of my findings to state and year effects with a fixed-effect linear probability model.

2.1 Corner outcomes and the two-part decision

I use a version of the Heckman two-step framework, which Wooldridge (2010, p. 697) refers to as exponential type 2 tobit (ET2T). Appendix C adapts the ET2T framework to the specifics of my case. In my adaptation, the response variable is size in MWh of new capacity, and is a function of the first-step decision to build. The decision is defined by an unobserved, latent variable. Thus, I model the expected response as an exponential function of the explanatory variables if the latent variable is greater or equal to zero. The response variable is set to a corner outcome of zero whenever the latent variable is negative.

$$y = \begin{cases} \exp(x\beta) & \text{if } (z\gamma) \geq 0, \\ 0 & \text{if } (z\gamma) < 0 \end{cases} \tag{25}$$

In (25), $\exp(x\beta)$ is the conditional expectation of the size of new capacity. To obtain the unconditional expectation, $\exp(x\beta)$ is weighted by the probability of a positive new capacity.

$$y = \Phi(z\gamma)\exp(x\beta) \tag{26}$$

In (26), probability Φ is a function of a vector of explanatory variables, z. For identification, vector z must include at least one variable that is exogeneous to capacity size (Wooldridge, 2010, page 702). Our exogenous variation is electricity price markup, as described and justified below, which also acts as a proxy for a carbon tax and allows us to estimate the effects of this yet-to-be-implemented policy.

2.2 Marginal cost of electricity and price markup

The marginal cost MC to generate electricity involves a numerous components:

$$MC = \frac{CC + O\&M}{Q} + FC + \tau \times CI, \tag{27}$$

all in in dollars per MWh. Capital costs CC, and operations and maintenance $O\&M$, in dollars, are levelized by quantity Q in MWh (EIA SEP 2014). Fuel costs FC are purely additive. I convert the carbon tax τ into dollars per MWh by multiplying the carbon intensity CI of each generator, in tons of CO_2 emitted per MWh generated.

Clearly, a carbon tax increases the marginal cost of the two types of dirty producers: existing coal generators and, to a smaller degree, existing gas generators. Thus, the average retail price P of electricity also increases. The markup of a gas generator is defined as

$$m_{gas} = P(\tau) - \left(\frac{CC_{gas} + O\&M_{gas}}{Q_{gas}} + FC_{gas} + \tau \times CI_{gas} + T\&D \right), \tag{28}$$

where m_{gas} is markup for gas and $T\&D$ are levelized transmission and distribution costs.[9] Markups for coal and wind are defined analogously.

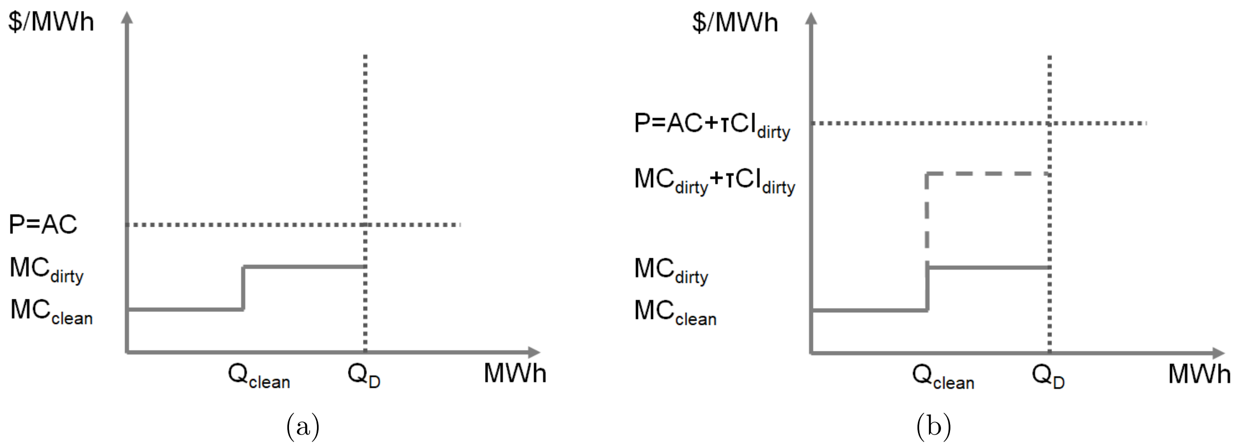
I model demand as growing at a constant rate (EIA AEO 2015). In addition, electricity producers face demand that is perfectly inelastic with respect to price, as in Fell and Kaffine (2018) and Linn and Muehlenbachs (2018). Perfectly inelastic demand allows for complete pass-through of the tax to consumers in the long run. Because of complete pass-through, an increase in retail price is equal to the change in MC of any of the dirty producers.

I argue that markup is exogenous to capacity because it affects the likelihood that a generator is built but not the size of the generator. A positive markup indicates that, if built, the new generator will be profitable, thus building is more likely. However, new capacity leads to short-run shutdown of legacy generation because of inelastic demand and the marginal production by legacy generators. Thus, the size of the new capacity is determined by the size and type of current generators that are forced into retirement rather than markup. This displacement of legacy occurs if the new generator has levelized average costs per MWh are lower than the marginal cost of a MWh produced by at least one legacy electricity generator.

A stylized example of an electricity market in Figure 6 shows the comparative statics of a carbon tax that increases the retail price. The marginal costs of supplying electricity

[9] Transmission and distribution companies are natural monopolies, are regulated by the Federal Energy Regulatory Commission under FERC order No. 1000, and are allowed to charge a fixed price per MWh (T&D) that covers their costs.

Figure 6: Effect of a carbon tax in a stylized electricity market.



The comparative statics of (a) and (b) stylize the effect of a per ton CO_2 tax on the electricity market. Supply curve (solid line) consists of generators of different fuel types dispatched in their merit order of increasing marginal cost of a MWh. The retail price of electricity is the marginal cost of the marginal generator plus levelized fixed costs. Carbon tax increases the marginal cost of the dirty generators but does not affect the inframarginal clean units (dashed line). The tax is passed through onto consumers, elevating the retail price of electricity. At the new high price, the markup of inframarginal generators increases (the vertical distance between MC_{clean} and P=AC+$\tau\mathrm{CI}_{dirty}$), whereas the markup of the dirty units remains unchanged (P minus MC_{dirty}+ $\tau\mathrm{CI}_{dirty}$).

are mostly determined by fuel costs: wind and nuclear power have the lowest costs and are cleaner, and gas and coal have the highest costs and are dirtier. For simplicity, I represent only two types of producers, with MC_{clean} and MC_{dirty}. The marginal cost is constant within the fuel type if two conditions hold: the fuel market is competitive within the state and the efficiency of heat-to-electricity conversion is the same for all the generations of a given fuel type.[10] In (a), the market is in equilibrium at the quantity Q_D as determined by the perfectly inelastic demand. The retail price P is determined by the average cost of producing a MWh AC. In (b), a carbon tax τ multiplied by the carbon intensity CI_{dirty} adds to the marginal cost of dirty generators. Provided that the dirty capacity is marginal, it drives up the retail price of electricity to $P = AC + \tau CI_{dirty}$, which is the new average cost of a dirty MWh. The markup of clean capacity, the vertical distance between MC_{clean} and $P + \tau CI_{dirty}$, is larger than without the tax. The markup of dirty capacity remains small. Electricity producers in the state now have a greater incentive to build clean capacity that will force dirty legacy capacity into shutdown and take its place in a market limited by the price-inelastic demand. The optimal size of new capacity is the size of the market minus the clean legacy capacity for which the marginal cost is lower than the average cost of the new generator, $Q_D - Q_{clean}$.

However, markup affects the capacity-size decision in two contexts that would violate the exclusion restriction. Both contexts have an upward-sloped supply curve within fuel type. The first occurs with differing marginal costs for generators within the same fuel type. This exists with either differences in the ability to convert fuel into electricity (heat rate, [mmbtu/MWh]), or price discrimination from suppliers of fuel. Yet neither is consistent with

[10] In Appendix H, I show why these assumptions are valid for the US electric industry.

the data.[11] The second occurs with variation in carbon intensity within a fuel type, so that a larger carbon tax would force shutdown condition on a larger share of the generator of a give fuel type. Again, there is not much variation in carbon intensity within a given fuel type.[12]

Uniform heat rates, input fuel prices, and carbon intensities indicate that the electricity supply curve is composed of an upward sequence of horizontal segments (step function) each representing the capacity of a given fuel type and giving the supply curve the appearance of a staircase, as in Green and Newbery (1992) or Bialek (2002). This shape justifies exclusion of markup from the capacity decision in the empirical model.

2.3 State-year level analysis

The appropriate unit of analysis for electricity markets is state-level. In practice, states balance generation and consumption of electricity even while belonging to larger interconnections: Interstate sales of electricity are typically scheduled as bilateral transactions. Balancing authorities are mostly state-level and ensure that supply meets demand within the state/authority.

Decisions on construction of new capacity are also made on the state level. The state public services commission (PSC) is in charge of planning of the state's generating portfolio by types of fuels and capacity sizes. It also makes decisions on siting new plants and trans-

[11] In Appendix H, Figure 13 shows that the heat rates of the majority of the US generators are nearly identical. Price discrimination is not consistent with the commodity exchange-style integrated US gas market. Coal contracts show price variation across regions, however, price differences in coal are due to geography rather than anything else.

[12] The average carbon intensity of coal in 2014 across the 44 states (excluding outliers AK, CA, ID, ME) in 2014 is 1.03 tons per MWh with the standard deviation of 0.05 tons/MWh. The carbon intensity of gas across 44 states (excluding outliers KS, ND, VT, WY) is 0.48 tons/MWh with standard deviation 0.08 tons/MWh.

mission lines. Most importantly, a state's PSC receives and approves applications to build generators from individual firms.

Our model is consistent with this industry practice. I interpret firms submitting applications to PSC as evidence that they can generate electricity profitably, and the markup is positive for them. A high markup increases the likelihood that proposals are accepted. The size of approved capacity is independent of the markup and instead depends on the PSC's plans of meeting the demand and desired proportions of fuel types in the generating portfolio.

Each year can also have US-wide shocks: A year with low gas prices will increase the markup and therefore the decision to build new gas generators. Another possibility is that it is a good year for construction (e.g. concrete prices are cheap). Therefore, I include year fixed effects too.

2.4 Robustness tests: Adding state fixed effects

Heckman's ET2T is the model of choice because of (1) corner responses, (2) markup being independent of the size of the newly built capacity, and (3) possibility of inverse correlation between the error terms of participation and capacity, such as a tax making the new gas plants less probable but larger. However, the above model does not control for state fixed effects. Therefore, I check the robustness with several alternative specifications.

I add time dummies into the model to flexibly control for the 25 years of data. The ET2T is ill-suited for state fixed effects, so to mitigate omitted characteristics, I add a time-invariant variable, the interstate trade index. The interstate trade index is the ratio of electricity generated in the state to the electricity consumed in the state. A high electricity index implies that a state is a net exporter of electricity.

As an additional robustness check, I implement a linear probability model for only the participation decision: (29):

$$z_{st} = \lambda_s + \mu_t + m'_{st}\gamma + x'_{st}\beta + u_{st} \tag{29}$$

As before, z_{st} is the binary participation variable. Parameters λ_s and μ_t capture state and year effects, respectively. The fixed effects separate how fuel costs affect construction of new capacity from the state's time-invariant characteristics. The remainder of the variables and parameters are the same as in Heckman model.

3 Data

I collect state-level data on new generator builds, fuel costs, renewable portfolio requirements, and market size variables. I create balanced panel data of 23 years, from 1992 to 2014, for the 48 contiguous states.[13] Below, I describe the four groups of variables: new capacity commitments, markup, RPS, and market size. Summary statistics and source information are in Table 3.

Data availability also supports my decision to estimate at the state level rather than the firm or generator level: Fuel cost data by individual producer is incomplete because the EIA does not report the information for private firms, which provide 40% of electricity in

[13] The EIA provides annual information about the electricity generation data from forms EIA-860, EIA-861, and EIA-923, and from State Electricity Profiles (SEPs). Data for Vermont and Rhode Island are unavailable for most years.

the US. EIA-923 has some public utility data, but only for a sample of public utilities, and the sample changes annually. Thus I use the state-level average fuel cost data, which are free of bias arising from these omissions. The market size and price data are available at the state level. RPSs are adopted and fulfilled at the state level. The new commitment data is available for every planned generator, which I aggregate to the state level.

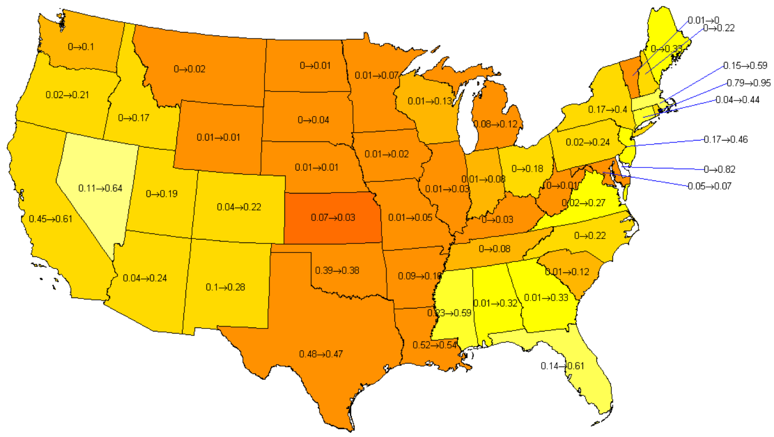
3.1 New electricity generating capacity commitments

Our outcome variable is capacity under construction: the sum of the capacities of all the generators of a given fuel type that have reached at least the stage of the beginning construction, based on Schedule 3 of EIA-860. The commitment is credible when a generator has a status of "Under construction, less than or equal to 50 percent complete (based on construction time to date of operation)" or higher.[14] Further, these generators were not under construction or a more advanced stage during the previous year.

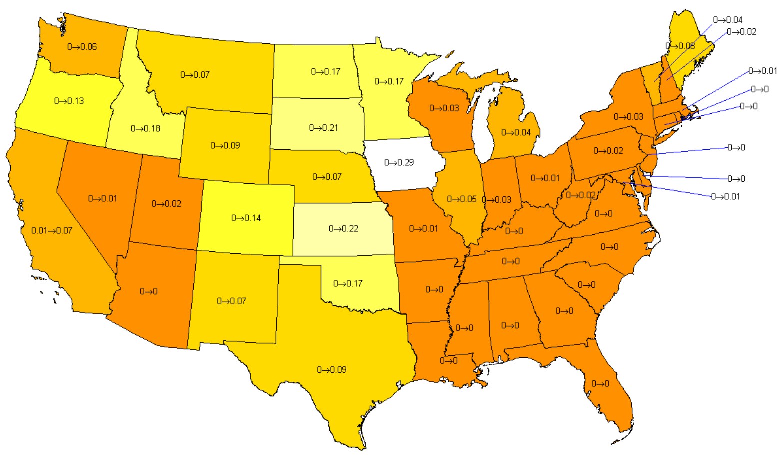
In the last 25 years, the states have overwhelmingly been building gas and wind generating capacity, as opposed to generators of other fuel types. Figure 7a shows that the non-central states, led by Nevada, spent the recent decades by shifting their generation to natural gas. The central plains states, from Texas to the Dakotas, almost uniformly saw the biggest gains in wind electricity generation(Figure 7b); this is a result of wind patterns, rather than natural gas prices. Overall, the gas price pattern does not coincide with the construction patterns (Figure 7c).

[14]The EIA assigns stages to generators: A generator is "proposed" when firm announces its intent to build it. But announcement is an insufficient indicator of commitment because the majority are never built or operational.

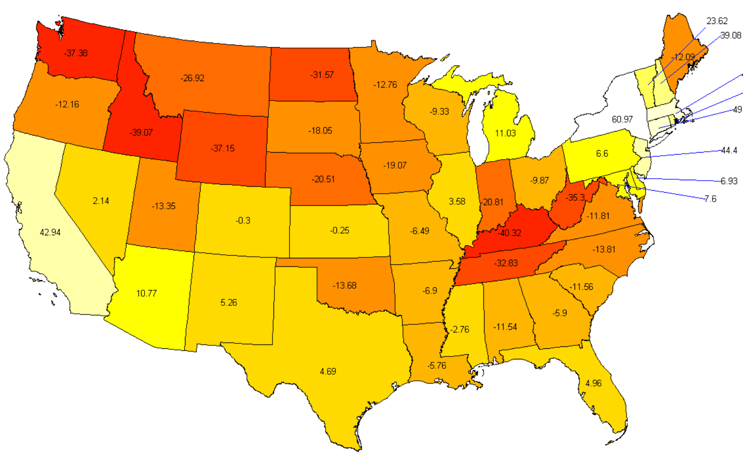
Figure 7: Evolution of gas and wind shares in states' electricity generation



(a) Change of the gas generation share, 1990⟶2014. The brighter areas reflect large increases. Investment in gas capacity was high in regulated markets of the SE and NE regions. The gas share did not grow in the areas where gas was prevalent by 1990, such as TX and LA, or the windy Great Plains.



(b) Change in wind generation share, 1998⟶2014 (limited change prior to 1998). The brighter areas represent larger growth. Wind turbines are most successful in the states that are windy (Great Plains), have legislative environmental initiatives (IL, NY, and CA), or both (IA and MN).



(c) Difference in the gas markup in a state and the national average markup, average of 1990-2014, \$/MWh. Average retail price: \$90/MWh. Average cost of gas/MWh-generated: \$45. The brighter areas represent larger differences. The difference is negative where coal or hydro-power is abundant and is positive where electricity retail price is high with easy access to gas infrastructure.

Table 3: Summary statistics and sources

Variable and unit	Mean (b/w state SD)	Definition and sources
Response variables		
New gas capacity commitment (MW)	288 (321)	Proposed gas generation, status of 'regulatory approval' and higher; codes T, U, V of EIA-860, Schedule 3.
New CCGT commitment (MW)	175 (245)	Proposed combined cycle gas turbine, a subset of gas generation; codes T, U, V of EIA-860, Schedule 3.
New wind capacity commitment (MW)	44 (87)	Proposed wind generation; codes T, U, V of EIA-860, Schedule 3.
New solar capacity commitment (MW)	9 (39)	Proposed solar generation; codes T, U, V of EIA-860, Schedule 3.
Variables excluded from capacity estimation		
Markup gas ($/MWh)	44.18 (27.46)	Difference of the product of fuel cost ($/mmbtu) and heat rate (mmbtu/MWh) from the price of electricity ($/MWh); EIA SEP 2014 and EIA-923.
Markup coal ($/MWh)	75.15 (22.69)	
Markup min ($/MWh)	19.27 (37.48)	Minimum value, coal or gas markup.
Markup max ($/MWh)	53.78 (35.60)	The maximum value, coal or gas markup.
Markup trend ($/MWh/year)	-0.61 (2.54)	Slope of linear trend of 4 observations of markup min., year t and previous 3.
Markup volatility ($/MWh)	22.30 (14.33)	Standard deviation of 4 observations of markup min., year t and previous 3.
Markup of neighbors ($/MWh)	18.76 (30.46)	The average of markups in the states that share a land border with the state in question.
Variables in both the participation and capacity estimations		
Capacity factor gas (dimensionless)	0.27 (0.22)	State electricity generation from U.S. Energy Information Administration (EIA SEP 2014), Table 5, divided by state electric power industry capability from U.S. Energy Information Administration (EIA SEP 2014), Table 4.
Capacity factor coal (dimensionless)	0.64 (0.10)	
RPS incremental requirement (fraction of total generation)	0.18 (0.04)	Difference between existing share of renewables and the required share; Lawrence Berkeley National Laboratory (RPS Compliance Data 2017).
RPS in adjacent states (fraction of total generation)	0.003 (0.005)	The average of the RPS requirement in adjacent states (RPS Compliance Data 2017).
Total operational capacity (MW)	18,250 (16,556)	U.S. Energy Information Administration (EIA SEP 2014).
Operational capacity gas (MW)	5,875 (9,749)	U.S. Energy Information Administration (EIA SEP 2014).
Operational capacity coal (MW)	6,719 (5,934)	U.S. Energy Information Administration (EIA SEP 2014).
Operational capacity min (MW)	5,539 (7,238)	Capacity of the fuel type of the marginal fossil fuel generator.
Operational capacity max (MW)	7,297 (6,578)	Capacity of the fuel type of the inframarginal fossil fuel generator.
Recently added capacity (MW)	428 (478)	Change in operational capacity, year t less the previous year.
Recently added fossil-fuel powered capacity (MW)	341 (387)	Change in fossil-fuel operational capacity, year t less the previous year.
Scheduled retirements, total capacity (MW)	77 (121)	EIA-860, Schedule 3.
Scheduled retirements, fossil-fuel capacity (MW)	61 (104)	EIA-860, Schedule 3.
State fixed-effect proxies		
Interstate trade index (dimensionless)	1.14 (0.52)	U.S. Energy Information Administration (EIA SEP 2014).
Share of independent power producers (dimensionless)	0.25 (0.23)	U.S. Energy Information Administration (EIA SEP 2014).

Data for the 48 contiguous US states, pooled 1990 to 2014. Exceptions are gas and wind capacity commitments, which are from 1992 and CCGT commitments, which are from 2001. Standard deviations (between states) in parentheses.

3.2 Markup

Markup is my proxy for a potential carbon tax, thus only fossil fuel markups are relevant for my estimations. A markup, in $/MWh, is the difference between the state retail electricity price and the respective gas or coal fuel cost.[15] The average electricity price in the panel of 1200 observations is 98.36 $/MWh. The average cost of gas is 54.17 $/MWh and coal is 23.21 $/MWh. Thus, the average *Markup gas* is 44.19 $/MWh and the *Markup coal* is 75.15 $/MWh.

However, instead of using *Markup gas* and *Markup coal*, I test two alternative measures of mark up: markup minimum as the markup of the marginal generator *Markup min*, and markup maximum as the markup of the other fossil fuel, *Markup max*. This approach accounts for instances of coal and gas switching positions in the electricity supply curve because in a given state-year, either can be marginal.[16]

I use also include *Markup trend* and *Markup volatility* because new capacity decisions are forward-looking in nature. I define these variable as the four-year trend of markups and standard deviation of markups in the preceding four years, respectively. Much of the variation in markup is caused by negotiations between utilities and PSCs, the business cycle, and the overarching trends of the world hydrocarbon market. The pacing of these events is reasonably comparable to the timeframe of a potential carbon policy. Finally, I control for possible spillovers of a carbon tax policy by including *Markup neighbors*, which

[15] All dollars in 2014$. I convert fuel costs from dollars per million British thermal units (mmbtu) to dollars/MWh using each plant's heat rate parameter (mmbtu per MWh). Heat rate reflects the generator's ability to produce electricity from heat. Appendix H gives median heat rates; most US generators are roughly 10 mmbtu/MWh.

[16] For example, with the introduction of CCGT and cheaper natural gas, in many states gas generators became inframarginal, making coal the marginal fuel type. However, my results do not rely on reordering within the supply curve: Appendix G provides robust results with average markups included.

is the average of states that share a land border with the state in question, as an additional exogenous explanatory variable for capacity choice.

3.3 Renewable portfolio requirement

I obtain renewable portfolio standards (RPS) from Berkeley Lab's Lawrence Berkeley National Laboratory (RPS Compliance Data 2017). RPSs try to promote the construction of renewable generators at the expense of the fossil fuel capacity. In a state that requires a higher share of its electricity generation to come from renewable sources, the construction of coal or gas generators may be less likely. As of 2015, 29 states have adopted RPSs, all of which impose a minimum share of renewable capacity in the state portfolio.

In this analysis, I condition on *RPS incremental requirement*, as proposed by Yin and Powers and update the nominal RPS from EIA NEMS (referenced in U.S. Energy Information Administration (EIA AEO 2015)) and RPS compliance summary data (RPS Compliance Data 2017):

$$incremental\_requirement = nominal\_requirement \times coverage - \frac{existing}{total}.$$

The *nominal_requirement* is the named goal of the state. However, *coverage* is rarely 100 percent of energy producers. In a typical RPS, only private electricity providers are required to maintain the nominal renewable portfolio. And private generation is less than half of a state's generation. An RPS only binds if the required share of renewables is higher than the share of renewables in private producers' existing portfolios. The average nominal RPS requires 21% of privately-owned (independent power producer, IPP) capacity, whereas the *incremental_requirement* is only 14% on average. I also control for possible effects of the RPSs of neighbor states on new construction in the state in question by calculating average RPS requirement among neighbors, *RPS adjacent*.

3.4 Market size variables

Market size variables are measured in MW and include *Operational capacity* in total, for gas and coal, and for marginal and non-marginal fossil fuel; *Recently added* for capacity in total and for fossil-fuel generators; and *Scheduled retirements* in total and for fossil-fuel generators (EIA-SEP and EIA-860). Retirements are typically scheduled for within five years of the report. Firms do not always follow the retirement plans, yet these announcements are my best indicator.

3.5 State fixed effect proxies

I add two controls for underlying state characteristics: state trade index and proportion of generation supplied by independent power providers (IPP's). Both variables are persistent allowing me to use them as proxies for state fixed effects in the two-step Heckman model. The state trade index is the ratio of the electricity generated and electricity consumed in a state-year. Share of electricity supplied by IPP's is the share of the private, as opposed to public, generation in a state. Throughout the 1990s, the US electricity industry went through the process of deregulation until stabilizing after the 2001 Enron scandal.

4 Estimation

4.1 Estimation results

I first estimate the participation choice: the probability of the commitment to build power generators, using state-year data. The second-stage provides estimates for the factors affecting the capacity size of the power generators. I conduct separate estimations for the outcomes of two energy sources: new gas capacity commitments, then the subset of the gas capacity that uses CCGT, and new wind turbine commitments. After the initial decision to build a generator is made, the construction and completion takes time: typically two to three years (Costs of Generating Technologies, EIA AEO 2017). Therefore I lag the response variable by one year, both in participation and capacity size estimations. I test the robustness of my results to changing the lags in Appendix G, Table 14.[17] Censored observations sum over all state-years with none of the generator types built. The regressors remain the same across the estimations for each energy source. Table 4 provides the results.

The primary coefficients of interest are on the *Markup* variables, which give the percent change in participation due to an additional \$/MWh of a particular markup.[18] These estimates proxy for the semi-elasticity responses of a potential per unit carbon tax. Markup of gas generation has a significant positive effect on the probability that new gas-fueled gener-

[17]The effects of markup fade away as the lag increases. Old fuel prices have a diminishing effect on decisions to build as new price information updates. By contrast, time-persistent variables, such as RPS requirements or trends of markups, retain their effect on new capacity decisions.

[18]The key estimate provides the marginal effect of markup on the argument of the probit part of the Heckman model. To convert it into the marginal effect on probability, I adjust it by the slope of the probit function. On average, nonzero new capacity happens 40% of the time. In this likelihood range, the PDF (the marginal effect of the random variable on the probability) is close to 0.4. Therefore, in the interpretation of results, I multiply the estimates by 0.4 to obtain marginal effects for participation.

ating capacity is built in a state. An additional dollar/MWh of the markup increases the probability of a non-zero response by $0.56 \times 0.4 = 0.22$ percentage points. This result remains the same if only combined-cycle gas turbines, a subset of gas generators, are counted as new capacity. The effect of markup on wind turbines is small, negative, and statistically insignificant. This key result is robust in value and significance across virtually all Heckman specifications and relevant sub-samples attempted. In Appendix G, Table 10 shows the results without the effects of neighbor states and results in Table 11 use gas generator markup only, rather than position switching between gas and coal in main specification. The value and significance of the markup on gas generators remains constant through specifications, whereas the effect of markup on the CCGT subset is sensitive to specification change, likely due to a smaller sample.

Trends of markups have no effect on capacity commitments of all types. Markup volatility, however, is significantly inversely related to the probability that new generators are built, for all fuel types. Average markup of neighboring states has no statistically significant effect on gas and CCGT construction, but increases the probability of new wind turbines. Increase in wind turbines in response to higher costs (or carbon tax) in neighboring states suggests a possibility of carbon policy spillover.

Markups of the neighboring states are strongly correlated. In a linear fixed-effect regression of markup on average markup of neighbors, the coefficient of determination is 58%, suggesting that markups of the adjacent states explain half of the variation in markups. To ensure that inclusion of both of the regressors does not change the result, I report the results of the analysis without neighbor states markups in Appendix G, Table 10. Exclusion of neighbor states does not significantly change the reported estimates.

Table 4: Results of Heckman estimation of participation and capacity, by energy source

Variable	**Gas**	**CCGT**	**Wind**
Number of observations	851	565	727
Number censored observations	495	434	541
Participation estimation			
Markup min ($/MWh)	**0.006** (0.003)**	0.004 (0.003)	-0.003 (0.003)
Markup trend ($/MWh/year)	-0.009 (0.006)	-0.002 (0.008)	5.3E-4 (6.8E-3)
Markup volatility ($/MWh)	**-0.014*** (0.005)**	**-0.019*** (0.006)**	**-0.126** (0.006)**
Markup max ($/MWh)	-0.004* (0.003)	3.9E-4 (0.003)	6.7E-4 (0.003)
Markup adjacent ($/MWh)	-5.2E-4 (0.003)	0.005 (0.004)	**0.007** (0.003)**
Incremental RPS (%)	**5.899* (3.207)**	4.902 (3.717)	1.410 (3.416)
RPS adjacent (%)	**14.500*** (4.662)**	4.338 (5.040)	-1.757 (5.348)
Share of IPP (%)	0.015 (0.231)	-0.515 (0.323)	0.006 (0.264)
Trade index (%)	**-0.458*** (0.146)**	**-0.748*** (0.242)**	0.005 (0.161)
Capacity factor gas (%)	0.413 (0.261)	**1.368** (0.543)**	-0.460 (0.378)
Capacity factor coal (%)	**0.896** (0.405)**	0.872 (0.536)	**1.167** (0.511)**
Log min capacity (MW)	**0.088* (0.053)**	0.093 (0.811)	**-0.109* (0.061)**
Log max capacity (MW)	**0.128* (0.069)**	-0.007 (0.096)	**-0.133* (0.083)**
Log total capacity (MW)	0.126 (0.113)	**0.301** (0.152)**	**0.360** (0.143)**
Recent fossil additions (MW)	-3.4E-4 (2.6E-4)	**-5.5E-4 (3E-4)**	**-1.6E-3*** (3.6E-4)**
Recent total additions (MW)	**4.3E-4* (2.5E-4)**	**6.6E-4** (2.9E-4)**	**1.6E-3*** (3.5E-4)**
Scheduled retirements, fossil (MW)	1E-4 (4.9E-4)	4.1E-4 (5.2E-4)	4.9E-4 (6.6E-4)
Scheduled retirements, total (MW)	-5.6E-5 (4.2E-4)	-3.1E-4 (4.5E-4)	-4.9E-4 (6.2E-4)
Capacity size estimation			
Incremental RPS (%)	8.240 (5.476)	8.043 (5.443)	**11.020** (5.289)**
RPS adjacent (%)	**-16.031** (7.559)**	-1.619 (8.037)	-5.737 (9.489)
Share of independent producers (%)	-0.435 (0.359)	**-0.993** (0.384)**	**-1.159*** (0.373)**
Trade index (%)	**-0.892*** (0.294)**	**-1.351*** (0.422)**	**0.495** (0.240)**
Capacity factor gas (%)	**1.227** (0.475)**	1.054 (0.720)	-0.985 (0.613)
Capacity factor coal (%)	0.317 (0.683)	0.848 (0.713)	0.841 (0.936)
Log min capacity (MW)	-0.044 (0.080)	0.121 (0.088)	0.040 (0.094)
Log max capacity (MW)	-0.095 (0.120)	-0.020 (0.116)	**-0.295** (0.117)**
Log total capacity (MW)	**0.758*** (0.184)**	**0.591*** (0.217)**	**0.893*** (0.253)**
Recent fossil additions (MW)	1.4E-4 (3.4E-4)	1.5E-4 (2.9E-4)	-1.9E-4 (3.6E-4)
Recent total additions (MW)	-1.5E-4 (3.3E-4)	-2.2E-4 (2.7E-4)	3.0E-4 (3.5E-4)
New scheduled retirements, fossil (MW)	-2.5E-4 (7.3E-4)	1.6E-4 (6.2E-4)	5.7E-4 (6.6E-4)
New scheduled retirements, total (MW)	3.3E-4 (6.2E-4)	2.2E-4 (5.1E-4)	-4.7E-4 (5.8E-4)
Correlation of errors (ρ)	0.066	0.731	0.156
Standard error of the capacity equation (σ_u)	1.459	1.121	1.164

Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance

The capacity equation provides the semi-elasticities of the size of new capacity built in a given state-year with respect to the independent variables, in % per unit of the independent variable.

Incremental renewable portfolio standards (RPS) require that electricity producers generate a share of their electricity from renewables. The incremental characteristic denotes the fraction of the requirement that has not been fulfilled yet. There is no correlation between RPS and the probability of new capacity of any type. However, the semi-elasticity of the size of wind capacity in MW with respect to RPS is significant and is 10.29:1. For every percentage point of the generating portfolio that is required to be renewable but is not renewable yet, the size of wind turbine capacity commitments jumps by 10.29%. This estimate suggests that to a large extent, on the order of tens of percents, wind turbines are built to fulfill RPS requirements.

RPS are positively correlated with probability (but not the expected size) of gas and capacity built. The probability of new gas capacity increases by $5.87 \times 0.4 = 2.35$ percentage points as unfulfilled RPS requirement increases by one percentage point. The relationship is only marginally significant. A possible explanation of this correlation is that environmentally-minded states impose more stringent RPS and simultaneously replace their coal generators with gas.

I estimate the effect of RPS of adjacent states to account for how electricity generation in a given state may be affected by its neighbors. A state can export electricity within an interconnection by producing more than it consumes, or import by generating less than it consumes. Transmission costs build up with distance and limit the ability of states to export and import. Incremental RPS in adjacent states increase the probability of new gas generators in the state. If the surrounding states, on average, have to convert one more percent of their total generation to renewables, the probability of new gas capacity in the state increases by 14 percentage points. RPS in adjacent states inhibits construction of wind turbines in the state, but the effect is smaller that for gas and not statistically significant. These relationships point to a general equilibrium effect, where RPS in a state are partially offset by the new gas capacity in neighboring states, whereas wind turbine locations are drawn into the state at the expense of the neighbor.

The state trade index universally reduces the probability and the size of new gas capacity. Intuitively, in the states that already generate more electricity than they consume, it is less tempting to build new capacity. However, the correlation between the trade index and probability of wind is statistically insignificant, and a higher trade index is directly correlated with the size of wind capacity. A reverse causality is possible, as RPS promotes larger wind capacity, that capacity drives the electricity trade surplus in the state.

The share of independent power producers (IPP), which are privately owned and do not own transmission and distribution networks has a negative effect on the size of capacity across all three types of generators. That is, private companies build capacity as frequently as public utilities, but on a smaller scale.

Market size variables produce strong, unambiguous and intuitively straightforward conclusions. High capacity factors imply high intensity of use of the existing generators, and have positive effect on probability and size of new capacity. Larger electricity markets welcome larger new capacity and have generators built more frequently. A notable exception is that wind turbines are less probable in states with large fossil capacity. If a state recently built fossil-fueled capacity, it makes new generators less probable, although without affecting the aggregate size of capacity if any is built. Recent total additions have the opposite effect, as if suggesting autoregressive behavior for the generator builds. Scheduled retirements of capacity consistently fail to influence new capacity commitments in any significant manner.

The year fixed effects (2014 is omitted), which are not reported but available on request, match my expectations. The years of the CCGT boom, 1999-2003, have a positive effect on probability and capacity size for gas. Conversely, being in the recessionary 2007-2008, reduces the probability and expected size of a new generator. For wind, cheapening glass fiber and other wind turbine technology achievements result in increasing year effects on the expected size of wind capacity in years after 2004.

4.2 Robustness of results to a fixed-effect linear probability model

I perform a robustness check using a panel fixed-effect specification. The Heckman model already includes the fixed effects within each year. Here, the added state-level dummies control for the extent that constant attributes within states correlate with the probability of generators being built. For example, there may be state-specific responses, such as in Alabama, which is remarkable in its persistent energy exports, and thus has a lower probability and a smaller expected size of new capacity. Also, Massachusetts seldom builds gas plants, which may be because the gas prices there are consistently high or because residents are more averse to having a gas plant nearby. This specification helps establish whether the effect of markup on the probability of building survives when accounting for state fixed effects.

The benefit of the panel fixed-effect model comes at the cost of having a linear proba-

Table 5: Results of linear probability fixed-effect estimation of participation, by energy source.

Variable	**Gas**	**CCGT**	**Wind**
Number of observations	851	565	727
Participation estimation			
Markup min ($/MWh)	0.001 (7.7E-4)	0.001 (9.6E-4)	**-0.001* (7.6E-4)**
Markup trend ($/MWh)	-0.001 (0.002)	-3.5E-4 (0.002)	5.9E-4 (0.001)
Markup volatility ($/MWh)	**-0.002* (8.8E-4)**	-0.003 (0.002)	-4.4E-4 (7.6E-4)
Markup max ($/MWH)	9.8E-5 (0.001)	8.4E-4 (0.001)	2.2E-4 (9.9E-4)
Markup adjacent ($/MWH)	5.1E-5 (0.001)	8.2E-4 (0.001)	**0.002** (9.8E-4)**
Incremental RPS (%)	1.372 (1.170)	1.691 (1.074)	-0.287 (1.003)
RPS adjacent (%)	**4.583*** (1.615)**	1.691 (1.507)	-1.167 (1.390)
Share of IPP (%)	0.098 (0.114)	0.047 (0.436)	-0.035 (0.122)
Trade index (%)	-0.229 (0.145)	-0.145 (0.189)	**-0.272* (0.139)**
Capacity factor gas (%)	-0.005 (0.117)	-0.129 (0.244)	0.029 (0.121)
Capacity factor coal (%)	-0.103 (0.183)	0.152 (0.208)	0.007 (0.169)
Log min capacity (MW)	**-0.089** (0.043)**	**-0.142** (0.065)**	0.006 (0.043)
Log max capacity (MW)	**-0.131** (0.052)**	**-0.204*** (0.075)**	0.034 (0.055)
Log total capacity (MW)	0.026 (0.073)	0.025 (0.165)	-0.062 (0.069)
Recent fossil additions (MW)	-8.9E-5 (7.9E-5)	**-1.3E-4* (7.2E-5)**	-1.1E-4 (6.9E-5)
Recent total additions (MW)	7.9E-5 (7.8E-5)	**1.3E-4* (7.1E-5)**	9.6E-5 (6.7E-5)
Newly scheduled retirements, fossil (MW)	1.3E-4 (1.7E-4)	1.5E-4 (1.5E-4)	2.4E-5 (1.4E-4)
Newly scheduled retirements, total (MW)	-1.6E-4 (1.5E-4)	-1.8E-4 (1.3E-4)	-7.6E-5 (1.2E-4)
Capacity size estimation			
Incremental RPS (%)	4.002 (8.220)	11.924 (17.547)	2.715 (6.839)
RPS adjacent (%)	-23.811 (21.832)	0.294 (18.038)	0.265 (12.811)
Share of IPP (%)	-0.628 (0.745)	0.396 (8.419)	0.416 (2.328)
Trade index (%)	-0.798 (1.585)	-4.707 (4.285)	0.644 (1.878)
Capacity factor gas (%)	-0.111 (0.909)	0.729 (2.872)	-3.605 (1.996)
Capacity factor coal (%)	1.785 (1.189)	0.224 (3.964)	1.937 (1.652)
Log min capacity (MW)	-0.003 (0.459)	-0.615 (0.917)	0.258 (0.570)
Log max capacity (MW)	-0.136 (0.670)	-0.594 (0.976)	0.192 (0.604)
Log total capacity (MW)	0.521 (0.430)	-0.563 (3.820)	-1.380 (2.670)
Recent fossil additions (MW)	6.1E-5 (5.3E-4)	6.7E-4 (7.2E-4)	4.7E-4 (3.6E-4)
Recent total additions (MW)	-2.0E-4 (5.0E-4)	-7.1E-4 (7E-4)	**-5.8E-4* (3.4E-4)**
Newly scheduled retirements, fossil (MW)	-1.1E-3 (9.7E-4)	0.002 (0.002)	-0.001 (8.3E-4)
Newly scheduled retirements, total (MW)	7.8E-4 (9.7E-4)	-0.001 (0.001)	8.0E-4 (6.8E-4)
Fitted participation stage values	1.705 (4.019)	-0.378 (0.760)	0.560 (0.424)

Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance threshold. Output for time dummies is suppressed.

bility model. Normally, observed values are mapped into probabilities by the error function of the normal distribution. In it, the effect of the observed values on probability is high around the probability of 0.5 and lower toward the extreme values of 0 and 1 probability. A linear probability approximation may be accurate around 0.5, but will be biased upward at the extremes. Thus, the Heckman model produces unbiased estimates, while the fixed effect model checks whether the sign, order of magnitude, and significance of the Heckman estimates hold up once the fixed effect is accounted for.

It is technically possible to specify a linear model that establishes correlation between markup and the size of newly built capacity. However, without the theory from Section 2.2, it is hard to argue for causality in such a model. Furthermore, the variation in size of capacity is likely to crowd out any significance that is otherwise present in the participation decision.

The outcome is binary: one if "build" and zero if "not build." Estimation is performed separately for gas generators, CCGT subtype of gas generators, and wind power generators. I parallel the specifications from the Heckman model, minimum and maximum markups, minimum markup only, and gas and coal markups. The results are in Table 5.

For every dollar-per-MWh increase of the markup in a particular state, the probability of new capacity there increases by 0.1-0.3 percentage points, depending on the specification. This is very similar to the Heckman model results and is marginally significant (significant in the gas markup specification in Appendix G).

The effect of the markup, and therefore a carbon tax, is of the same strength in the fixed-effect linear probability model as in the Heckman specification. However, the effect is marginally significant.

5 Effect of a carbon tax policy on capacity

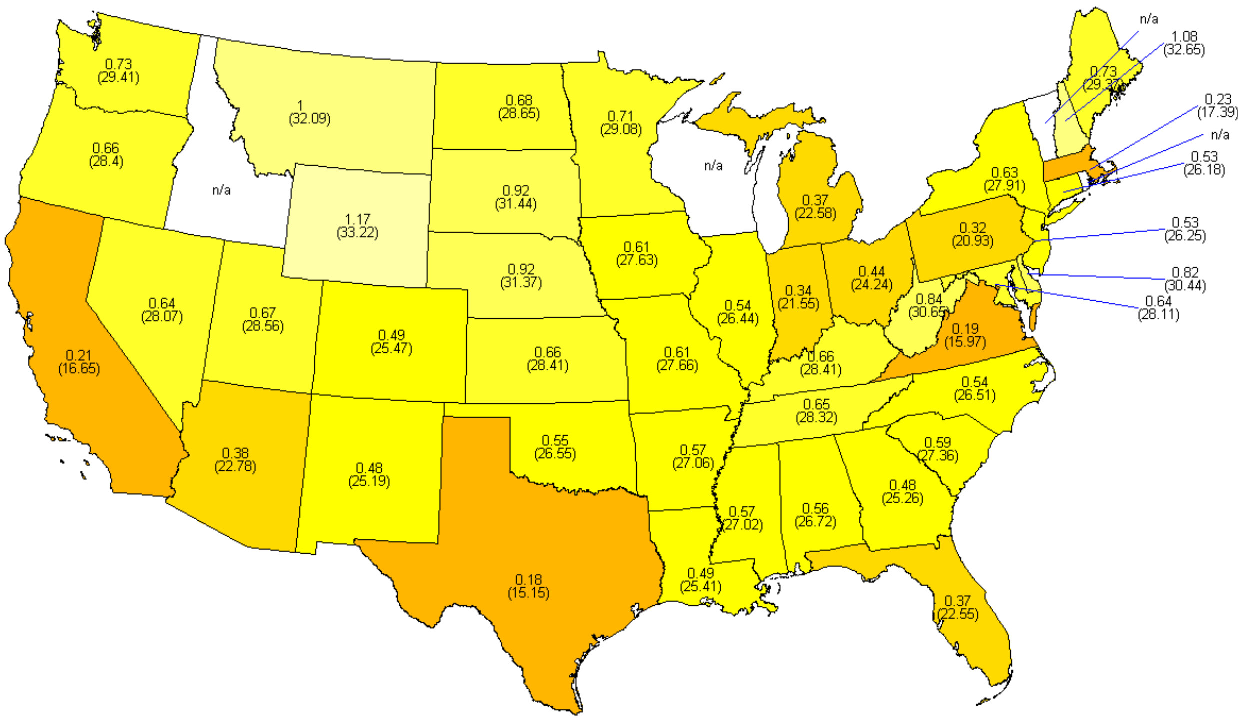
5.1 MW of capacity per dollar of tax

I interpret the estimation results in terms of the effect of a state-level carbon tax on the state generating capacity. If a state adopts a carbon tax, what effect will it cause on the construction of electricity generators? I approach the interpretation of the results of estimation by (1) calculating the unconditional expectation of capacity commitments, (2) finding the marginal effect of the markup on the unconditional expectation, (3) producing semi-elasticities for every state, and (4) making inferences for the relevant values of carbon tax. Figure 8 shows the semi-elasticities of capacity with respect to markup by state for gas generators. The errors are obtained by the delta method using the data for 2013 as a representative year.

The semi-elasticities obtained in the described procedure are statistically insignificant. However, they still allow for interpretation of the regression estimates, which are significant. On average, a one dollar increase of the markup leads to a 0.6% increase in gas capacity commitments. Mean emission intensity of the natural gas generators in the US is 0.5 metric tons of CO_2 per MWh. Therefore, a modest \$10 per ton carbon tax reduces gas capacity commitments by an average of 3%. The effect of markup on CCGT is five times smaller. The CCGT result is affected by greater average values for the inverse Mills ratio, $\phi(\bullet)/\Phi(\bullet)$, and greater correlation between the errors in the participation and the capacity equations, ρ, in (163).

Also of interest are the effects of RPS requirements on wind generation, established in Table 4. A one percent increase in the incremental RPS requirement leads to a 10% increase

Figure 8: Semi-elasticities of gas capacity commitments with respect to markup by state, percent per dollar of tax, as of 2014



The sensitivity of the new gas generator construction to the markup in the state is fairly uniform for most states. The larger states are penalized by the model, as is the Midwest. The discussion for Table 6 attributes these deviations to the way the model treats large markets and to unfulfilled renewable portfolio requirements, respectively.

Table 6: Breakdown of the differences in the value of the inverse Mills ratio that is responsible for the variation across states of the semi-elasticity of capacity with respect to markup

State	Markup min	Markup trend	Markup volatility	Markup max	RPS	RPS adjacent	Share IPP	Trade index	CF coal	CF gas	Ln cap min	Ln cap max	Ln cap total	Added fossil	Added total	Retired fossil	Retired total	Year and intercept	Inv Mills value
AR	0.11	-0.02	-0.2	-0.11	7.2E-3	0.06	1.2E-3	-0.53	0.63	0.09	0.77	1.09	1.24	-7.6E-3	9.6E-3	0.18	-0.1	-3.75	1.09
CA	0.19	0.03	-0.09	-0.64	0.04	5.9E-4	3.3E-3	-0.33	0.33	0.12	0.49	1.37	1.45	-1.45	2.86	0.2	-0.25	-3.75	0.42
IN	0.19	-0.08	-0.2	-0.14	0.51	0	7.6E-4	-0.42	0.5	0.07	0.76	1.26	1.32	-0.28	0.38	1.7E-3	-0.01	-3.75	0.66
TX	0.22	0.06	-0.11	-0.17	7E-6	0.05	3.9E-3	-0.45	0.63	0.14	0.89	1.42	1.5	-0.5	0.73	0.16	-0.09	-3.75	1.26
WY	-0.11	-0.06	-0.24	-0.12	0	0	7E-4	-1.22	0.73	0.19	0.42	1.12	1.17	0	0	0	0	-3.75	2.17

All columns except the first and the last contain values for $\gamma_i z_i$. For example, cell [2,2] gives the value for the effect of markup of the fuel type that has the smallest markup in Arkansas on the probability that anything is built, multiplied by the Arkansas 2013 value of the markup of this fuel type.

in the scale of new wind turbine construction for every percentage point of unfulfilled RPS requirement.

Territorially, there is a pattern of responsiveness to a carbon tax being lower in the Southwest and in the Midwest (0.4 of a percent of capacity per dollar of markup) and higher in coal-rich Wyoming and West Virginia. The largest states California are penalized by the construction of the model. A reference to (163) is instructive regarding the differences across states:

$$\frac{d}{dx_i}\ln y_{st} = \beta_i - \rho\sigma_u\gamma_i\frac{\phi(\bullet)}{\Phi(\bullet)}\left[m\gamma_m + x'\gamma_x + \frac{\phi(\bullet)}{\Phi(\bullet)}\right] + \gamma_i\frac{\phi(\bullet)}{\Phi(\bullet)}$$

Small estimate for ρ (Table 4) weighs down the second element in the equation. Markup is excluded from the capacity equation, therefore β_i is zero. Thus, semi-elasticity of capacity construction with respect to markup largely depends on the product of the markup coefficient in the participation equation (marginal effect of markup on the probability that anything at all is built in a state-year) and the inverse Mills ratio. The markup coefficient is the same for all states. Table 6 illustrates how the components of the inverse Mills ratio affect the outcome for a number of characteristic states.

It is interesting to compare southern Arkansas to Midwestern Indiana. The key difference is the absence of the huge incremental RPS effect in the latter. The resulting value of $\sum_i \gamma_i z_i$ produces similar values of PDF=0.4, but on different sides on the bell curve, with CDF's of 0.3 and 0.54 respectively. Thus, lower inverse Mills values and therefore lower semi-elasticies in this instance are due to unfulfilled RPS requirements in Indiana.

It is immediately obvious from the breakdown that the huge penalties on California and Texas stem from the large values of recent additions and retirements in those states. Simply inserting zeros in those cells lifts the inverse Mills values for the two states to roughly the country averages.

The breakdown of the inverse Mills value for Wyoming shows that resource-rich states are so sensitive to markup because of their high values of interstate electricity trade index.

5.2 Policy implications of the findings

From 2005 to 2014, construction of gas and wind generators proceeded at a constant pace with 8.5 GW of new gas and 4.5 GW of new wind capacity built annually.[19] Mean capacity factor was 25% for both gas and wind. Thus, every year, an average state has been replacing with new gas and wind generators $(8.5+4.5)/48 \times 25\% \times 8766 = 600$ GWh, the total of which remained stable at 85,000 GWh. I estimate that a carbon tax decreases the new gas capacity at the rate of three percent for every ten dollars per ton. For the purposes of assessing the tax effect, I assume that whenever a tax reduces the size of a new gas generator, the state fills the resulting gap by either electricity imports or new carbon-neutral capacity.

[19]During this time the country was adding 1.9 GW of coal generators annually on average, but with a declining trend. Starting in 2010, solar generator construction has been proceeding at a pace of 2 GW a year.

Table 7: Ten-year carbon tax scenarios, applied to an average US state

Tax scenario	$0	10	35	100	10⟶35
2014 total generation, GWh	82				
2014 total emissions, tons CO_2	43,000				
2014 carbon intensity in an average state, tons/MWh	0.53				
2014 carbon intensity of natural gas, tons/MWh	0.46				
Generation from new capacity, GWh	570	547	492	346	
Emissions from new capacity, tons	172	162	136	68	
Carbon intensity of new capacity, tons/MWh	0.303	0.296	0.277	0.199	
10-year effect, tons	0	-568	-1991	-5688	-1047

I consider an average US state adopting four carbon tax regimes: $10, $35, $100, and a linear increase from $10 to $35 per ton of CO_2 over the span of ten years. The last option is inspired by the gradual history of the British Columbia carbon tax. In Table 7, I summarize the decrease of emissions in tons of CO_2 after ten years in various carbon tax regimes. A $10 tax, maintained for ten years in an average state, reduces emissions by 568 tons in this scenario. Scaling up the tax to $100 results in a proportional decrease in CO_2 to 5.7 thousand tons savings for the state. In a scenario where an initial $10 tax reaches the level of $35 by annual increments of $2.8 a year, the tax reduces emissions by a thousand tons over ten years.

The state-level emission reductions are in thousands of tons across the scenarios. The effect of a carbon tax is seemingly small when compared to an average state's electricity industry emissions of forty thousand tons of CO_2 annually. However, I isolate the effect of a carbon tax on building of new generators. Other effects of the tax, such as shutting down existing coal plants, are likely, but are beyond my focus. Therefore, a more useful frame of reference is to measure how the carbon intensity of new capacity changes under tax.

Currently, the carbon intensity of new capacity is 0.303 tons CO_2 per MWh. This is cleaner than the average carbon intensity of the current US electricity generation, at 0.5 tons/MWh. A $10 tax makes new capacity only 2% cleaner, at 0.296 tons/MWh. A $35 tax, on par with British Columbia, makes new capacity 10% cleaner, at 0.277 tons/MWh. A high but realistic $100 tax makes new generators one-third cleaner on average, at 0.2 tons/MWh. Absent other effects, such as shutdowns of coal plants, the effect on emissions will take time to accumulate as more legacy capacity is replaced by new builds. However, in the long term, it is possible to reduce the carbon intensity of a state's electricity by 60%.

By contrast, having no carbon tax is equivalent to letting gas generation to run unopposed. The carbon intensity of a CCGT is 0.45 tons/MWh, about the current legacy capacity average and higher than the average of new generators. Our empirical result is that a carbon tax is effective at curtailing new gas generating capacity. In the context of carbon intensities, the tax ensures that newly built generators are significantly cleaner than today's legacy capacity average.

6 Conclusion

Fuel choice for electricity generation continues to have profound effects on carbon emissions, a major cause of anthropogenic climate change. Over the last 20 years, the share of coal began to recede, natural gas use tripled, and wind power became a relevant source. Most recently, the pace of construction of solar generators is comparable to those of new natural gas and wind generators.

A carbon tax, though yet to be implemented in the US, will affect construction of new generators and make newly built capacity cleaner, or less carbon-intensive, on average. I infer its effect from the relationship between the fuel cost and new generating capacity. Fuel cost is the major component of the marginal cost of a megawatt-hour. For a new generator entering the market with a given price of electricity, a high marginal cost implies a low markup and reduces the project's viability. A carbon tax effectively increases the marginal cost of electricity equivalently to fuel cost.

In a given state and year, new capacity is either zero or a positive quantity of megawatts. I use the two-part Heckman model to adequately incorporate this feature in the analysis. With Heckman model, I estimate how independent variables affect the probability of anything at all built in a given state-year, and how independent variables affect the size of the newly built capacity. I examine the robustness of my findings to state and year fixed effects with a linear probability model that utilizes the panel structure of the data. The effect of the markup, and therefore, a carbon tax, is robust to this specification change.

I estimate that implementation of a tax of \$10 per ton of CO_2 makes new generating capacity 3% cleaner. While carbon tax does not directly promote new wind turbines, renewable portfolio requirements increase the size of wind capacity. Every percentage point of a state's generating capacity that is required to be renewable but is not renewable yet, increases the size of new wind capacity by 10%.

The instant emissions effect of cleaner new generators is small. This is because only about 1% of the US generators is being replaced by new capacity every year. However, without carbon tax, new generating capacity will continue to be dominated by gas generators. At 0.45 tons CO_2 per MWh, gas is already as dirty as the legacy capacity average. It has

50% higher carbon impact per MWh than new capacity on average. New gas generators perpetuate the carbon intensity of the US electricity. I show that carbon tax is effective at discouraging new gas generators – to the extent of making the new capacity 33% cleaner on average at a realistic \$100 per ton CO_2 tax.

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Chapter III. A framework for modeling shale oil extraction on the distribution of wealth resources across the US states

1 Introduction

Technological developments of the late 2000s made feasible the production of oil and gas from locations in which previously the costs exceeded the benefits. The oil and gas extracted from low-permeability geological formations, colloquially known as shale oil and gas, led to almost a tripling of the United States oil output and doubling of gas output. This turned the US into the third-largest oil producer in the world and balanced the American oil and gas trade for the first time in 40 years. Compounded by the worldwide economic slowdown in the wake of the 2007-2009 financial crisis, the shale revolution halved the price of oil in the US between June 2014 and January 2015.

Shale oil and gas reduce the cost of energy inputs into the production and contribute to the sustained economic growth in the US. However, the windfall of benefits is uneven territorially and across the social strata. The only significant crude production increases are taking place in Texas, North Dakota, and the Federal offshore in the Gulf of Mexico (which is unrelated to shale technology). Furthermore, property rights on shale are firmly private, benefiting people that hold the mineral rights. The technologies that allow to profitably recover these oil and gas – hydraulic fracturing of bearing formations ("fracking"), directional drilling, and multilateral wells are capital-intensive and are a factor in the oil firms' decisions to drill. Although there is no question that the nation benefits from shale, it is important to understand how shale affects the immediate benefactors, owners of land, the oil firms, the states. Equally crucial is the understanding of how that wealth filters into the general population and the regions far from shale basins. Monetary and fiscal policies may affect the outcome, and the scope of these effects needs to be understood.

The goal of this work is to set up the procedure of estimating the effect of shale oil on the incomes and wealth in the US states. How much of it goes to landowners, oil companies, the populations of oil-bearing states, the US population, and the rest of the world? How fast is the distribution of wealth from immediate benefactors to general population? The estimation achieves these goals by obtaining the size of changes in macroeconomic indicators such as household income in response to abundance of shale oil and the speed of this response. At the core of this approach is a theoretical general equilibrium model that demonstrates the causality between shale shocks and macroeconomic indicators for key types of economic agents in the locations of interest. I adapt existing general equilibrium estimation methods to the question of shale shocks and innovate by adapting the microeconomic foundations of natural resource production to implement and endogenous oil sector driven by rational oil firms.

This study constructs a dynamic stochastic general equilibrium (DSGE) model to track the impulse responses by economic variables to an shale shock. It is a basic New Keynesian model in the formulation by Clarida, Gali, and Gertler (1999) with a number of necessary extensions. First, it is a multi-country model. Second, production of intermediate goods uses labor, capital, and oil as inputs (1992). Third, while the reserve of economically recoverable oil is subject to exogenous shocks, production of oil is an endogenous process carried out by rational firms (1978). Finally, the model contains the standard Taylor rule to represent monetary policy effects and a severance tax imposed on oil producers and transferred to households to represent fiscal policy implications for shale wealth.I outline an approach to estimate the structural parameters of the model by maximum likelihood and use them to construct the response of the macroeconomic indicators to the shock of shale "discovery".

In contrast to this study's structural approach, most of the existing literature relies on reduced-form empirics. A rich strand measures the effects of shale production on a variety of socioeconomic indicators. Feyrer, Mansur, and Sacerdote (2017) perform a linear fixed-effect analysis of the relationship between new oil and gas production and wages in the county. The authors find that a million dollars worth of oil and gas increased wage bill and royalties by $35,000 to $343,000, depending on the size of the benefiting area. The paper also provides values for the dispersion of benefits across space. These results are a useful benchmark for this paper's dynamic model estimates.

A similarly reduced-form work by Bartik et al. (forthcoming) expands the range of economic indicator values available as benchmarks for the estimation of a structural model in this study. The authors employ a difference-in-differences approach to estimate the effect of fracking on a number of economic indicators. Under this approach, the identification is provided by the coefficient of the interaction of the county being richly endowed, and the production of oil or gas being under way. An empirically similar work by Allcott and Keniston (2018) focuses on the Dutch disease aspect of the American shale: the authors explore the possibility of the booming oil and gas industry crowding out manufacturing investment and find no evidence thereof. Appreciably, Allcott and Keniston employ the

Rosen–Roback open economy general equilibrium framework (Moretti 2010) to justify the reduced-form estimation of effects of shale on labor market indicators. While the above literature relies on reduced-form methods to draw conclusions on the spread of shale wealth locally and to larger population, I estimate a structural macroeconomic model.

This paper builds on two major results in the literature on country-level effects of the oil sector. First, Kilian (2009) categorizes shocks to oil price into oil supply shocks, oil-specific demand shocks, and general-economy oil demand shocks. The author uses a structural vector autoregression model to separate and quantify the effects of the oil shocks on macroeconomic indicators. Second, a line of papers introduces the oil sector into the neoclassical growth model framework, but unlike Kilian (2009) relies on the oil price as the shock variable. Kim and Loungani (1992) implement an oil sector that produces an intermediate oil input into production of the final good in a real business cycle (RBC) model. Atkeson and Kehoe (1999) propose a continuum of types of nonoil capital, where each type is optimal for a given oil intensity. This putty-clay property of capital realistically increases the length of response of the economy to an oil price shock. Backus and Crucini (2000) expand Kim and Loungani's RBC model to a multi-country setting and calibrate the effects of the oil price shocks on external macroeconomic indicators. Following the breakthrough by Ireland (2004) on implementation of MLE and Kalman filter techniques in DSGE models, Bodenstein, Erceg, and Guerrieri (2011) estimate a two-country RBC model with oil by maximum likelihood.

The above ideas of a distinct oil supply shock, oil being an intermediate input in the economy, the gradual adjustment of the economy to an oil shock, oil use in a multi-economy model, and a feasible way to estimate such a model, allow me to address the question of the effects of a sudden shale abundance by estimating a structural macroeconomic model of the US. I outline the process of estimating the differential responses of macroeconomic variables across states (primarily those with the shale and those without). I include the rest of the world to allow examination of the impact on the country's current account. This approach complements the existing reduced-form microeconometric results on the local, regional, and country-level economic variables.

This is the first study to implement endogenous choices of production of shale oil in a structural macroeconometric model. This innovation is crucial for a convincing representation of how shale production generates revenue for oil firms, which then proceeds to spread across the state and the rest of the country. I set up the model and outline the process of estimating it. The approach to estimation developed in this chapter is beneficial in terms of direct theoretical explanation of the observed phenomena, capture of the general equilibrium effects, and compelling dynamics. The tradeoff is that a theoretical model necessarily imposes artificial restrictions on reality and is less flexible than a reduced-form estimation.

2 The model

The theory of the interaction between recoverable shale reserves and macroeconomic indicators is based on the standard New Keynesian framework, as in Clarida, Gali, and Gertler (1999). The US states are modeled as a set of trading economies. The economies consist of four types of agents: households, general economy monopolistic intermediate and competitive final good firms, and oil sector firms. The government conducts monetary policy in line with the Taylor rule and a neutral fiscal policy that taxes the oil firms and transfers the revenue to households. It also awards production licenses to oil firms. The resource markets are given by capital, labor, oil, oil-specific capital, and recoverable oil reserve in the ground. The resources, with the exception of labor and oil reserve, are traded among the states and with the rest of the world (ROW) on imperfect markets, in which the resource price increases in trade deficit. The model introduces an oil sector, in which oil firms extract oil from shale. This innovation extends the standard New Keynesian model to adequately implement the production of shale wealth.

The values of the variables and the relationships between them arise from solutions to the agents' maximization problems. I outline the problem of each agent type, list the conditions they impose on the economy, and express the general equilibrium as a set of variables and conditions.

2.1 Households

A household maximizes its present discounted utility subject to its budget constraint

$$\max_{c,i,n,k,b,m} E_t \sum_t \beta^t U \text{ s.t.} \tag{30}$$

$$c + \frac{p^*}{p} i + \left(k_1 + \frac{p^*}{p} b_1 + \frac{m_1}{p} + k_{v,1} \right) (1+g) = \tag{31}$$

$$wl + rk + qo + \pi + t + k(1-\delta) + \frac{p^*}{p} b(1 + r^* - \delta) + \frac{m}{p} +$$

$$q^*(v - o) + k_v(1 - \delta_v)$$

The household receives flows of wages for the share of time it works, wl, rent on capital it lends to firms, rk, revenues of the oil firms that it owns. These revenues come from domestic sales, qo, and oil exports, $q^*(v-o)$. Aside from factor income, the household receives income on claims on assets in other states and in ROW (assets abroad), $b(r^*-\delta)$, and seigniorage, t, from money injections by the government.

The household spends its budget on consumption of in-state final output (consumption of domestic goods, c), final output of other states and ROW (imports, i), and purchases of additional capital, k_1-k, oil-specific capital, $k_{v,1}-k_v$, and claims on abroad, b_1-b.

The budget constraint also incorporates the combined steady-state growth rate of population and technology, $1+g$. The instantaneous utility is an additively separable function of consumption of domestic and foreign goods, leisure time, $1-l$, and money holdings m/p.

$$U=\frac{\left(\omega_c^{\frac{\mu}{1+\mu}}c^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu}}{\nu}-\Psi\frac{(1-l)^{1-\xi}}{1-\xi}+\Theta\ln\frac{m}{p} \tag{32}$$

Constrained maximization with respect to variables c,i,l,m_1,k_1, and b_1 produces the household's six first order conditions, (33)–(37), with the budget constraint (31) being the sixth.

$$\begin{aligned}
\frac{\left(\omega_c^{\frac{\mu}{1+\mu}}c^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c}\right)^{\frac{\mu}{1+\mu}}}{\left(\omega_c^{\frac{\mu}{1+\mu}}c_1^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i_1^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c_1}\right)^{\frac{\mu}{1+\mu}}} &= \beta\frac{1+r_1-\delta}{1+g} && (33)\\
\left(\frac{c}{c_1}\frac{i_1}{i}\right)^{\frac{\mu}{1+\mu}} &= \frac{1+\pi_1}{1+\pi_1^*} && (34)\\
\left(\frac{1-l_1}{1-l}\right)^{\xi}\frac{w_1}{w} &= \beta\frac{1+r_1-\delta}{1+g} && (35)\\
\beta\left(\omega_c^{\frac{\mu}{1+\mu}}c_1^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i_1^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c_1}\right)^{\frac{\mu}{1+\mu}} &- \\
\left(\omega_c^{\frac{\mu}{1+\mu}}c^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c}\right)^{\frac{\mu}{1+\mu}}(1+\pi_1)(1+g) &= \beta\Theta/\frac{m_1}{p_1} && (36)\\
(1+r_1-\delta)\,\frac{p^*}{p}\Big/\frac{p_1^*}{p_1} &= (1+r_1^*-\delta) && (37)
\end{aligned}$$

In total, household problem contributes six variables and six conditions (times number of states) to the general equilibrium.

2.2 Firms

Competitive nonoil firms produce the final good, Y by combining intermediate goods, Y_j in an aggregator,

$$Y = \left(\int_{j=0}^{\infty} Y_j^{\frac{1}{1+\eta}} dj \right)^{1+\eta}. \tag{38}$$

Each monopolistic firm produces its differentiated intermediate good, Y_j, using production factors k, o, and l in a Cobb-Douglas aggregator with a nested constant elasticity of substitution, as in Backus and Crucini (2000).

$$Y_j = \left(\omega_k^{\frac{\rho}{1+\rho}} K^{\frac{1}{1+\rho}} + \omega_o^{\frac{\rho}{1+\rho}} O^{\frac{1}{1+\rho}} \right)^{(1+\rho)\alpha} (AL)^{1-\alpha} \tag{39}$$

A monopolistic intermediate firm takes demand as given. Therefore, its problem is to minimize the factor costs subject to a fixed demand.

$$\min_{K,O,L} rK + qO + wL \text{ s.t. } Y_j(K, O, A, L) = (p_j/p)^{-\frac{1+\eta}{\eta}} Y \tag{40}$$

Obtaining the first order conditions for rent r, oil price q, wage w, and the marginal cost λ_j generates four restrictions to go with the price system.

$$
\begin{aligned}
r &= \lambda_j \alpha \left(\omega_k^{\frac{\rho}{1+\rho}} K^{\frac{1}{1+\rho}} + \omega_o^{\frac{\rho}{1+\rho}} O^{\frac{1}{1+\rho}} \right)^{(1+\rho)\alpha - 1} (AL)^{1-\alpha} \left(\frac{\omega_k}{K} \right)^{\frac{\rho}{1-\rho}} && (41) \\
O &= K \left(\frac{r}{q} \right)^{\frac{1+\rho}{\rho}} \frac{\omega_o}{\omega_k} && (42) \\
w &= r \frac{1-\alpha}{\alpha} \left(\omega_k^{\frac{\rho}{1+\rho}} K^{\frac{1}{1+\rho}} + \omega_o^{\frac{\rho}{1+\rho}} O^{\frac{1}{1+\rho}} \right) / L \left(\frac{\omega_k}{K} \right)^{\frac{-\rho}{1-\rho}} \\
&= r \frac{1-\alpha}{\alpha} \left(\omega_k^{\frac{\rho}{1+\rho}} K^{\frac{1}{1+\rho}} + \left(\frac{r}{q} \right)^{\frac{1}{\rho}} \omega_o \omega_k^{\frac{-1}{1+\rho}} K^{\frac{1}{1+\rho}} \right) / L \left(\frac{\omega_k}{K} \right)^{\frac{-\rho}{1-\rho}} && (43) \\
L &= \frac{r}{w} \frac{1-\alpha}{\alpha} \left(1 + \left(\frac{r}{q} \right)^{\frac{1}{\rho}} \omega_o / \omega_k \right) K && (44)
\end{aligned}
$$

The final good firm problem is to maximize the difference between the revenue from selling the final good and costs of intermediate goods.

$$
\max pY - \int_{j=0}^{1} p_j Y_j dj \qquad (45)
$$

I follow the standard steps of the New Keynesian model (1999) to express aggregate output as a combination of intermediate variety production function and price dispersion.[20]

$$\left(\omega_k^{\frac{\rho}{1+\rho}} K_j^{\frac{1}{1+\rho}} + \omega_o^{\frac{\rho}{1+\rho}} O_j^{\frac{1}{1+\rho}}\right)^{(1+\rho)\alpha} (AL_j)^{1-\alpha} = (p_j/p)^{-\frac{1+\eta}{\eta}} Y \tag{50}$$

Using the intermediate firm's cost-minimizing first-order condition (42) to substitute out oil and integrating over j, gives

$$\left(\omega_k^{\frac{\rho}{1+\rho}} + \omega_o \omega_k^{\frac{-1}{1+\rho}} \left(\frac{r}{q}\right)^{\frac{1}{\rho}}\right)^{(1+\rho)\alpha} A^{1-\alpha} \int_0^1 K_j^\alpha dj \int_0^1 L_j^{1-\alpha} dj = Y \int_0^1 (p_j/p)^{-\frac{1+\eta}{\eta}} dj \tag{51}$$

Further, defining aggregate factor inputs K and L, allows to show that a greater price dispersion lowers the aggregate demand.

$$Y = \frac{\left(\omega_k^{\frac{\rho}{1+\rho}} + \omega_o \omega_k^{\frac{-1}{1+\rho}} \left(\frac{r}{q}\right)^{\frac{1}{\rho}}\right)^{(1+\rho)\alpha} K^\alpha (AL)^{1-\alpha}}{\int_0^1 (p_j/p)^{-\frac{1+\eta}{\eta}} dj} \tag{52}$$

[20] The first order condition for the final good firm results in a following condition:

$$p\left(\int_{j=0}^{\infty} Y_j^{\frac{1}{1+\eta}} dj\right)^{\eta} Y_j^{\frac{1}{1+\eta}-1} = p_j \tag{46}$$

which simplifies to the relative demand curve for an intermediate variety:

$$Y_j = (p_j/p)^{-\frac{1+\eta}{\eta}} Y \tag{47}$$

By defining the nominal output as the sum of products of prices and quantities,

$$pY = \int_0^1 p_j Y_j dj \tag{48}$$

express for the price aggregator:

$$p = \left(\int_0^1 p_j^{-\frac{1}{\eta}} dj\right)^{-\eta} \tag{49}$$

Plugging the conditions for oil and labor inputs into the interest rate, one can express marginal cost as a function of technology and factor prices.

$$\begin{aligned} r &= \lambda\alpha \left(\omega_k^{\frac{\rho}{1+\rho}} + \omega_o \omega_k^{\frac{-1}{1+\rho}} \left(\frac{r}{q} \right)^{\frac{1}{\rho}} \right)^{(1+\rho)\alpha - 1} \omega_k^{\frac{\rho}{1-\rho}} A^{1-\alpha} \\ &\times \left(\frac{r}{w} \frac{1-\alpha}{\alpha} \left(1 + \left(\frac{r}{q} \right)^{\frac{1}{\rho}} \omega_o / \omega_k \right) \right)^{1-\alpha} \end{aligned} \tag{53}$$

This identity eliminates heterogeneity in the marginal cost, λ, which I reflect by abandoning the subscript j for the variable.

2.3 Price rigidity

The intermediate firm problem internalizes price rigidities by focusing on the expected present value of the monopolistic firm profits, adjusted by the household discount factor for the possibility of not being able to reset its price on a given period. This part of the model is close to the standard Clarida, Gali, and Gertler (1999) treatment. The only difference is that derivation and the results are based on the production function from Kim and Loungani (1992), rather that the basic New Keynesian AK-style linear production.

Instantaneous profit of an intermediate firm j in real terms is

$$\Pi_j = \frac{p_j}{p} Y_j - rK_j - qO_j - wL_j \tag{54}$$

Possible to write factor expenditures in terms of output. For example, interest rate becomes

$$r = \frac{\lambda_j \alpha}{1 + \omega_o/\omega_k \left(\frac{r}{q}\right)^{\frac{1}{\rho}}} Y/K \tag{55}$$

Then instantaneous profit of a monopolistic intermediate firm is

$$\Pi_j = \frac{p_j}{p} Y_j - \lambda_j Y_j \left(\frac{\alpha}{1 + \omega_o/\omega_k \left(\frac{r}{q}\right)^{\frac{1}{\rho}}} + \frac{\alpha}{w_k/w_o \left(\frac{q}{r}\right)^{\frac{1}{\rho}} + 1} + (1-\alpha) \right) \tag{56}$$

The constant terms in the large parentheses add up to one. Then the profit of all intermediate firms is

$$\begin{aligned}
\Pi &= \int_0^1 \frac{p_j}{p} Y_j - \lambda_j Y_j dj \\
&= Y \int_0^1 \left(\frac{p_j}{p}\right)^{-\frac{1}{\eta}} - \lambda_j \left(\frac{p_j}{p}\right)^{-\frac{1}{\eta}-1} dj \\
&= Y \left(p^{\frac{1}{\eta}} \int_0^1 p_j^{-\frac{1}{\eta}} dj - \lambda p^{\frac{1}{\eta}+1} \int_0^1 p_j^{-\frac{1}{\eta}-1} dj \right) \\
&= Y - \lambda Y
\end{aligned} \tag{57}$$

Optimal price maximizes the present value of expected profit of a firm stuck with the chosen price. The discounting is both by intertemporal choice and by the probability the price will remain as chosen.

$$\max_{p(j)} E \sum_{s=0}^{\infty} (\beta\phi)^s \frac{U'(c_s)}{U'(c)} \left(\frac{p_j}{p_s} \left(\frac{p_j}{p_s}\right)^{-\frac{1+\eta}{\eta}} Y_s - \lambda_j \left(\frac{p_j}{p_s}\right)^{-\frac{1+\eta}{\eta}} Y_s \right) \tag{58}$$

The first order condition for the price setting problem is

$$\begin{aligned}
0 = E\sum_{s=0}^{\infty}(\beta\phi)^s\frac{U'(C_s)}{U'(C)}\left(-\frac{1}{\eta}\right)p_j^{-\frac{1+\eta}{\eta}}p^{\frac{1}{\eta}}Y_s &\quad - \\
E\sum_{s=0}^{\infty}(\beta\phi)^s\frac{U'(C_s)}{U'(C)}\lambda_j\left(-\frac{1+\eta}{\eta}\right)p_j^{-\frac{1+2\eta}{\eta}}p^{\frac{1+\eta}{\eta}}Y_s &\quad = \\
\left(-\frac{1}{\eta}\right)p_j^{-\frac{1+\eta}{\eta}}/U'(C)E\sum_{s=0}^{\infty}(\beta\phi)^sU'(C_s)p^{\frac{1}{\eta}}Y_s &\quad - \\
\left(-\frac{1+\eta}{\eta}\right)p_j^{-\frac{1+2\eta}{\eta}}/U'(C)E\sum_{s=0}^{\infty}(\beta\phi)^sU'(C_s)\lambda_jp^{\frac{1+\eta}{\eta}}Y_s &
\end{aligned}$$

This first order condition reveals the price a monopolistic firm attempts to set for the period. However, Calvo rigidity dictates that a fraction of the firms is not able to change its output's price. Therefore, the prevailing price is between the last period's price and the optimal price the firms wish to reset to. Expressing for the reset price, gives

$$p_j^{reset} = (1+\eta)E\frac{\sum_{s=0}^{\infty}(\beta\phi)^sU'(C_s)\lambda_jp^{\frac{1+\eta}{\eta}}Y_s}{\sum_{s=0}^{\infty}(\beta\phi)^sU'(C_s)p^{\frac{1}{\eta}}Y_s} \tag{59}$$

The entire right-hand side is uniform for all intermediate firms. So is the reset price.

$$p^{reset} = (1+\eta)\frac{X_1}{X_2} \tag{60}$$

$$X_1 = U'(C)\lambda_jp^{\frac{1+\eta}{\eta}}Y_s + \beta\phi EX_{1,1} \tag{61}$$

$$X_2 = U'(C)p^{\frac{1}{\eta}}Y_s + \beta\phi EX_{2,1} \tag{62}$$

Following through the New Keynesian steps with Kim and Loungani (1992) production function that includes oil as the production factor, produces the standard New Keynesian conditions that govern the final goods price and output. However, the New Keynesian analysis does not account for the role of oil in production. The general equilibrium literature that does, treats production of oil as an exogenous stochastic process (Backus and Crucini (2000), Bodenstein, Erceg, and Guerrieri (2011)). By contrast, in the framework presented here, production of oil is the result of forward-looking behavior of profit-maximizing oil firms.

2.4 Oil sector

I formalize the licensing authority's goal of prevention of overdrilling of shale wells as the maximization of the discounted net present value of the cash flow from oil sales, V_t, at the price q_t, subject to the initial capital investment, $K_{v,0}$. While the firms maximize static profits, licensing authority maximizes the net present value of the cash flows from operations.

$$\max_{K_{v,0}} \mathrm{E}_{t=0}\left[\sum_{t=l+1}^{\infty} \frac{q_t V_t}{\prod_{i=1}^{t} 1 + r_i - \delta}\right] - K_{V,0} \tag{63}$$

In (63), r_t is the cost of capital in the general economy. The problem is only partly recursive – the oil authority determines the maximum $K_{v,0}$, then the firms receive licenses and invest maximum amounts of capital possible for every license because the static marginal product in the oil sector exceeds the one in general economy. The action, choice of $K_{v,0}$, is made in $t = 0$, and is irreversible. Oil-specific capital begins to depreciate at the rate δ_v as soon as the oil starts flowing:

$$k_{v,t+1} = k_{v,t}\left(1 - \delta_v\right) \tag{64}$$

In order to make oil output a function of initial conditions exclusively, it is necessary to eliminate the current reserve and current oil-specific capital from the oil output function. Oil production at time t is a function of the stock of oil-specific capital at time $t-1$. Given that oil-specific capital is non-withdrawable, its stock at any point in time is a function of the initial capital investment. The oil production is now a function of the initial capital investment and the remaining oil reserve at the time t:

$$v_t = Dk_{v,0}^{\gamma}\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t z_t^{\eta}\epsilon_{v,t} \tag{65}$$

Oil production is a flow that subtracts from the stock of the proven reserve. A common assumption (DeJong and Dave 2011) is that the logarithm of the oil production shock, $\epsilon_{v,t}$, is a white noise process. The expectation of oil output becomes a differential equation for the stock of reserves:

$$\mathrm{E}_{t=0}\left[\frac{dz_t}{dt}\right] = -Dk_{v,0}^{\gamma}\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t z_t^{\eta} \tag{66}$$

For the remainder of the oil sector optimization, all the values for the time periods $t > 0$ are expectations, and I omit expectation terms from the equations for readability. The differential equation for oil reserve is integrated to express oil stock at any time period as a function of initial capital investment and initial reserve. Multiplication of both sides by an integrating factor transforms the equation to

$$dz_t\left(z_t^{-\eta}\right) = -Dk_{v,0}^{\gamma}\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t dt. \tag{67}$$

and it is now possible to take the antiderivative of both sides of the equation:

$$\frac{1}{1-\eta}z_t^{1-\eta} = -Dk_{v,0}^{\gamma}\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t \frac{1}{\gamma\ln(1-\delta_v)-\ln(1+g)} + IC \tag{68}$$

The initial condition, IC, is found by setting t=0 in the integrated equation:

$$\frac{1}{1-\eta}z_0^{1-\eta} = -Dk_{v,0}^{\gamma}\frac{1}{\gamma\ln(1-\delta_v)-\ln(1+g)} + IC \tag{69}$$

From here, at any time $t > l$ the expected value of oil reserve is only a function of the initial oil-specific capital and initial oil reserve.

$$z\left(k_{v,0}, z_0, t\right) = \left[z_0^{1-\eta} + \frac{(1-\eta)Dk_{v,0}^{\gamma}}{\gamma\ln(1-\delta_v)-\ln(1+g)}\left(1-\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t\right)\right]^{\frac{1}{1-\eta}} \tag{70}$$

Further, oil output also becomes a function of initial oil endowment.

$$v_t = Dk_{v,0}^{\gamma}\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t\left[z_0^{1-\eta} + \frac{(1-\eta)Dk_{v,0}^{\gamma}}{\gamma\ln(1-\delta_v)-\ln(1+g)}\left(1-\left(\frac{(1-\delta_v)^{\gamma}}{1+g}\right)^t\right)\right]^{\frac{\eta}{1-\eta}} \tag{71}$$

The bracketed expression under the exponent term is the current stock of capital. This version of the formula for oil output suggests that its rate of change evolves hyperbolically:

$$\begin{aligned}\frac{\partial v_t/\partial t}{v_t} &= \gamma\ln(1-\delta_v)-\ln(1+g)+\eta \\ &\times \left[\frac{1-\eta}{\gamma\ln(1-\delta_v)-\ln(1+g)} - \left(\frac{z_0^{1-\eta}}{Dk_{v,0}^{\gamma}} + \frac{1-\eta}{\gamma\ln(1-\delta_v)-\ln(1+g)}\right)\left(\frac{1+g}{(1-\delta_v)^{\gamma}}\right)^t\right]^{-1}\end{aligned} \tag{72}$$

This characterization is useful in two ways: first, if the rate of change of production evolves hyperbolically over time, the asymptote of the hyperbola predicts the point in time at which oil runs out. The asymptote is found by solving for t that would produce zero for the bracketed term in (72):

$$t = \left[\ln\left(\frac{1-\eta}{\gamma \ln(1-\delta_v)} \right) - \ln\left(\frac{Z_o^{1-\eta}(1-\delta_v)^{l\gamma}}{DK_{V,1}^{\gamma}} + \frac{1-\eta}{\gamma \ln(1-\delta_v)} \right) \right] \Big/ \left[-\gamma \ln(1-\delta_v) \right] \quad (73)$$

Second, the rate of change that evolves hyperbolically will begin to pick up the pace fairly late into the production history. By that point most of oil will have been produced and the compounded discounting will have diminished the value of the output. The decisionmaking becomes much simpler with the assumption that the rate of change of oil output is constant and is equal to the rate at the time of discovery. Rewriting (72) produces a drastically simpler condition:

$$\begin{aligned} \frac{\partial \bar{v}_t / \partial t}{\bar{v}_t} &= \gamma \ln(1-\delta_v) - \ln(1+g) + \eta \\ &\times \left[\frac{1-\eta}{\gamma \ln(1-\delta_v) - \ln(1+g)} - \left(\frac{z_0^{1-\eta}}{Dk_{V,0}^{\gamma}} + \frac{1-\eta}{\gamma \ln(1-\delta_v) - \ln(1+g)} \right) \left(\frac{1+g}{(1-\delta_v)^{\gamma}} \right)^0 \right]^{-1} \\ &= \gamma \ln(1-\delta_v) - \ln(1+g) - \eta D k_{V,0}^{\gamma} z_0^{\eta-1} \end{aligned} \quad (74)$$

To assess the loss of precision that arises from the simplification from (72) to (74), I assign realistic (as estimated in Chapter I, Section 4) values to the parameters and initial inputs, so that elasticity of oil output with respect to capital, $\gamma = 0.45$, elasticity with respect to reserve, $\eta = 0.55$, scale parameter $D = 0.094$, rate of depreciation of oil capital $\delta_v = 0.06$, time lag of two years, an initial discovery of $Z_0 = 1000$ million sm3, and capital investment $K_{V,0} = 420$.

Given these inputs, the production in the first year is 67 million sm3. The oil runs out in 93 years. The output begins to decrease at the rate of 6.5% a year, and it takes it 35 years to hyperbolically accelerate to 7% a year. It takes 46 years to accumulate a one percent difference between the annual production with a hyperbolic growth rate and the production with constant 6.5% growth rate. The difference between the precise present value of revenues and the present value of revenues at a constant rate of change is less that 0.1%. In light of these figures, the simplification of the revenue function to a geometric series is entirely justified. The oil producer's problem is now a function of initial capital investment, initial resource stock, and time:

$$
\begin{aligned}
&\max_{k_{v,0}} \sum_{t=0}^{\infty} \frac{q_t v\left(k_{V,0}, z_0, t\right)}{\prod_{i=1}^{t} 1 + r_i - \delta} - k_{v,0} = \\
&\max_{k_{v,0}} \sum_{t=0}^{\infty} \frac{q_t D k_{v,0}^{\gamma} z_0^{\eta} \left(1 + \gamma \ln(1-\delta_v) - \ln(1+g) - \eta D k_{v,0}^{\gamma} Z_0^{\eta-1}\right)^t}{\prod_{i=l+1}^{t} 1 + r_i - \delta} - k_{v,0}
\end{aligned}
\tag{75}
$$

The numerator term is the rate of change of output in the first period from (71). The series is converted to a static problem. The present value is maximum if

$$
\begin{aligned}
&\sum_{t=0}^{\infty} \frac{q_t \frac{dV\left(K_{V,0}, Z_0, t\right)}{dK_{V,0}}}{\prod_{i=1}^{t} 1 + r_i - \delta} = 1 \\
&\sum_{t=0}^{\infty} \frac{\gamma q_t D k_{v,0}^{\gamma-1} z_0^{\eta} \left(1 + \gamma \ln(1-\delta_v) - \ln(1+g) - \eta D k_{v,0}^{\gamma} Z_0^{\eta-1}\right)^t}{\prod_{i=1}^{t} 1 + r_i - \delta} - \\
&\sum_{t=0}^{\infty} \frac{\eta q_t D k_{v,0}^{2\gamma-1} z_0^{2\eta-1} t \left(1 + \gamma \ln(1-\delta_v) - \ln(1+g) - \eta D k_{v,0}^{\gamma} Z_0^{\eta-1}\right)^{t-1}}{\prod_{i=1}^{t} 1 + r_i - \delta} = 1
\end{aligned}
\tag{76}
$$

In recursive terms, this condition becomes

$$
\begin{aligned}
1 &= X_{3,0} \\
&= q_0 \frac{dV\left(K_{V,0}, Z_0, t=0\right)}{dK_{V,0}} + \left(1 + r_1 - \delta\right)^{-1} \sum_{t=1}^{\infty} \frac{q_t \frac{dV\left(K_{V,0}, Z_0, t\right)}{dK_{V,0}}}{\prod_{s=2}^{t} 1 + r_s - \delta} \\
&= q_0 \frac{dV\left(K_{V,0}, Z_0, t=0\right)}{dK_{V,0}} + \left(1 + r_1 - \delta\right)^{-1} X_{3,1} \qquad (77)
\end{aligned}
$$

A measure of rigidity of oil production and the law of motion for oil reserves round out the description of the oil sector. Oil firms take time to go from discovery and obtaining a license to production of oil and gas. I reflect this technological gestation period by a Calvo rigidity: at any time period, only a fraction ϕ_v of oil firms can change their production plan by adding oil-specific capital:

$$
v_{t+1} = \left[\phi_v D k_{v,t+1}^{\gamma} z_{t+1}^{\eta} + \left(1 - \phi_v\right) D k_{v,t}^{\gamma} z_{t+1}^{\eta} \frac{\left(1 - \delta_v\right)^{\gamma}}{1 + g}\right] \epsilon_{v,t} \qquad (78)
$$

Production of oil depletes the oil remaining in the shale. Oil reserve evolves as the difference between new discoveries, af, and production, v, and is adjusted by the technological and population growth, g.

$$
(1+g) z_1 = z^{\epsilon_{z,t}} - v + af \qquad (79)
$$

2.5 Equilibrium conditions and variables

The household problem supplies variables c, l, r, w, p, p^*, m/p, b, k, π, t, conditions 33–37 and the budget constraint 31. Firm adds q, o, λ, X_1, X_2, p^{reset}, intermediate firm cost minimization 53, firm profits 56, price aggregator 49, and aggregate demand 52. The intermediate firm optimal pricing adds system 60–62. Oil sector adds z, v, k_v and corresponding conditions.

Heterogeneous prices, one for each monopolistic firm, make it unfeasible to solve and estimate the model. I follow the standard steps to eliminate heterogeneity. First, it is possible to break up aggregator 49 into the reset price and the last period's price.

$$\begin{aligned} p^{-\frac{1}{\eta}} &= \int_0^{1-\phi} p^{reset,-\frac{1}{\eta}} dj + \int_{1-\phi}^1 p_{j,-1}^{-\frac{1}{\eta}} dj \\ &= (1-\phi) p^{reset,-\frac{1}{\eta}} + \int_{1-\phi}^1 p_{j,-1}^{-\frac{1}{\eta}} dj \\ &= (1-\phi) p^{reset,-\frac{1}{\eta}} + \phi \int_0^1 p_{j,-1}^{-\frac{1}{\eta}} dj \\ &= (1-\phi) p^{reset,-\frac{1}{\eta}} + \phi p_{-1}^{-\frac{1}{\eta}} \end{aligned} \tag{80}$$

Also rewrite the reset price in terms of inflation rate, rather than price level.

$$\begin{aligned} x_1 &= \frac{X_1}{p^{\frac{1+\eta}{\eta}}} \\ &= U'(c)\lambda_j Y_s + \beta\phi E \frac{X_{1,1}}{p^{\frac{1+\eta}{\eta}}} \\ &= U'(c)\lambda_j Y_s + \beta\phi E \frac{X_{1,1}}{p_1^{\frac{1+\eta}{\eta}}} (1+\pi_1)^{\frac{1+\eta}{\eta}} \\ &= U'(c)\lambda_j Y_s + \beta\phi E x_{1,1} (1+\pi_1)^{\frac{1+\eta}{\eta}} \end{aligned} \tag{81}$$

Similarly,

$$x_2 = \frac{X_2}{p^{\frac{1}{\eta}}} \tag{82}$$

so that

$$
\begin{aligned}
p^{reset} &= p(1+\eta)\frac{x_1}{x_2} && (83)\\
1+\pi^{reset} &= (1+\pi)(1+\eta)\frac{x_1}{x_2} && (84)
\end{aligned}
$$

Now it is possible to restate the full set of model conditions, while having eliminated heterogeneous and nonstationary terms. Households problem yields optimality conditions,

$$
\begin{aligned}
\frac{\left(\omega_c^{\frac{\mu}{1+\mu}}c^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c}\right)^{\frac{\mu}{1+\mu}}}{\left(\omega_c^{\frac{\mu}{1+\mu}}c_1^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i_1^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c_1}\right)^{\frac{\mu}{1+\mu}}} &= \beta\frac{1+r_1-\delta}{1+g} && (85)\\
\left(\frac{\omega_i c}{\omega_c i}\right)^{\frac{\mu}{1+\mu}} &= \frac{p^*}{p} && (86)\\
\left(\frac{1-l_1^{reset}}{1-l}\right)^{\xi}\frac{w_1}{w} &= \beta\frac{1+r_1-\delta}{1+g} && (87)\\
\beta\left(\omega_c^{\frac{\mu}{1+\mu}}c_1^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i_1^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c_1}\right)^{\frac{\mu}{1+\mu}} &- \\
\left(\omega_c^{\frac{\mu}{1+\mu}}c^{\frac{1}{1+\mu}}+\omega_i^{\frac{\mu}{1+\mu}}i^{\frac{1}{1+\mu}}\right)^{(1+\mu)\nu-1}\left(\frac{\omega_c}{c}\right)^{\frac{\mu}{1+\mu}}(1+\pi_1)(1+g) &= \beta\Theta/\frac{m_1}{p_1} && (88)\\
(1+r_1-\delta)\,\frac{p^*}{p}\Big/\frac{p_1^*}{p_1} &= (1+r_1^*-\delta) && (89)
\end{aligned}
$$

budget constraint,

$$
\begin{aligned}
&c+\frac{p^*}{p}i+\left(k_1+\frac{p^*}{p}b_1+\frac{m_1}{p_1}/(1+\pi_1)\right)(1+g)=\\
&=wl+rk+qo+y(1-\lambda)+t+k(1-\delta)+\frac{p^*}{p}b(1+r^*-\delta)+\frac{m}{p} && (90)
\end{aligned}
$$

as well as labor market rigidity and the fiscal neutrality condition that requires the transfer of seigniorage from money emissions to households,

$$l_1 = \phi_l l_1^{reset} + (1-\phi_l) l \tag{91}$$

$$t_1 = \frac{m_1 - m}{p} = \frac{m}{p}/\pi_1 q. \tag{92}$$

Firm problem imposes the production function and factor markets equilibria:

$$r = \lambda\alpha \left(\omega_k^{\frac{\rho}{1+\rho}} k^{\frac{1}{1+\rho}} + \omega_o^{\frac{\rho}{1+\rho}} o^{\frac{1}{1+\rho}}\right)^{(1+\rho)\alpha-1} l^{1-\alpha} \left(\frac{\omega_k}{k}\right)^{\frac{\rho}{1-\rho}} \tag{93}$$

$$o = k \left(\frac{r}{q}\right)^{\frac{1+\rho}{\rho}} \frac{\omega_o}{\omega_k} \tag{94}$$

$$l = \frac{r}{w}\frac{1-\alpha}{\alpha}\left(1 + \left(\frac{r}{q}\right)^{\frac{1}{\rho}} \omega_o/\omega_k\right) k \tag{95}$$

$$y = \left(\omega_k^{\frac{\rho}{1+\rho}} k^{\frac{1}{1+\rho}} + \omega_o^{\frac{\rho}{1+\rho}} o^{\frac{1}{1+\rho}}\right)^{(1+\rho)\alpha} l^{1-\alpha} \tag{96}$$

Price rigidity for intermediate firms determines the evolution of inflation and nominal exchange rate:

$$(1+\pi)^{-\frac{1}{\eta}} = (1-\phi)(1+\pi^{reset})^{-\frac{1}{\eta}} + \phi \tag{97}$$

$$1+\pi^{reset} = (1+\pi)(1+\eta)\frac{x_1}{x_2} \tag{98}$$

$$x_1 = U'(c)\lambda_j Y_s + \beta\phi E x_{1,1}(1+\pi_1)^{\frac{1+\eta}{\eta}} \tag{99}$$

$$x_2 = U'(c) Y_s + \beta\phi E x_{2,1}(1+\pi_1)^{\frac{1}{\eta}} \tag{100}$$

$$\frac{p^*_{1ROW}}{p_1} = \frac{1+\pi_{ROW}}{1+\pi_1}\frac{p^*_{ROW}}{p} \tag{101}$$

Oil sector provides oil production function and imposes conditions on oil reserve and rigidity of oil capital:

$$1 = x_{3,0} \tag{102}$$
$$x_{3,0} = q_0 \frac{dv\left(k_{v,0}^{reset}, z_0, t=0\right)}{dk_{v,0}^{reset}} + x_{3,1}\frac{1+g}{1+r_1-\delta} \tag{103}$$

$$v_{t+1} = \left[\phi D k_{v,1}^{\gamma} z_{t+1}^{\eta} + (1-\phi)\, D k_{v,t}^{\gamma} z_{t+1}^{\eta} \frac{(1-\delta_v)^{\gamma}}{1+g}\right] \epsilon_{v,t} \tag{104}$$

$$z_1(1+g) = z^{\epsilon_z} - v + af \tag{105}$$

$$k_{v,1} = \phi_v k_{v,1}^{reset} + (1-\phi_v)k_v \tag{106}$$

Taylor rule represents the monetary policy,

$$r_t = (1-\tau_r)r_{ss} + \tau_r r_{t-1} + (1-\tau_r)\left[\tau_\pi(\pi_t - \pi_{ss}) + \tau_y(y_t - y_{ss})\right] \tag{107}$$

Finally, the rest of the world is represented by the ROW price system. Similarly to Mendoza and Uribe 2000, the international markets are assumed to be incomplete: large trade imbalances increase the transaction cost of moving the resource across the border.

$$r_t^* = r_{ROW}\left(\frac{k_t}{a_t}\right)^{\chi_r} \tag{108}$$
$$q_t = q_{ROW}\left(\frac{o_t}{v_t}\right)^{\chi_q} \tag{109}$$
$$\frac{p^*}{p} = \frac{p_{ROW}^*}{p}\left(\frac{i_t}{i_{ss}}\right)^{\chi_p}. \tag{110}$$

For example, if a state exports oil, it is cheaper locally than in ROW. Conversely, if a state borrows, rent on capital is higher there. This reasonably realistic assumption closes an otherwise non-stationary model.

2.6 Steady state

The steady state results from erasing the timestamps from the variables. This reduces the 26×51-equation system of conditions to a subsystem of eight conditions isolated for each state and eight corresponding variables, r, q, w, k, o, l, c, i. The conditions are as follows:

$$
\begin{aligned}
r &= \frac{1+g}{\beta} - (1-\delta) && (111)\\
i &= \left(\frac{p^*}{p}\right)^{-\frac{1+\mu}{\mu}} \frac{\omega_i}{\omega_c} c && (112)\\
\Psi(1-l)^{-\xi} &= -\left(\omega_c^{\frac{\mu}{1+\mu}} c^{\frac{1}{1+\mu}} + \omega_i^{\frac{\mu}{1+\mu}} i^{\frac{1}{1+\mu}}\right)^{\nu(1+\mu)-1} \left(\frac{\omega_c}{c}\right)^{\frac{\mu}{1+\mu}} w && (113)
\end{aligned}
$$

$$
\begin{aligned}
k &= \left(\frac{\lambda\alpha}{r}\right)^{\frac{1}{1-\alpha}} \left(\omega_k^{\frac{\rho}{1+\rho}} + \omega_o \omega_k^{\frac{-1}{1+\rho}} \left(\frac{r}{q}\right)^{\frac{1}{\rho}}\right)^{\frac{(1+\rho)\alpha-1}{1-\alpha}} Al\omega_k^{\frac{\rho}{1+\rho}/(1-\alpha)} && (114)\\
o &= k\left(\frac{r}{q}\right)^{\frac{1+\rho}{\rho}} \frac{\omega_o}{\omega_k} && (115)\\
l &= \frac{r}{w}\frac{1-\alpha}{\alpha}\left(1+\omega_o/\omega_k\left(\frac{r}{q}\right)^{\frac{1}{\rho}}\right) k. && (116)
\end{aligned}
$$

Further algebraic elimination of variables and an efficient numerical algorithm in Matlab is available upon request.

This description of the steady state is in line with the literature on oil in an open economy. The difference here is that the oil price and quantity are determined by the steady-state level of oil reserve, which itself is an outcome of the balance of the oil sector production and new shale reserves becoming accessible. By contrast, existing literature

(Bodenstein, Erceg, and Guerrieri 2011) treats oil flows as a stochastic exogenous process.

The eight variables of the steady state serve two purposes: first, the other steady-state values of interest, such as household income, are calculated from them. Second, the steady-state values serve as the basis for expressing the real-world data in terms of log deviations from the steady state values. In Section 3.1, I show how model conditions for the US shale variables allow to estimate the structural parameters and obtain the responses to a shale shock.

3 Estimation approach

3.1 Log-linearization

The reaction of macroeconomic variables, such as income, to shale oil, is evaluated in the form of impulse response functions to an oil reserve increase. The two particular metrics are magnitude of the deviation from the steady state and the half-life of the reversal to it. Thus, the goal of the estimation stage is to obtain a system of linear difference equations to be estimated by the Kalman filter maximum likelihood method. It is possible to write the model constructed in the previous section in the standard format for linearized systems

$$0 = Fx_{t+1} + Gx_t + Hx_{t-1} + L\epsilon_{t+1} + M\epsilon_t \tag{117}$$

where x_t is a vector of endogenous variables that can be changed at time t. The variables in the vector here are relative deviations from the steady state, as opposed to absolute values. x_{t-1} is a vector of endogenous state variables that cannot be changed at time t and x_{t+1} is the vector of the next-period endogenous "control" variables. Vector ϵ_t at any moment in time contains exogenous stochastic state variables

$$\epsilon_t = \begin{bmatrix} \epsilon_{z,t} & \epsilon_{v,t} & \epsilon_{q,t} \end{bmatrix}^{\mathsf{T}} \tag{118}$$

In the context of the US shale model, the number of endogenous variables is 26×51. Out of the 26 total, 14 variables and conditions are static, and the remaining 12 are dynamic. The rank of the dynamic system (117) is equal to the number of dynamic conditions. Therefore, the static conditions are used to solve out for the static variables prior to log-linearization. The simplest way to do it is to log-linearize the equations first and then solve out for the static variables. While it is common to perform the log-linearization algebraically, it is possible to relegate this job to a machine script, utilizing the chain rule. In general

$$\begin{aligned}
Gx_t &= \frac{\mathrm{d}\ln(conditions_{ss})}{\mathrm{d}\ln x_{ss}} \ln\left(\frac{x_t}{x_{ss}}\right) \\
&= \frac{1}{conditions_{ss}} \frac{\mathrm{d}conditions_{ss}}{\mathrm{d}x_{ss}} \frac{\mathrm{d}x_{ss}}{\mathrm{d}\ln x_{ss}} \ln\left(\frac{x_t}{x_{ss}}\right) \\
&= \frac{\mathrm{d}conditions_{ss}}{\mathrm{d}x_{ss}} x_{ss} \ln\left(\frac{x_t}{x_{ss}}\right) \qquad (119)
\end{aligned}$$

The last transformation works because log conditions (117) of the model have to be equal to zero around the steady state. Thus, the matrices F, G, H, L, M in the log-linearized conditions of the model are the elements of the Jacobian matrix of the unaltered system of conditions (Euler equation, law of motion for assets, and oil sector), evaluated at the steady state and multiplied by the steady state values of the respective variables.

Applied to the US shale setup, the length of vector x_t is 12 variables times 51 states and

ROW. By default, algebraic elimination produces the vector of i, r^*, q, w, o, y, v, x_3, π, π^{reset}, λ, p, but it is straightforward to express some of them for more interesting variables, such as household income, unemployment, and state net exports. With the 12×51 corresponding log-linearized dynamic conditions, the system is full rank.

There is a number of methods to solve the log-linear system of difference equations (Blanchard and Kahn 1980; Sims 2001; Uhlig 1999). Here I use the method of undetermined coefficients as in Uhlig (1999), although the QZ-decomposition method (Sims 2001; Klein 2000) yields the same (correct) solution.

The core principle of the method is that if we are looking for the policy rule of the form

$$x_{t+1} = Px_t + Qz_t \tag{120}$$

then the coefficient matrix P is found by solving the quadratic matrix equation

$$0 = FP^2 + GP + H \tag{121}$$

Once the quadratic system is solved, the coefficients Q for stochastic state variables are found by plugging the policy rule (120) into the system of log-linearized conditions (117) of the model,

$$0 = \left[(FP + G)\,P + H\right] x_{t-1} + \left[(FQ + L)\,N + (FP + G)\,Q + M\right] z_t \tag{122}$$

In models with autoregressive behavior of shocks matrix N is the recursive law for the structural shock terms. Here N is a matrix of autoregressive terms for $\epsilon_{z,t}$, $\epsilon_{v,t}$ and $\epsilon_{q,t}$.

The solution of the system generates coefficient matrices P and Q for the policy rule. These matrices are functions of the deep parameters of the model and can be estimated by maximum likelihood. Furthermore, plugging the shale shock values into the policy rule (120) produces the impulse responses for the macroeconomic variables of interest, primarily household income across states and oil firm profits. An implementation of this framework to characterize the response to shale shock is an interesting direction of future research.

3.2 Policy rule and Kalman filter

The convenient fit between the policy rule and the structure of Kalman filter was exploited by Ireland (2004) and has become standard since. Kalman filter tracks the evolution of a variable with a transition equation, which describes the evolution of the true values of an unobserved variable, and a measurement equation that updates the prediction of the unobserved variable based on the observation of some related variable. Ireland (2004) treats state variables as the unobserved variables, and other endogenous variables as the observables in the measurement equation. For details on the Kalman filter estimation procedure itself, refer to Hamilton (1994) and DeJong and Dave (2011)[21].

I form the transition equation out of the linear recursive laws of motion for state variables (the values are relative deviations from the steady state values), $[P, Q]$, and the measurement equation from the laws of motion for nonstate variables, $[R, S]$. The Kalman filter is advantageous for estimation using state-level data because many macroeconomic variables crucial to the question of shale wealth are unobserved on the state level. The 12×51 system

[21]A Gauss script is publicly available at David DeJong's personal webpage hosted by the University of Pittsburgh. A MATLAB code used to estimate the model of this section is available upon request.

of dynamic conditions is expressed to include the the variables of most interest. The variables of interest that are observed are household income, unemployment rate, price index, wages and oil prices, as well as oil reserves and production. The unobserved variables are consumption, oil and nonoil net exports, interest rates, capital stocks. While this is the most interesting lineup of the 12 state variables in the structural model, other combinations are possible.

4 Data and modeling of the structural parameters

The data for the listed observed series are available on a quarterly basis from the Bureau of Economic analysis and the Energy Information Administration. The relevant stretch of the US shale history, between 2008 and the most recent dates available, provides ten years of quarterly state-level data (Table 8).

With this framework, the plan for a future empirical implementation is as follows: collect the data on the 12 variables for the US states, transform them into the log deviations from the steady-state values, adopt the structural parameter values widely accepted in the existing literature. Use the Kalman filter to obtain the value of likelihood. Continue to choose the parameter values following Newton-Rapson and Nelder-Mead methods until a maximum-likelihood combination of parameters is found. Then, use the parameters to construct the impulse responses of household income, unemployment, state net exports, and other macroeconomic variables of interest. Finally, measuring the maximum deviations from the steady state and the half-life of reversal, allows to characterize the effects of shale on the US population wealth and its distribution. Here, I provide an example of this analysis

Table 8: US quarterly state-level data for model variables, 2008–2017

Input Data	Notation	Average value	Source/Method
Model inputs			
Output, thousand 2018 dollars	y_t	65.19 (13.5)	Bureau of Economic Analysis (BEA), quarterly GDP in 2005 dollars, seasonally adjusted.
Unemployment rate, %	l_t	6.60 (2.03)	Bureau of Labor Statistics (BLS), Local area unemployment statistics.
Inflation, %	π_t	1.86 (1.20)	Change in the state consumer price index, BLS.
Wage, thousand 2018 dollars	w_t	49.56 (6.70)	BLS Occupational Employment Statistics.
Oil price, \$ per barrel	q_t	76.44 (24.34)	EIA Spot prices for crude oil and petroleum products.
Oil reserve, barrels per person	z_t	82.97 (218.51)	EIA Proved oil reserves. Annual data, extrapolated to quarterly by cubic spline.
Oil production, barrels per person per quarter	v_t	3.13	(8.41) EIA Crude oil production series.
Dynamic variables treated as unobserved in the Kalman filter estimation			
Consumption	c_t	—	Data do not allow to distinguish between consumption of state-made goods and imports from neighbors. Forms a part of the transition equation in Kalman filter.
Net export of oil and gas, dollars	$q_t(v_t - o_t)$	—	Not feasible to separate within-state consumption of oil and gas due to them being processed in refineries around the nation. A part of the transition equation.
Net nonoil export, dollars	$y_t - c_t - (p^*/p)i_t$	—	Data do not track state-level imports and exports to other states.
Interest rate, %	r_t	—	Due to limited comparability of capital costs in states to national indicators (10-year corporate bond, etc.), it is preferable to treat the interest rate as part of the Kalman filter transition equation.
Stock of assets	a_t	—	No data on state-level asset holdings that would allow to distinguish between ownership of within-state capital and claims on assets in other states.

Aggregate variables are in the intensive form, divided by the state population (BEA civilian non-institutional population) and total factor product of the state (set to zero for the first quarter of 2008 and calculated by the GDP growth accounting method). Standard errors are in parentheses.

by comparing the shape of household income in the shale-bearing state to income is a state with no oil.

I implement the described algorithm for two states, North Dakota and Minnesota, among which the former experiences a shock to its oil reserve, and the other one does not. This limits the size of the matrices in the Kalman filter equation 120 to 12 equations and conditions for the model variables in Table 8 times two states plus three conditions for each state that equate the foreign prices of capital, r, oil, q, and goods, p/p^* of one state to the domestic prices of the other state. Additionally, the system includes three stochastic shock variables for oil production, ϵ_v, oil price, ϵ_q, and reserve, ϵ_z. Thus, the rank of matrix P is 30, and the rank of matrix Q is 3.

For this system and state data, I calibrate the structural parameters of the model. Table 9 reports the values that approximate the observed behavior of the state-level variables. When subjected to shock, North Dakota experiences growth in per-capita output and consumption, equivalent to a 20% deviation from steady state. The half-life of the response is 20 quarters. Minnesota's response is much more muted (the economy deviates from the steady state by single percentage points) and lagged, with output taking around 50 quarters to revert halfway to the steady state. This suggests that the economy reacts to sudden resource wealth by building up savings and gradually consuming them over time. Furthermore, this evidence suggests that direct benefactors receive a benefit from shale that is concentrated and quick. The rest of the economy experiences smaller-scale and more protracted effects, suggesting a lag in filtering of the benefits through to the general population.

An expansion of this analysis to 50 states can fully utilize the variability of the available US state-level data, although at a computational cost.

Table 9: Structural parameters based on a two-state application of the DSGE framework (Minnesota and North Dakota).

Parameter	Notation	Value
Parameters inferred from data		
Exogenous growth rate of population and technology	g	0.02
Rate of nonoil capital depreciation	δ	0.04
Intertemporal preference rate	β	0.97
Aggregation weight of imports	w_m	0.7
Elasticity of substitution imports/domestic	μ	-1.1
Elasticity of nonoil production wrt non-labor inputs	α	0.3
Aggregation weight of capital	ω_k	0.98
Aggregation weight of oil	ω_o	0.02
Scale parameter in nonoil production	B	20
Scale parameter for oil production	D	0.1
Rate of oil capital depreciation	δ_v	0.05
Elasticity of substitution capital / oil	ρ	-2
Elasticity of oil output wrt oil capital	γ	0.6
Elasticity of utility wrt total consumption	ν	0.8
Interest rate premium on borrowing from other states	χ_r	1.001
Cost premium on importing oil	χ_q	1.005
Transaction cost of importing goods from other states	χ_p	1.002
Elasticity of aggregator of intermediate goods	η	0.9
Calvo-style stickiness in oil production	ϕ_q	0.2
Calvo-style stickiness in labor	χ_l	0.15
Calvo price stickiness	χ_p	0.25
Marginal cost of a monopolistic firm	λ	0.53
Marginal cost of a monopolistic firm	λ	0.53

5 Conclusion

Sudden abundance of North American shale oil and gas defied the industry forecasts and sent ripples across a multitude of dimensions of the US economy. Outside of the immediate shocks to oil and gas reserves and production, these changes were caused by people and businesses adjusting their behavior in response to the new energy sector realities. I assert that these responses can be modeled in line with the principles of modern macroeconomic theory and estimated by frequentist macroeconometric methods. I set up a structural model that complements the dominant reduced-form approach to the study of shale benefits.

This work offers a comprehensive estimable open-economy general equilibrium model with the oil sector. I extend the toolset of resource-centered DSGE by setting up an oil sector that optimally produces a finite reserve. This work encompasses the theoretical component of estimating a macroeconomic effect of shale shocks. I derive and describe the general equilibrium, solve for steady state, compose the estimable system of linear difference conditions and variables, and transform it into the form compatible with the Kalman filter estimation. I apply the method to a two-state scenario, which allows to discuss the structural parameters that govern the response of the US economy to the shock. Further, I outline the necessary steps and methods to estimate the structural parameter values, obtain the impulse response functions for variables that represent population wealth, and characterize the distribution of wealth in terms of how much and how fast the households and firms within and outside the oil-bearing regions benefit from shale oil. This sets up the foundation and makes possible future work that can focus on obtaining the empirical results for a wider range of states.

This will allow a comparison between the structural estimates found here to the conclusions from reduced-form estimation in the literature on the subject.

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Appendices

Appendix A Model conditions and elimination of static variables

A.1 The household problem

The households allocate resources among the five options, c_t, m_t, j_{t+1}, $k_{v,t+1}$, and b_{t+1}. The proportions are determined by the standard conditions: marginal utility has to equal the shadow price of capital, and the marginal return on domestic shares and foreign bonds have to be equal. An exception is the oil-specific capital, which generates higher returns than nonoil capital, but is restricted by the oil sector licensing authority to prevent overdrilling, as described in the previous section. The households' revenues compensate for the nonoil physical capital depreciation that takes place at the rate δ, and the depreciation of oil-specific capital at the rate δ_v.

The households solve the recursive problem of utility maximization by choosing the values for endogenous variables so as to satisfy the optimality conditions. Maximization of utility subject to the budget constraint yields a set of equations:

$$\begin{aligned}
\beta^t \frac{\partial U_t}{\partial c_t} - \lambda_t &= 0 & (123)\\
\beta^t \frac{\partial U_t}{\partial m_t} - p_t \lambda_t &= 0 & (124)\\
\beta^t \frac{\partial U_t}{\partial n_t} - \lambda_t \omega_t &= 0 & (125)\\
-\lambda_t (1+g) + \lambda_{t+1} (1 + r_t - \delta) &= 0 & (126)
\end{aligned}$$

The Lagrangian equations result in three optimality conditions for households: the marginal rate of substitution between domestic goods and imports equals their relative price, fixed to unity in this research, (127), optimal tradeoff between leisure time and consumption depends on the wage (128), and the Euler equation states that consumption across time depends on the interest rate, time preference rate, and the growth rates of population and technology (129).

$$\begin{aligned}
&[\text{c+m}] & \partial U_t \partial c_t / \, \partial U_t \partial m_t &= p_t & (127)\\
&[\text{c+n}] & \partial U_t \partial n_t &= -\omega_t \partial U_t \partial c_t & (128)\\
&[\text{c+k}] & \partial U_t \partial c_t / \, E\left[\partial U_{t+1} \partial c_{t+1}\right] &= E\left[\frac{1 + r_{t+1} - \delta}{1+g} \beta\right] & (129)
\end{aligned}$$

Although the conditions allow for a degree of substitutability between domestic goods and imports, without prices in the model this aspect of household preferences is redundant. Essentially the nonoil trade is dictated by the fact that, given the constant and exogenous relative price, the households are adamant about a fraction of their total consumption being imports.

A.2 The nonoil firm problem

Profit maximization conditions for 15 equate the marginal products of nonoil production inputs and their market prices.

$$\frac{\partial y_t}{\partial k_t} = r_t \tag{130}$$

$$\frac{\partial y_t}{\partial n_t} = \omega_t \tag{131}$$

$$\frac{\partial y_t}{\partial o_t} = q_t \tag{132}$$

A.3 Algebraic elimination of static variables

Once specific functional forms are adopted, it is possible to perform stepwise elimination of static variables. I begin by expressing for imports. The left-hand side of the Euler equation for households (129) is in terms of marginal utilities. Imports are eliminated from the expression for utility using the household MRS condition (127):

$$m_t = \frac{w_m}{w_c} c_t \tag{133}$$

Elimination of imports greatly simplifies the expression for marginal utility of domestic consumption. Exploiting the assumption that the aggregation weights of home consumption w_c and imports w_m add up to unity, gives a simpler marginal utility:

$$\begin{aligned}\frac{\partial U_t}{\partial c_t} &= \left[w_c^{\frac{\mu}{1+\mu}} c_t^{\frac{1}{1+\mu}} + w_m^{\frac{\mu}{1+\mu}} m_t^{\frac{1}{1+\mu}}\right]^{(1+\mu)\phi-1} \phi \left(\frac{w_c}{c_t}\right)^{\frac{\mu}{1+\mu}} (1-n_t)^{\varphi-\phi} \\ &= \phi \left(\frac{w_c}{c_t}\right)^{1-\phi} (1-n_t)^{\varphi-\phi}\end{aligned} \tag{134}$$

Further simplification of marginal utility is possible with the use of the MRS between leisure and consumption (128). For the choice of (standard) functional forms, the condition becomes

$$-(\varphi-\phi)\left[w_c^{\frac{\mu}{1+\mu}}c_t^{\frac{1}{1+\mu}}+w_m^{\frac{\mu}{1+\mu}}m_t^{\frac{1}{1+\mu}}\right]^{(1+\mu)\phi}(1-n)^{\varphi-1-\phi}=$$
$$-\frac{\partial y}{\partial n}\left[w_c^{\frac{\mu}{1+\mu}}c_t^{\frac{1}{1+\mu}}+w_m^{\frac{\mu}{1+\mu}}m_t^{\frac{1}{1+\mu}}\right]^{(1+\mu)\phi-1}\phi\left(\frac{w_c}{c_t}\right)^{\frac{\mu}{1+\mu}}(1-n_t)^{\varphi-\phi} \tag{135}$$

This rewrite of the leisure-consumption condition (128) conveniently eliminates consumption:

$$c_t=\frac{\partial y}{\partial n}\frac{\phi}{\varphi-\phi}w_c\left(1-n_t\right) \tag{136}$$

Write the marginal product of labor in terms of output and labor to remove wages:

$$c_t=\left(1-\alpha\right)y_t\frac{\phi}{\varphi-\phi}w_c\frac{1-n_t}{n_t} \tag{137}$$

Such a combination of conditions (127)–(129) removes most of the variables from the Euler equation for households. Only output and the endogenous supply of labor are left:

$$\frac{\partial U_t}{\partial c_t}\bigg/\frac{\partial U_{t+1}}{\partial c_{t+1}}=\frac{y_t^{\phi-1}n_t^{1-\phi}\left(1-n_t\right)^{\varphi-1}}{y_{t+1}^{\phi-1}n_{t+1}^{1-\phi}\left(1-n_{t+1}\right)^{\varphi-1}}=\frac{1+r_{t+1}-\delta}{1+g}\beta \tag{138}$$

Next, the law of motion for resources is simplified. It is convenient to write the sum of capital and claims on foreign economy as households' nonoil assets,

$$a_t=k_t+b_t \tag{139}$$

I rewrite the household budget constraint for assets and use the firm profit maximization condition to turn it into the country's resource constraint:

$$(a_{t+1} + k_{v,t+1})(1+g) = y_t - c_t - m_t - r_t k_t + a_t(1+r_t-\delta) + q_t v(z_t) - q_t o_t + k_{v,t}(1-\delta_v) \quad (140)$$

I use the household's MRS (127) conditions to express imports as a function of domestic goods

$$m_t = \frac{w_m}{w_c} c_t \quad (141)$$

and eliminate imports from the resource constraint

$$a_{t+1}(1+g) = y_t - c_t/w_c - r_t k_t + a_t(1+r_t-\delta) + q_t v(z_t) - q_t o_t \quad (142)$$

I eliminate factor prices by simply using up the cross-border premium conditions (110) and (111). With the factor prices out of the way, I find quantities of production inputs. First, the ratio of the marginal products,

$$\left(\frac{\omega_k}{\omega_o}\frac{o_t}{k_t}\right)^{\frac{\rho}{1+\rho}} = \frac{r_{ROW}\,(k_t/a_t)^{\chi}}{q_{ROW}\,(v(z_t)/o_t)^{\zeta}} \quad (143)$$

gives insight into oil inputs:

$$o_t = \left[\left(\frac{\omega_k}{\omega_o}k_t\right)^{\frac{\rho}{1+\rho}} \frac{r_{ROW}(k_t/a_t)^{\chi}}{q_{ROW}v(z_t)^{\zeta}}\right]^{\frac{1}{\frac{\rho}{1+\rho}+\zeta}} \quad (144)$$

Along the same logic, I use the condition on the marginal product of capital (110) to express for labor supply.

$$n_t = \left\{ \frac{\alpha B \left[w_k^{\frac{\rho}{1+\rho}} k_t^{\frac{1}{1+\rho}} + w_o^{\frac{\rho}{1+\rho}} \left[\left(\frac{\omega_k}{\omega_o} k_t \right)^{\frac{\rho}{1+\rho}} \frac{r_{ROW}(k_t/a_t)^{\chi}}{q_{ROW} v(z_t)^{\zeta}} \right]^{\frac{1}{\rho+(1+\rho)\zeta}} \right]^{(1+\rho)\alpha} \left(\frac{\omega_k}{k_t} \right)^{\frac{\rho}{1+\rho}}}{\left[r_{ROW}(k_t/a_t)^{\chi} \right]} \right\}^{\frac{1}{\alpha-1}} \tag{145}$$

As the result of the above eliminations, the steady state problem consists of only three variables k_{ss}, a_{ss}, z_{ss} and three equations that are static reductions of the Euler equation, the resource constraint, and the law of motion for the oil reserves. Expansion of the problem to the entire balanced growth path adds three $t+1$ variables k_{t+1}, a_{t+1}, z_{t+1} and six exogenous stochastic state variables, $\epsilon_{z,t}$, $\epsilon_{q,t}$, $\epsilon_{v,t}$, $\epsilon_{z,t+1}$, $\epsilon_{q,t+1}$, $\epsilon_{v,t}$. The autoregressive conditions for the stochastic variables are:

$$\begin{aligned} \epsilon_{z,t+1} &= ar_z \epsilon_{z,t} + u_{z,t+1}, \\ \epsilon_{q,t+1} &= ar_q \epsilon_{q,t} + u_{q,t+1} \\ &\text{and} \\ \epsilon_{v,t+1} &= ar_v \epsilon_{v,t} + u_{v,t+1}, \end{aligned} \tag{146}$$

where ar_i are the coefficients of autoregression and $u_{i,t+1}$ are the innovations. Calvo rigidities for oil production and nonoil capital employment require addition of two variables, k^* and

v^* and two dynamic conditions to the system:

$$
\begin{aligned}
v_{t+1} &= \eta v_{t+1}^* + (1-\eta)v_{t-1} \\
&\text{and} \\
k_{t+1} &= \lambda k_{t+1}^* + (1-\lambda)k_t
\end{aligned}
\tag{147}
$$

Appendix B Parameters and data

B.1 Parameters of the utility function

I begin with the parameters in the utility function, w_c, w_m, μ, and ϕ. The aggregation weights of domestic consumption, w_c, and imports, w_m, are set to add to unity. I use the result from the theory section: with no prices of domestic and foreign goods (implicitly the relative price is set to one), consumption/imports ratio is equal to the ratio of the weights, w_c/w_m. The ratio of the parameters is obtained as the mean of the results of elementwise division of the vector of imports by the vector of total final consumption less imports, m_t/c_t.

Figure 9 shows that, aside from a few years in the 1970s in Norway, the share of imports has not changed significantly in either country and can be treated reasonably as a constant. I set the aggregation weight for imports to $w_m = 0.524$ for Norway and $w_m = 0.319$ for the UK to produce the share of imports equal to the mean. The weights are different for home and foreign economies, depending on the relative size of their populations (which, assuming foreign economy is the European Union, is identical to the relative size of their GDP's).

The ability of an economy to export to the ROW is set to a constant. For each of the

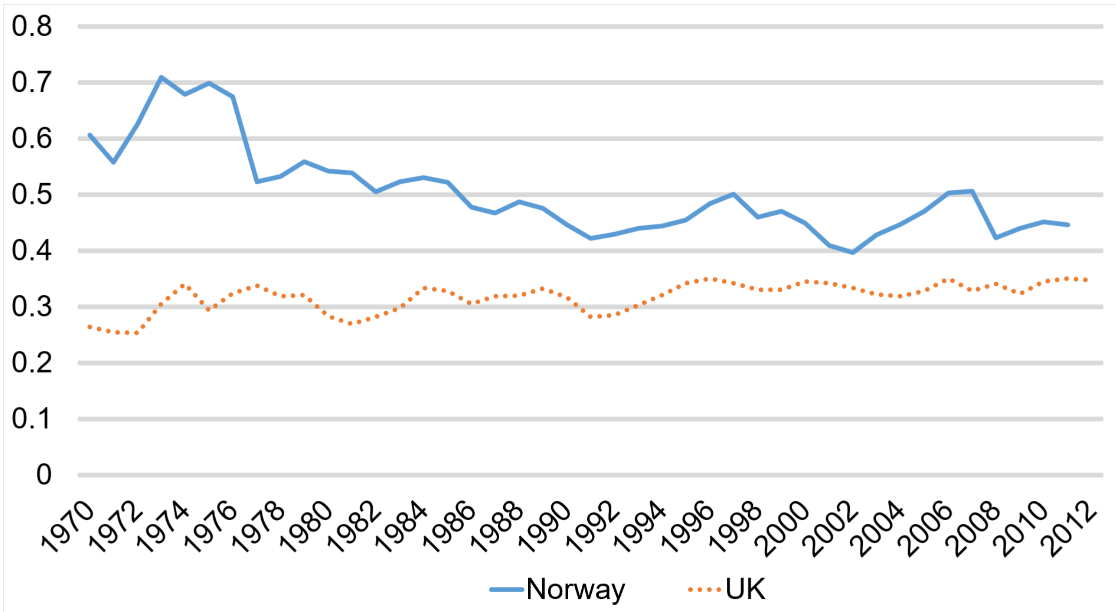


Figure 9: Ratio of Imports to Total Final Consumption (Private and Public). Source: National Accounts, NOS and HM ONS for Norway and the UK, respectively.

two countries, I assume that the ROW mirrors their preferences for imported goods and adjusts them by the relative size of the country's population, L_t, to the 28 countries that constituted European Union as of 2013, L_t^*. The values are 1/83 for Norway and 1/7.1 for the UK. Thus, a country's exports are fixed at

$$x_t = \left(1 - \omega_m \left(\frac{L_t^*}{L_t}\right)^{-1}\right) c_{ss} \frac{L_t^*}{L_t} \tag{148}$$

The value of the elasticity of substitution between imports and consumption of domestic goods, a transformation of the parameter μ, is irrelevant due to the relative price of home and foreign goods being set to unity. In such a simplified scenario, the households will always consume imports and domestic goods in proportion to their respective aggregation weights, regardless of the households' ability to substitute. The utility function is set to have constant returns to scale, so that elasticities of consumption (home goods and imports) and leisure time add up to one.

Elasticity of utility with respect to consumption (of home goods and imports), ϕ, is estimated so as to produce realistic labor force participation in both countries. With the value of the parameter of $\phi = 0.5$, the households choose the value of endogenous labor supply in the vicinity of $n_t \simeq 0.45$, depending on the parameterization of the model, which is consistent with the common calibration results in the literature.

B.2 Parameters of the production function

Parameters of the production function include production factor weights, w_k and w_o, elasticity of output with respect to the aggregate capital-oil input, α, elasticity of substitution between oil and capital, ρ, and a scale parameter, B. Aggregation weights of capital and oil are found by the factor payment method. A common result in microeconomic theory is that with complete markets the revenues of a competitive firm are split among the factor payments in proportion to their respective elasticities in the production function.

$$\frac{r}{q} = \frac{\partial y/\partial k}{\partial y/\partial o} = \left(\frac{w_k o}{w_o k}\right)^{\frac{\rho}{1+\rho}}$$

or

$$\left(\frac{rk}{qo}\right)^{\frac{1+\rho}{\rho}} \left(\frac{k}{o}\right) = \frac{w_k}{w_o} \tag{149}$$

Elasticity of output with respect to nonlabor inputs is obtained by the same principle.

$$rk + qo = \frac{\partial y}{\partial k} y + \frac{\partial y}{\partial o} y \tag{150}$$

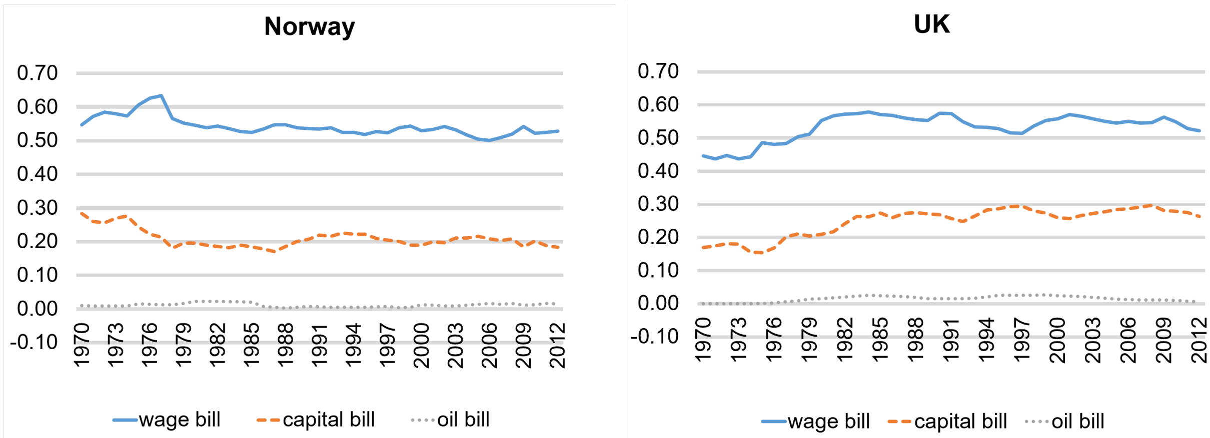


Figure 10: Factor Bills as Proportions of GDP.

Using the functional form of a CES between capital and oil, nested in the Cobb–Douglas between labor and non-labor inputs, an expression can be obtained for alpha in terms of the available data.

$$rk + qo = \alpha y \tag{151}$$

I obtain the values for capital and labor bills from the ”operating surplus” and ”compensation of employees” entries of each of the countries. The resulting values for elasticity of output with respect to labor are $\alpha = 0.288$ for Norway and $\alpha = 0.33$ for the UK. In a closed economy, the oil bill would simply be equal to the revenue of the upstream oil sector firms. In an economy that exports oil, that revenue needs to be multiplied by the domestic consumption of oil and divided by the domestic production of oil. Figure 10 illustrates the relative stability of the shares of the production factors in the economy.

While the Norwegian national accounts provide a complete picture of the oil bill (because NOS provides a breakdown of the revenue by industry), the UK data is limited. While I have the capital and wage bills, it is difficult to subtract the oil bill without knowing the shares of labor and capital in the oil industry. Norwegian data suggests that 15% of the oil industry net income goes to the wage bill, and 85% goes to the capital bill. Thus, I apply these percentages to the UK and subtract 15% of the net income of the oil industry from the UK wage bill and the remaining 85% from the capital bill. Furthermore, the UK oil bill data is not available prior to 1997. I calculate the mean proportion of the oil bill to the output of physical oil and gas for 1997–2012 and extrapolate it on the prior years, where only the output series are available. That proportion on average is equal to the market oil price. Finally, data for oil-specific capital for the UK becomes available starting in 1997. I infer the missing years using the permanent inventory method. Oil capital is formed in accordance with the values in Oil & Gas UK Economic Report 2014, and is assumed to depreciate at the annual rate δ_v. The value for depreciation rate of 6% produces the best fit to the capital stocks data that becomes available starting in 1997.

The scale parameter of the production function, B, is computed as the mean of the ratio of the actual output for every year and the one predicted by the remainder of the production function.

Elasticity of substitution between oil and capital is low for Norway and slightly less than unity for the UK. The aggregation parameter estimate is at $\rho_{NO} = -2.97$ for Norway and $\rho_{UK} = -13.77$ for the UK. This finding is consistent with the results of calibration carried out by Backus and Crucini (2000), and further confirmed by Miyazawa (2009), who also report low elasticity of substitution. The finding contradicts the choices of high elasticity between capital and energy made by Kim and Loungani (1992).

The population grows at a constant rate of about 0.3% in each country. I approximate a constant growth rate that would produce the observed population in 2012, L_{2012} given the starting population in 1970, L_{1970}. The growth rate formula is derived from geometric series. If

$$L_{2012} = L_{1970} \left(1 + g_L\right)^{2012-1970}, \tag{152}$$

then the growth rate is expressed as

$$g_L = \exp\left[\left(\ln L_{2012} - \ln L_{1970}\right) / \left(2012 - 1970\right)\right] - 1. \tag{153}$$

I use growth accounting to compute the series of technology variable A_t as the Solow residual. Technology is Harrod-neutral in the production function. The residual is obtained by totally differentiating the output function and expressing it for technology residual (Solow 1957).

The data on output is reported as GDP, which corresponds to the output function adopted in the theory section, but in extensive terms:

$$Y_t = B\left[w_k^{\frac{\rho}{1+\rho}} K_t^{\frac{1}{1+\rho}} + w_o^{\frac{\rho}{1+\rho}} O_t^{\frac{1}{1+\rho}}\right] \left(A_t L_t n_t\right)^{1-\alpha}. \tag{154}$$

It is useful to write the total derivative of output as a function of the variables of the model: capital, K_t, consumption of oil (as a production input), O_t, technology stock, A_t, total labor reserve, L_t, and the share of the economically active population that participates in labor force, n_t.

$$\mathrm{d}Y = \frac{\partial Y}{\partial K}\,\mathrm{d}K + \frac{\partial Y}{\partial O}\,\mathrm{d}O + \frac{\partial Y}{\partial A}\,\mathrm{d}A + \frac{\partial Y}{\partial L}\,\mathrm{d}L + \frac{\partial Y}{\partial n}\left\{\frac{\partial n}{\partial C}\,\mathrm{d}C + \frac{\partial n}{\partial Y}\,\mathrm{d}Y\right\} \tag{155}$$

Plugging the adopted functional forms into the total differentiation results in rate of change of output as a function of the model variables and their rates of change:

$$\begin{aligned}
\frac{\mathrm{d}Y}{Y} &= \frac{\alpha}{w_k^{\frac{\rho}{1+\rho}} K_t^{\frac{1}{1+\rho}} + w_o^{\frac{\rho}{1+\rho}} O_t^{\frac{1}{1+\rho}}} \left[\left(\frac{w_k}{K}\right)^{\frac{\rho}{1+\rho}} \mathrm{d}K + \left(\frac{w_o}{O}\right)^{\frac{\rho}{1+\rho}} \mathrm{d}O \right] \\
&+ (1-\alpha)\left(\frac{\mathrm{d}A}{A_t} + \frac{\mathrm{d}L}{L_t}\right) + \\
&+ \frac{1-\alpha}{n_t} \left\{ \left(1 + \frac{C}{Y}\frac{\varphi-\phi}{\phi}\frac{1}{(1-\alpha)w_c}\right)^{-2} \frac{C}{Y}\frac{\varphi-\phi}{\phi}\frac{1}{(1-\alpha)w_c} \left(\frac{\mathrm{d}C}{C} - \frac{\mathrm{d}Y}{Y}\right) \right\} \quad (156)
\end{aligned}$$

Collecting the terms containing technology on the left-hand side results in the expression for the rate of technology growth in terms of this model:

$$\begin{aligned}
\frac{\mathrm{d}A}{A_t} &= \frac{1}{1-\alpha}\frac{\mathrm{d}Y}{Y} - \frac{\alpha/(1-\alpha)}{w_k^{\frac{\rho}{1+\rho}} K_t^{\frac{1}{1+\rho}} + w_o^{\frac{\rho}{1+\rho}} O_t^{\frac{1}{1+\rho}}} \left[\left(\frac{w_k}{K}\right)^{\frac{\rho}{1+\rho}} \mathrm{d}K + \left(\frac{w_o}{O}\right)^{\frac{\rho}{1+\rho}} \mathrm{d}O \right] \\
&- \frac{1}{n_t} \left\{ \left(1 + \frac{C}{Y}\frac{\varphi-\phi}{\phi}\frac{1}{(1-\alpha)w_c}\right)^{-2} \frac{C}{Y}\frac{\varphi-\phi}{\phi}\frac{1}{(1-\alpha)w_c} \left(\frac{\mathrm{d}C}{C} - \frac{\mathrm{d}Y}{Y}\right) \right\} - \frac{\mathrm{d}L}{L_t}
\end{aligned}$$

I set A_{1970} to unity and obtain the observed technology levels from plugging the data series into the formula for growth rate. I regress logs of technology levels on time and a constant. The resulting slope parameter is the growth rate. The constant exogenous steady-state growth rate is a combination of technology and population growth rates:

$$g = (1 + g_L)\exp[g_A] - 1 \quad (157)$$

B.3 Parameters of the oil sector

The oil sector relies on parameters γ and D. Oil production is shaped by elasticities of output with respect to oil-specific capital, γ, and with respect to the volume of remaining

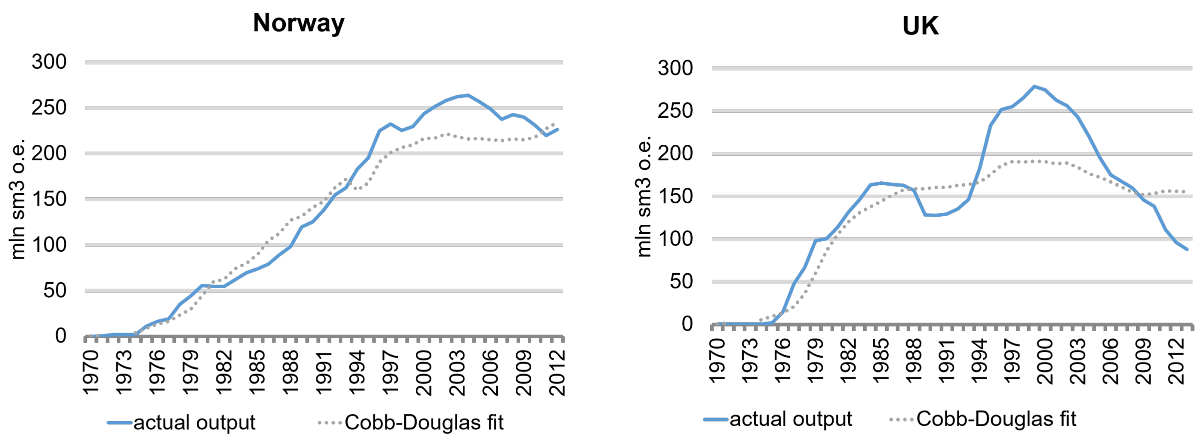


Figure 11: Cobb-Douglas fit of oil production. Parameters are $D_{NO} = 0.12$, $\gamma_{NO} = 0.49$, $D_{UK} = 0.52$, and $\gamma_{UK} = 0.54$.

reserves, $1 - \gamma$. Its magnitude is determined by the scale parameter, D. Rather than using the factor payment method to establish input elasticities, as I did for the production function of the nonoil sector, I estimate them instead. I rely on estimation rather than theory for two reasons: lack of consensus on the specification of oil production function and missing data. First, there exists a variety of specifications of the oil production function. My specification of oil output as a Cobb–Douglas function of oil-specific capital and the remaining reserve follows Bohn and Deacon (2000). Among other examples, Pindyck (1978) specifies production cost function as a hyperbolic relationship with the reserve, and Gross and Hansen (2013) include labor as a factor.

Estimation of the model produces the values of oil elasticities equal to $\gamma_{NO} = 0.49$ for Norway and $\gamma_{UK} = 0.54$ for the UK. The interpretation suggests that reserves and oil capital play roughly equal parts in determining oil output. Throughout the data, the oil output in Norway is building up for as long as discoveries are outpacing production. The industry plateaues when the reserves start to shrink. In the UK, most of the reserves are discovered in the very beginning of the series, with a secondary spike of natural gas in 1990s, but production lags, taking a decade to pick up as capital slowly flows into the industry. Figure 11 is the visualization of the ability of the Cobb-Douglas function to explain output as a function of capital and reserves. It is an overlay of output modeled with the above parameters and the observed output of oil and gas. Notably, the capital-heavy production function for the UK understates the distinctive two-hump pattern of the UK oil output. The second hump is driven by natural gas made available by technological advances. To make the humps better defined, heavier weight can be placed on reserves in the production function.

I calculate the scale parameter, D, in the same way as for the nonoil production function. For every period, the observed oil output is divided by the output modeled by the Cobb-Douglas function. The mean of the ratios is the scale parameter.

In a log-linearized model, the current level of reserves is expressed in terms of percentage deviation from the steady state value, z_{ss}. Therefore, a steady state value of zero, at which home would completely run out of oil, is unfeasible in the log-linearization approach to the policy rule. I introduce small volumes of steady-state discovery that compensates for the steady-state production v_{ss} and the dilution of reserve among the increasing number of effective workers, gz_{ss}. The choice of the steady-state reserve is influenced by two considerations. If shocks take the reserve far from the steady-state value, precision of the solution by linear approximation is affected. If, however, the steady-state value is set high enough, the country remains a net oil exporter in the steady state, implying that it never runs out of oil. I set the steady-state value to $z_{ss,NO} = 252$ and to $z_{ss,UK} = 2.6$, at $1/3^{rd}$ and $1/10^{th}$ of the average reserve in the time series, respectively.

Discoveries of oil register in the resource accounts as shocks to the oil reserve, z_t. Empirically, the shocks follow autoregressive patterns for both countries. The same is true for the oil price shocks. Autoregressive coefficients of the stochastic shock variables, $\epsilon_{z,t}$ and $\epsilon_{q,t}$, can be estimated as part of the model. However, the theory behind the autoregressive behavior of shocks is beyond the scope of the paper. Thus, ar_q and ar_q instruments to conform the data to the standard model assumptions, rather than structural parameters.

With these model inputs, only ten of the model parameters remain to be estimated: the time preference parameter in the utility function, β, elasticity of substitution in the production function, ρ, elasticity of oil production with respect to oil-specific capital, γ, elasticity of utility with respect to consumption, ϕ, interest rate premium for borrowing abroad, χ, the cost premium for importing oil, ζ, and AR(1) coefficients for the shocks, ar_q and ar_q. Further, I allow the interest rate premium to decrease over time to reflect the tendency of the balance sheets to expand over the timeframe in question. I estimate the rate, $\chi_{t+1}/\chi_t - 1$, which is held constant. Lastly, I estimate the Calvo-style rigidity of oil production to reflect the fact that it evolves much smoother than the oil discoveries it depends on.

B.4 Data

The model operates three endogenous variables (capital, total assets, and oil reserve) and three exogenous autoregressive stochastic variables (discoveries, domestic oil output shocks, and world oil price shocks). The current account response to an oil discovery depends on the values of these macroeconomic variables at the moment of the shock. For example, if the oil price changes, a net exporter of oil will experience the effects of changing terms of trade. By contrast, the current account of a country with balanced trade in oil is not directly affected by oil price shocks.

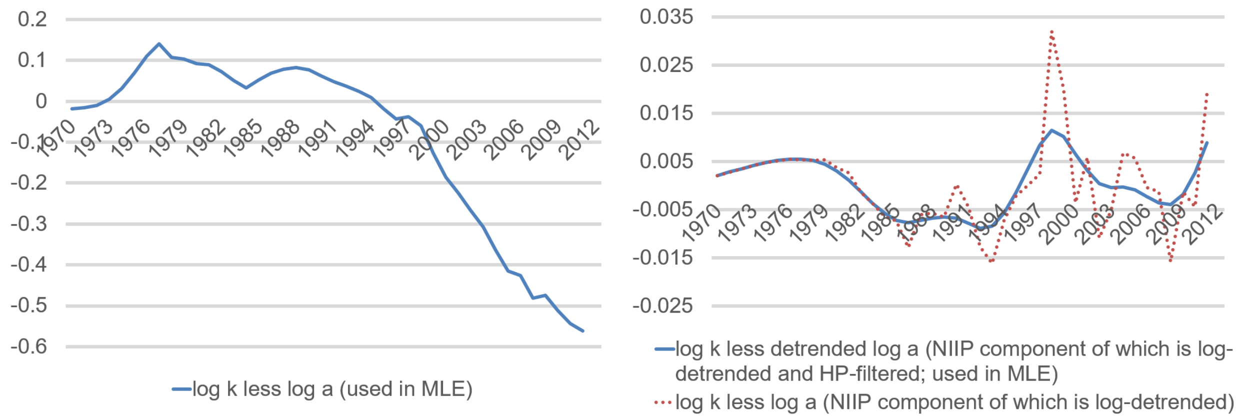
The resulting real output series are converted to intensive-term values by elementwise division by the population and technology residual series.

Nonoil capital, k_t, is set equal to the gross capital stock (National Accounts Norway, National accounts UK, and OECD STAN for the pre-1997 UK) minus the capital employed in the upstream oil industry (National accounts: Oil and gas extraction including services for Norway and O&G UK economic report 2014 for the UK).

Nonoil assets, a_t, are the sum of nonoil domestic capital and claims on foreign assets, measured as NIIP. Nonoil capital is obtained by subtracting oilfield capital from the aggregate capital reported in the national accounts. Oilfield capital in the UK is only available starting in 1997. I construct the missing values by the permanent inventory method from its flow counterpart, gross fixed capital formation (GFCF) for oil industry, which is available starting from 1970.

Data on NIIP, b_t, is available starting in 1998 for Norway and 1970 for the UK. The missing Norwegian data is constructed using the current account series. The values of the current account are the flow counterparts of the NIIP.

In Figures 12a and 12b, it is evident that the Norwegian capital-assets ratio behaves predictably and consistently. The UK ratio, however, demonstrates exponential growth of the international balance sheets and increased volatility beginning in the 1990s. Since the erosion of the net investment position and volatility are unrelated to any developments in the British oil sector, I logarithmically detrend the UK NIIP series and HP-filter the capital-assets ratio. Figure 12b show how this treatment eliminates all but the last shocks and



(a) (b)

Figure 12: A comparison between Norway's (left) and the UK's (right) k_t/a_t variable that represents the current account in the estimation. While the Norwegian series are smooth and show a clear trend of increasing NIIP, the UK series become very volatile in the latter decades and need to be filtered.

leaves the long-term series where the capital-asset ratio is low (NIIP is high) immediately after the oil shock in the 1970s and the natural gas shock in 1995. The ratio decreases (NIIP increases) as discovered oil reserve is gradually produced.

Information on oil reserve, z_t, is drawn from the Norwegian Petroleum Directorate (NPD) publications (annual reports and, starting 1997, resource accounts), and the Department for Business, Energy and Industrial Strategy (BEIS, formerly DECC) of the UK, data tables that it collects from the operators, mostly "Aggregation of UK Reserves and Resources". Thus, the resource shock event is the moment the stock of resource in an annual report does not match the difference between last year's reserve and last year's production. The agencies of the two countries are trusted with defining what counts as reserve. The UK follows a traditional nomenclature of the oil industry, accounting for the proven, probable, and possible oil and natural gas. Proven reserves are oil and gas that are almost certain to be produced economically. Probable reserves have a 50% chance to be produced economically, and possible reserves have a 10% chance. The categories that are collected in Norway are slightly different: NPD reports oil and gas approved for production, proven reserves, and total recoverable potential.

Proven reserves is the most frequently referred to reserve category. It is also one of the more parsimonious categories (BP Statistical Yearbook). The two available reserve measures for the UK show a similar pattern of discoveries, both in the filtered and unfiltered series. An initial large appraisal in the 1970's, followed by a dry season throughout the 1980s, and a new spike in the 1990s due to the improvements in natural gas technology and the resolution of the oil glut on the world markets by 1990. Norwegian data of approvals for production and proven reserves suggests that discoveries were evenly spread throughout the history of the industry in the country. Of the selection of measures of oil reserve presented, I select proven reserves as the most common measure and the only one reported in both countries. Changes to the proven reserves (adjusted for oil production) serve as shock variables $\epsilon_{z,t}$ in the model.

Oil and gas production data is from Statistics Norway, BP statistical review, and DECC UK Petroleum Production and Reporting System (PPRS) monthly production data. The gross production volumes in sm3 o.e. are converted into the oil shocks by taking the difference between the values predicted by the oil production function (Equation 78) and the observed value.

The remaining inputs in the model are (the non-oil) output, capital, wage, and oil bills. They are necessary to find production factor elasticities by the factor payment method.

Appendix C Heckman exponential type 2 tobit (ET2T) model

Much of the time no capacity is built in a given state-year. In those instances, the response variable equals zero MWh of new capacity. For such corner response data, a linear econometric model produces downward-biased estimates. The family of econometric models for corner outcomes includes tobit (Tobin 1958) and hurdle models (Cragg 1971).

I use a version of the Heckman two-step framework, which Wooldridge (2010, p. 697) refers to as exponential type 2 tobit (ET2T). The response variable (in MWh of new capacity) is equal to a latent variable, which is a function of the explanatory variables, if the latent variable is greater than zero, as in (158). The response variable is set to zero whenever the latent variable is negative.

$$y_{st} = \begin{cases} f\left(x_{st}\right) & \text{if } f(x_{st}) \geq 0, \\ 0 & \text{if } f(x_{st}) < 0 \end{cases} \tag{158}$$

In a given state-year, electricity producers of the state choose how much new capacity to construct, y_{st}, based on three groups of variables. The first group is the markup, m_{st}, the difference between the retail price of a MWh and the average cost of generating it. The markup serves as a proxy for the carbon tax. The second group is renewable portfolio requirement (RPS), $x_{1,st}$, the share of the producer's electricity legislatively required to come from renewable fuels. The third group is a vector of variables describing the status of legacy capacity in a state-year $x_{\neg 1,st}$: shares of public and private electricity producers, shares of fuel types, average capacity factors, total operational capacity, recent additions, and scheduled retirements, in MWh by fuel type.

Applied to the model of electricity generation, new capacity under construction is equal to the sum of the nameplate capacities of new plants if any are built, and to zero if the firms in the state decide not to build new generators that year. The switching of the response variable is governed by the binary participation decision, z_{st}, as in (159).

$$y_{st} = \begin{cases} f\left(x_{st}\right) & \text{if } z_{st}\left(m_{st}, x_{st}\right) = 1, \\ 0 & \text{if } z_{st}\left(m_{st}, x_{st}\right) = 0 \end{cases} \tag{159}$$

Like all corner solution models, ET2T addresses the corner outcome bias. The main advantage of ET2T over the other models of its class is that it allows the explanatory variables to have different, even opposite, effects on participation and capacity. For example, a RPS may reduce the probability that a nonzero capacity is built but may increase the size of that capacity in MWh (in case it is nonzero).

For confident identification in ET2T, the model needs to satisfy the excludability condition, so that the variables of the capacity size decision are a strict subset of the variables in the participation decision. In Section 2.2, I show theoretically that markup affects the participation decision but does not affect the capacity size decision. Empirically, markup also has a significant effect on participation and no effect on the size of capacity. Since markup is a regressor in the participation equation but is excluded from the capacity size equation, the requirement for a credible two-step Heckman is satisfied.

I account for the state and year effects to separate the effect of the fuel cost on new capacity from year-specific developments such as technology breakthroughs or state-specific effects such as wind patterns. To capture time effects, I incorporate year dummies into the regression. For the state fixed effect, I include the interstate electricity trade index, the ratio of how much electricity is produced in a state and how much is consumed. This ratio is almost completely time-invariant for any state in the data.

In addition to controlling for state and year effects in Heckman, I take advantage of the panel data structure and estimate the tax effect in a linear fixed-effects model described in Section 2.4. In this specification, the markup retains a significant effect on new capacity commitments even after the state and year effects are controlled for. The estimates of the fixed-effects linear probability model are inherently biased, however, whereas Heckman is a fitting model for this research question and data.

Practically, the two-step approach and the exclusion of markup result in new capacity commitments being a product of two functions, as in (160).

$$y_{st} = z\left(m_{st}, x_{st}\right) \times f\left(x_{st}\right) \tag{160}$$

In a given state-year, the decision to add any capacity, z_{st}, responds to all three groups of independent variables: legacy market size, fuel costs, and the stringency of RPS requirements.

$$z_{st} = 1 \text{ if } m'_{st}\gamma_m + x'_{st}\gamma_x + v_{st} > 0 \tag{161}$$

In equation (161) v_{st} is the error term. The capacity decision, $f(x_{st})$, only responds to the market size group of variables.

Here, however, I estimate the effect of a carbon tax on new capacity construction. The proxy for the carbon tax is fuel cost. In Section 2.2, I justify its exclusion from the capacity-size equation. Therefore, the unconditional expectation (162) is of interest here. I derive it in Appendix D.

$$E\left[y|x,v\right] = \exp\left(x'\beta + \rho\sigma_u \frac{\phi\left(m'\gamma_m + x'\gamma_x\right)}{\Phi\left(m'\gamma_m + x'\gamma_x\right)} + \frac{\sigma_u^2}{2}\right)\Phi\left(m'\gamma_m + x'\gamma_x\right) \tag{162}$$

The unconditional semi-elasticity of new capacity addition with respect to markup is (163). It is a straightforward differentiation of (162) with respect to the variable of interest, the markup.

$$\frac{d}{dx_i}\ln y_{st} = \beta_i - \rho\sigma_u\gamma_i \frac{\phi\left(\bullet\right)}{\Phi\left(\bullet\right)}\left[m\gamma_m + x'\gamma_x + \frac{\phi\left(\bullet\right)}{\Phi\left(\bullet\right)}\right] + \gamma_i \frac{\phi\left(\bullet\right)}{\Phi\left(\bullet\right)} \tag{163}$$

Exponential functional form of the model in (162) implies that (163) gives the expression for semi-elasticities, not marginal effects. To obtain the marginal effect for a given state, it is necessary to multiply (163) by the observed value of the response variable, capacity commitment. It is impractical, since the majority of capacity commitments is zero in any given state-year. Thus, I interpret the results from (163) times 100 as the percentage change in the expected capacity commitment as the result of a one-dollar increase in the markup.

Appendix D Interpretation of the Heckman model for the carbon tax and electricity generating capacity

The distinction of the ET2T from the general Heckman model is that it requires the capacity decision of the exponential, rather than linear, functional form. In ET2T specification, the model in (160) can be written down as in (164), where $I[...]$ is an indicator function that returns the value of one or zero.

$$y_{st} = I\left[\gamma_m m_{st} + x'_{st}\gamma_x + v_{st} = z_{st} > 0\right] \times \exp\left(x'_{st}\beta + u_{st}\right) \tag{164}$$

The requirement of the exponential functional form is because a linear model allows for negative outcomes. That amounts to a possible prediction of a negative capacity built in response to some parameter values. Negative capacity is not a concern in linear tobit models, where the same set of parameters governs the participation and the capacity decisions. It is not a concern in hurdle models, where the error terms in the participation and capacity decisions are assumed to be independent of one another. Here, however, I allow for the correlation between the errors in participation and capacity, as in (165), and therefore use the exponential form.

$$\begin{bmatrix} v \\ u \end{bmatrix} = \begin{bmatrix} 1 & \rho\sigma_u \\ \rho\sigma_u & \sigma_u^2 \end{bmatrix} \tag{165}$$

I make standard asssumptions (following Wooldridge, 2010, page 699) that the errors are independent of regressors in both the participation and capacity equations with zero mean and are bivariate-normally distributed.

$$E\left[u|v\right] = \rho\sigma_u\sigma_v v. \tag{166}$$

The covariance term, ρ, in (166) determines the degree to which the participation equation errors, v, affect the capacity construction, y, in the capacity equation. A number of properties of corner outcome models allow to express this adjustment in terms of independent variables. In Appendix E, I perform the reduction of the participation error terms, v, to the inverse Mills ratio, which results in (167).

$$E\left[u|v\right] = \rho\sigma_u \frac{\phi\left(m\gamma_m + x'\gamma_x\right)}{\Phi\left(m\gamma_m + x'\gamma_x\right)} \tag{167}$$

The benefit of the conversion is that the inverse Mills ratio is a function of the observed independent variables of the model, m and x, rather than the unobserved errors, v.

With the above set of assumptions the conditional expectation of the log capacity becomes

$$E\left[\ln\left(y\right)|z = 1\right] = x'\beta + \rho\sigma_u \frac{\phi\left(m\gamma_m + x'\gamma_x\right)}{\Phi\left(m\gamma_m + x'\gamma_x\right)} \tag{168}$$

Typically with the Heckman model, the conditional expectation (168) is the equation of interest because it removes the bias arising from the zero responses in y. Here, however, I estimate the effect of carbon tax on new capacity construction. The proxy for the carbon tax is fuel cost. In Section 2.2, I justify its exclusion from the capacity equation. Therefore, the unconditional expectation is of interest here.

I start deriving the unconditional expectation of new capacity by dropping the distinction between groups of independent variables in the conditional expectation for brevity

$$E\left[\ln\left(y\right)|m,x,z=1\right]=x\beta+\rho\sigma_u\frac{\phi\left(x\gamma\right)}{\Phi\left(x\gamma\right)}$$

and denote the observed terms by the functions of independent variables a and b so that

$$E\left[\ln\left(y\right)|m,x,z=1\right]=a+b\sigma_u$$

Then for any integer k,

$$E\left[e^{Yk}|m,x,z=1\right]=\int_{y=-\infty}^{\infty}e^{yk}\frac{1}{\sigma\sqrt{2\pi}}e^{-(y-(a+b\sigma_u))^2/\left(2\sigma^2\right)}dy$$

however,

$$\begin{aligned}
&yk-\tfrac{(y-(a-b\sigma_u))^2}{2\sigma^2}=\tfrac{2\sigma^2yk-y^2+2y(a+b\sigma_u)+(a+b\sigma_u)^2}{2\sigma^2}\\
&=\tfrac{-y^2+2\left[(a+b\sigma_u)+\sigma^2k\right]y-\left[(a+b\sigma_u)+\sigma^2k\right]^2-(a+b\sigma_u)^2+\left[(a+b\sigma_u)+\sigma^2k\right]^2}{2\sigma^2}\\
&=\tfrac{-\left(y-\left[(a+b\sigma_u)+\sigma^2k\right]\right)^2-(a+b\sigma_u)^2+(a+b\sigma_u)^2+2(a+b\sigma_u)\sigma^2k+\sigma^4k^2}{2\sigma^2}\\
&=\tfrac{-\left(y-\left[(a+b\sigma_u)+\sigma^2k\right]\right)^2}{2\sigma^2}+\left(a+b\sigma_u\right)k+\sigma^2k^2/2
\end{aligned}$$

therefore can obtain the moment generating function as:

$$E\left[e^{Yk}|m,x,z=1\right]=e^{(a+b\sigma_u)k+\sigma^2k^2/2}\int_{y=-\infty}^{\infty}\frac{1}{\sigma\sqrt{2\pi}}e^{-\left(y-\left[(a+b\sigma_u)+\sigma^2k\right]\right)^2/\left(2\sigma^2\right)}dy=e^{(a+b\sigma_u)k+\sigma^2k^2/2}$$

A transition from the conditional to the unconditional expectation is achieved by adjustment by the probability to observe a nonzero outcome (newly built generating capacity)

$$E\left[y|x,v\right] = \exp\left(x'\beta + \rho\sigma_u \frac{\phi\left(x\gamma\right)}{\Phi\left(x\gamma\right)} + \frac{\sigma_u^2}{2}\right)\Phi\left(x'\gamma_x\right)$$

From the unconditional expectation of the new capacity addition, I obtain the unconditional semi-elasticity of new capacity addition with respect to markup.

$$\frac{d}{dx_i}\ln y_{st} = \beta_i - \rho\sigma_u\gamma_i \frac{\phi\left(x'\gamma_x\right)}{\Phi\left(x'\gamma_x\right)}\left[x'\gamma_x + \frac{\phi\left(x'\gamma_x\right)}{\Phi\left(x'\gamma_x\right)}\right] + \gamma_i\phi\left(x'\gamma_x\right)$$

Appendix E Equivalence between the truncation correction and the inverse Mills ratio

I start by expressing the expected errors in a truncated regression, u, as a linear function of the selection equation errors, v:

$$E\left[u|v\right] = \rho\sigma_u\sigma_v v$$

In the equation above, v has the standard normal distribution, implying $\sigma_v = 1$. However, u are only nonzero if the realization of the latent (left-hand side) variable in the participation equation is greater than zero.

$$E\left[u|v\right] = \rho\sigma_u E\left[v|z=1\right] = \rho\sigma_u E\left[v|v > -x'\gamma\right].$$

Since the participation equation is a probit, I have already made the assumption that v has standard normal distribution. Therefore, without the truncation, its density is

$$\phi(v) = (2\pi)^{-0.5} \exp\left[-v^2/2\right]$$

Adjustment for truncation is done by dividing the original density by the probability that the observed v_{st} is greater than the truncation value, $-x_{st}\gamma$.

$$\phi\left(v|z=1\right) = \frac{\phi\left(v\right)}{1-\Phi\left(-x'\gamma\right)}.$$

The definition of the conditional expectation is the integration of the product of the values of the variable and its pdf over the conditioned range:

$$E\left[v|z=1\right] = \int_{v=-x'\gamma}^{\infty} \frac{v\phi\left(v\right)}{1-\Phi\left(-x'\gamma\right)} dv$$

Given the standard normal distribution of v, this is equivalent to

$$E\left[v|z=1\right] = \int_{v=-x'\gamma}^{\infty} \frac{-d\phi\left(v\right)/dv}{1-\Phi\left(-x'\gamma\right)} dv.$$

Evaluating the integral produces:

$$E\left[v|z=1\right] = \tfrac{-1}{1-\Phi(-x'\gamma)} \int_{v=-x'\gamma}^{\infty} -v\left(2\pi\right)^{-0.5} \exp\left[-v^2/2\right] dv =$$

$$= \tfrac{-1}{1-\Phi(-x'\gamma)} \left\{0-\left(2\pi\right)^{-0.5} \exp\left[-x'\gamma^2/2\right]\right\} = \tfrac{\phi(-x'\gamma)}{1-\Phi(-x'\gamma)}$$

Finally, I use the properties of normal distribution, $\phi(-a) = \phi(a)$ and $1 - \Phi(-a) = \Phi(a)$ to the effect of producing the equivalence between the conditional expectation of the participation equation errors and the inverse Mills ratio:

$$E[v|z = 1] = \frac{\phi(x'\gamma)}{\Phi(x'\gamma)}.$$

Appendix F Concern about state effects: crowding of areas suitable for wind generation

A wind turbine located in windy areas in the central states produces more electricity than a similar turbine placed in the South, where still weather dominates. Unsurprisingly, wind generation constitutes a higher share in the energy mix there. North and South Dakotas generate more than 20% of their electricity from wind, compared to the national average of four percent. It may be possible that as the windy areas become occupied, the marginal turbines become less productive, reducing the incentive for new wind capacity.

In terms of electricity variables, I formulate this hypothesis as an inverse relationship between the size of wind capacity in a state and the mean capacity factor, the ratio of actual electricity output to what a generator can produce in ideal conditions (nameplate capacity). I test this hypothesis with versions of a linear regression. First, I perform a pooled OLS regression of the capacity factor on the installed wind capacity. In the second version, I control for the state effects so as to focus on the evolution of the wind capacity within the state. In the third version, I control for both the state and time effects to account for the tendency of the wind turbines to become cheaper.

Our analysis does not support the hypothesis that windy land gets crowded. In the pooled analysis, the relationship is insignificant. Once the state fixed effect is accounted for, it is significant, but positive. The more wind capacity there is in a given state, the higher the capacity factor. Both the wind generation and the capacity factors tend to go up over time. Once the time effect, which I think of as wind technology improvement, is accounted for, the correlation between the capacity factor and the amount of megawatt-hours from wind disappears. None of the above tests support the possibility of a decreasing availability of windy land.

Appendix G Supplemental model specifications

The main specification of the model accounts for the possibility of fuel switching between gas and coal for the position of the marginal fuel type. I implement this property by choosing the smaller markup of the two as the value of the independent variable "markup min". I present the effect of markup min on new capacity in Table 4 and base the findings of the paper on it.

Here I ignore the possibility of position switching in the dispatch order and simply estimate the effect of the markup of gas generators on new capacity. The results in Table 11 suggest that this respecification does not change the key results. A dollar of gas markup increases the factor in the CDF by 0.0048, or probability of new capacity by $0.0048 \times 40\% \times 100\% = 0.19$ percentage points (40% in the expression represent the approximate slope of the standard normal CDF around the average probability of nonzero new capacity). The effect for CCGT is double that, and is double the estimate produced by the main model. Overall, the key result does not change with such redefinition of the explanatory variable.

I perform the analysis for the solar generation similarly to the three generator types discussed in the paper. Solar data suffer from the short timespan (six years of nonzero observations) and clustering of nonzero responses in four states. As of 2014, 83% of the US solar capacity is in CA, AZ, NV, and NC. The estimates in Table 12 show that neither markup nor RPS have significant effect on solar capacity. As more data become available, more reliable estimates may change this result.

In Table 13, I report the estimates of the linear probability model that calculates markup based on the natural gas price, rather than the cost of the marginal fuel source. The estimates are largely consistent with other specifications. Remarkably, a low markup (which is a proxy for a high carbon tax), inhibits new gas capacity at the same rate as in the Heckman specification and at a 10% significance margin.

Appendix H Additional insight into the data

In Section 2.2, I assume that markup, the difference between the market electricity price and the fuel cost, has effect on the probability of new capacity construction, but no effect on the size of the new capacity. This assumption is justified because generators of the same fuel type have the same marginal cost. This results in a staircase-shaped, rather than upward-sloping electricity supply curve. If a new generator has lower average cost than the marginal cost of legacy generators, it can force all the generators of that fuel type into shutdown and take their place on the market. The size of the legacy capacity to be shut down determines

Table 10: Results of the Heckman estimation, no neighbors specification

Variable	**Gas**	**CCGT**	**Wind**
# of observations	851	565	727
Of them censored	495	434	541
Participation Estimation			
Markup min ($/MWh)	**0.006** (0.002)**	**0.006** (0.003)**	-7.6E-4 (2.5E-3)
Markup trend	-0.009 (0.006)	-0.002 (0.008)	9.5E-4 (6.8E-3)
Markup volatility	**-0.014*** (0.005)**	**-0.018*** (0.006)**	**-0.116** (0.005)**
Markup max ($/MWh)	**-0.004* (0.002)**	9.9E-4 (0.003)	0.002 (0.003)
Incremental RPS (%)	**5.870* (3.202)**	5.279 (3.690)	1.942 (3.368)
RPS adjacent (%)	**14.461*** (4.660)**	4.544 (5.036)	-0.791 (5.276)
Share of IPP (%)	0.005 (0.225)	-0.371 (0.300)	0.149 (0.252)
Trade index (%)	**-0.456*** (0.145)**	**-0.748*** (0.240)**	-0.003 (0.160)
Capacity factor gas (%)	0.403 (0.257)	**1.512*** (0.530)**	-0.319 (0.361)
Capacity factor coal (%)	**0.886** (0.402)**	**0.903* (0.537)**	**1.250** (0.508)**
Log min capacity (MW)	**0.088* (0.053)**	0.083 (0.809)	**-0.110* (0.061)**
Log max capacity (MW)	**0.128* (0.069)**	-0.003 (0.097)	**-0.140* (0.082)**
Log total capacity (MW)	0.129 (0.112)	**0.269* (0.151)**	**0.315** (0.140)**
Recent fossil additions (MW)	-3.4E-4 (2.6E-4)	**-5.5E-4 (3E-4)**	**-1.6E-3*** (3.6E-4)**
Recent total additions (MW)	**4.3E-4* (2.5E-4)**	**6.4E-4** (2.9E-4)**	**1.6E-3*** (3.5E-4)**
New scheduled retirements, fossil (MW)	1.1E-4 (4.8E-4)	3.3E-4 (5.2E-4)	3.4E-4 (6.5E-4)
New scheduled retirements, total (MW)	-6.1E-5 (4.2E-4)	-2.5E-4 (4.5E-4)	-3.5E-4 (6.1E-4)
Capacity estimation			
Incremental RPS (%)	8.239 (5.476)	7.670 (5.329)	**10.288* (5.297)**
RPS adjacent (%)	**-16.032** (7.557)**	-1.508 (7.946)	-5.341 (9.506)
Share of independent producers (%)	-0.435 (0.359)	**-0.986*** (0.375)**	**-1.187*** (0.374)**
Trade index (%)	**-0.892*** (0.294)**	**-1.325*** (0.421)**	**0.510** (0.240)**
Capacity factor gas (%)	**1.227** (0.474)**	1.005 (0.709)	-0.931 (0.615)
Capacity factor coal (%)	0.317 (0.683)	0.870 (0.703)	0.569 (0.970)
Log min capacity (MW)	-0.044 (0.080)	0.125 (0.086)	0.082 (0.098)
Log max capacity (MW)	-0.095 (0.120)	-0.018 (0.114)	**-0.259* (0.119)**
Log total capacity (MW)	**0.758*** (0.184)**	**0.556*** (0.208)**	**0.786*** (0.261)**
Recent fossil additions (MW)	1.4E-4 (3.4E-4)	1.8E-4 (2.8E-4)	-2E-5 (3.8E-4)
Recent total additions (MW)	-1.5E-4 (3.3E-4)	-2.6E-4 (2.6E-4)	1.2E-4 (3.7E-4)
New scheduled retirements, fossil (MW)	-2.5E-4 (7.3E-4)	1.3E-4 (6E-4)	5.1E-4 (6.6E-4)
New scheduled retirements, total (MW)	3.3E-4 (6.2E-4)	2.4E-4 (5E-4)	-4.1E-4 (5.9E-4)
Correlation of errors (ρ)	0.066	0.678	-0.199
Standard error of the capacity equation (σ_u)	1.459	1.077	1.170

Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance threshold. Output for time dummies is suppressed.

Table 11: Results of the Heckman estimation, gas markup specification

Variable	**Gas**	**CCGT**	**Wind**
# of observations	1003	584	749
Of them censored	599	450	552
Participation estimation			
Markup gas ($/MWH)	**0.005** (0.002)**	**0.0136*** (0.0035)**	0.003 (0.003)
Incremental RPS (%)	**5.379* (3.079)**	5.577 (3.554)	3.287 (3.191)
RPS adjacent (%)	**13.800*** (4.447)**	4.129 (4.972)	-1.923 (5.346)
Share of IPP (%)	-0.137 (0.206)	**-0.556* (0.282)**	0.032 (0.235)
Trade index (%)	**-0.450*** (0.132)**	**-0.581** (0.257)**	0.167 (0.163)
Capacity factor gas (%)	0.028 (0.239)	**1.084* (0.536)**	-0.595 (0.365)
Capacity factor coal (%)	**0.696* (0.364)**	**1.175** (0.529)**	**1.164** (0.487)**
Log gas capacity (MW)	0.045 (0.054)	0.206 (0.127)	-0.078 (0.077)
Log coal capacity (MW)	**0.086* (0.049)**	0.011 (0.074)	**-0.230*** (0.057)**
Log total capacity (MW)	0.161 (0.099)	0.123 (0.181)	**0.395*** (0.138)**
Recent fossil additions (MW)	-3.1E-4 (2.3E-4)	**-6.3E-4** (3.1E-4)**	**-1.7E-4*** (3.6E-4)**
Recent total additions (MW)	**4.2E-4* (2.2E-4)**	**7.3E-4** (2.9E-4)**	**1.6E-3*** (3.5E-4)**
New scheduled retirements, fossil (MW)	1.6E-4 (4.9E-4)	3.9E-4 (5.6E-4)	2.9E-5 (6.7E-4)
New scheduled retirements, total (MW)	-8.3E-5 (4.4E-4)	-3.3E-4 (5E-4)	-3.3E-4 (6.2E-4)
Capacity estimation			
Incremental RPS (%)	7.822 (5.361)	6.497 (5.163)	10.317 (5.446)
RPS adjacent (%)	**-16.993** (7.318)**	-2.050 (7.723)	-9.941 (9.952)
Share of IPP (%)	-0.297 (0.353)	**-0.817** (0.370)**	**-1.356*** (0.387)**
Trade index (%)	**-1.249*** (0.307)**	**-1.826*** (0.479)**	**0.715** (0.313)**
Capacity factor gas (%)	**1.540*** (0.455)**	**1.522* (0.754)**	-0.990 (0.695)
Capacity factor coal (%)	0.377 (0.636)	0.818 (0.709)	1.315 (1.083)
Log gas capacity (MW)	-0.110 (0.927)	0.122 (0.164)	0.181 (0.136)
Log coal capacity (MW)	0.053 (0.082)	**0.184** (0.086)**	-0.203 (0.140)
Log total capacity (MW)	**0.779*** (0.165)**	**0.607*** (0.228)**	0.580 (0.310)
Recent fossil additions (MW)	1.6E-4 (3.3E-4)	2E-4 (2.8E-4)	-3.3E-4 (4.5E-4)
Recent total additions (MW)	-1.3E-4 (3.2E-4)	-2.4E-4 (2.7E-4)	4.1E-4 (4.3E-4)
New scheduled retirements, fossil (MW)	-2.2 (7.2E-4)	4.2E-5 (5.9E-4)	7.9E-4 (7E-4)
New scheduled retirements, total (MW)	3.1E-4 (6.1E-4)	-2.9E-4 (4.8E-4)	-7.1E-4 (6.3E-4)
Correlation of errors (ρ)	0.124	0.636	0.451
Standard error of the capacity equation (σ_u)	1.455	1.051	1.284

Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance threshold. Output for time dummies is suppressed.

Table 12: Estimation for solar generators

Variable	Full specification	Gas markup only
# of observations	401	410
Of them censored	304	313
Participation equation		
Markup min ($/MWH)	**0.008** (0.004)**	
Markup trend ($/MWH)	0.004 (0.012)	
Markup volatility ($/MWH)	-0.016* (0.010)	
Markup max ($/MWH)	-0.005 (0.004)	
Markup gas ($/MWH)		0.008 (0.005)
Incremental RPS (%)	5.061 (5.078)	5.250 (4.654)
RPS adjacent (%)	0.290 (5.261)	0.074 (4.962)
Share of IPP (%)	0.525 (0.398)	0.204 (0.379)
Trade index (%)	**-1.749*** (0.393)**	**-1.579*** (0.394)**
Capacity factor gas (%)	**3.121*** (0.818)**	**2.536*** (0.796)**
Capacity factor coal (%)	**1.766** (0.773)**	**1.722** (0.695)**
Log min capacity (MW)	**0.188* (0.106)**	
Log max capacity (MW)	**0.503*** (0.144)**	
Log gas capacity (MW)		0.241 (0.188)
Log coal capacity (MW)		**0.299*** (0.092)**
Log total capacity (MW)	**-0.594*** (0.200)**	**-0.467* (0.262)**
Recent fossil additions (MW)	8.0E-5 (3.1E-4)	-4.8E-4 (3E-4)
Recent total additions (MW)	2.0E-4 (2.6E-4)	3.6E-4 (2.5E-4)
New scheduled retirements, fossil (MW)	-1.8E-5 (6.8E-4)	-8.7E-5 (7E-4)
New scheduled retirements, total (MW)	4.2E-5 (6.2E-4)	1.7E-4 (6.6E-4)
Constant Term	-1.993 (1.428)	-2.780** (1.303)
Capacity equation		
Incremental RPS (%)	-4.739 (14.685)	-3.766 (13.026)
RPS adjacent (%)	-3.384 (15.705)	-0.139 (12.599)
Share of IPP (%)	**-2.392** (1.137)**	**-2.183** (1.001)**
Trade index (%)	**4.176* (2.373)**	**3.963* (2.304)**
Capacity factor gas (%)	-4.291 (4.010)	-4.397 (3.841)
Capacity factor coal (%)	**-5.409* (3.006)**	**-4.837* (2.624)**
Log min capacity (MW)	**-0.690** (0.344)**	
Log max capacity (MW)	-0.492 (0.592)	
Log gas capacity (MW)		-0.199 (0.625)
Log coal capacity (MW)		**-0.812* (0.399)**
Log total capacity (MW)	0.946 (0.754)	0.704 (0.902)
Recent fossil additions (MW)	-9.0E-4 (8.9E-4)	-8.3E-4 (7.4E-4)
Recent total additions (MW)	7.4E-4 (8.2E-4)	6.9E-4 (7.3E-4)
New scheduled retirements, fossil (MW)	1E-3 (1.3E-3)	1.2E-3 (1.1E-3)
New scheduled retirements, total (MW)	-8.8E-4 (1.2E-3)	1.2E-3 (0.001)
Constant Term	**14.133** (5.969)**	**13.591** (5.540)**
Correlation of errors (ρ)	-1.098	-1.019
Standard error of the capacity equation (σ_u)	3.106	2.592

Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance threshold. Output for time dummies is suppressed.

Table 13: Results of linear probability fixed-effect estimation of participation, by energy source, with gas markup used as the carbon tax proxy

Variable	**Gas**	**CCGT**	**Wind**
Number of observations	1003	584	749
Participation estimation			
Markup gas ($/MWH)	**0.001* (6.1E-4)**	**0.003* (1.4E-3)**	2.1E-4 (5.5E-4)
Incremental RPS (%)	1.375 (1.113)	1.347 (1.022)	0.124 (0.985)
RPS adjacent (%)	**4.698*** (1.573)**	1.516 (1.482)	-0.625 (1.402)
Share of IPP (%)	0.106 (0.103)	0.136 (0.434)	-0.034 (0.126)
Trade index (%)	**-0.199 (0.12)**	-0.211 (0.174)	**-0.296** (0.133)**
Capacity factor gas (%)	-0.029 (0.106)	-0.106 (0.228)	0.061 (0.121)
Capacity factor coal (%)	-0.133 (0.161)	0.214 (0.189)	0.026 (0.102)
Log gas capacity (MW)	**-0.073** (0.035)**	-0.096 (0.073)	0.009 (0.045)
Log coal capacity (MW)	-0.125 (0.103)	-0.046 (0.120)	0.026 (0.102)
Log total capacity (MW)	0.048 (0.103)	0.097 (0.201)	-0.055 (0.109)
Recent fossil additions (MW)	-7.6E-5 (7.4E-5)	**-1.3E-4* (7.1E-5)**	-1.1E-4 (6.8E-5)
Recent total additions (MW)	7.6E-5 (7.2E-5)	**1.3E-4* (7E-5)**	9.6E-5 (6.8E-5)
Newly scheduled retirements, fossil (MW)	1.9E-4 (1.6E-4)	1.6E-4 (1.5E-4)	-4.1E-5 (1.4E-4)
Newly scheduled retirements, total (MW)	-1.8E-4 (1.4E-4)	-1.9E-5 (1.3E-4)	-7.8E-6 (1.3E-4)
Capacity estimation			
Incremental RPS (%)	8.424 (10.659)	-4.724 (12.916)	0.688 (8.665)
RPS adjacent (%)	-10.219 (33.343)	-11.620 (14.360)	37.928 (33.249)
Share of IPP (%)	-0.225 (0.912)	-5.578 (3.745)	0.354 (2.272)
Trade index (%)	-2.073 (1.760)	-2.317 (2.409)	16.110 (14.475)
Capacity factor gas (%)	0.299 (0.850)	**4.590** (2.244)**	-5.311 (3.596)
Capacity factor coal (%)	0.678 (1.411)	1.656 (2.117)	-0.579 (2.060)
Log gas capacity (MW)	-0.416 (0.534)	-0.439 (0.823)	-0.673 (0.676)
Log coal capacity (MW)	-0.677 (1.079)	0.570 (1.282)	-0.579 (2.060)
Log total capacity (MW)	0.643 (0.717)	3.463 (2.108)	1.670 (3.530)
Recent fossil additions (MW)	-1.8E-4 (6.3E-4)	6.1E-4 (6.1E-4)	0.006 (0.005)
Recent total additions (MW)	8.3E-5 (6.3E-4)	6.7E-4 (6.1E-4)	-0.005 (0.005)
Newly scheduled retirements, fossil (MW)	-2.7E-4 (1.6E-3)	-6.1E-4 (1.0E-3)	0.001 (0.002)
Newly scheduled retirements, total (MW)	4.8E-5 (1.4E-3)	7.9E-4 (9.3E-4)	0.001 (8.1E-4)
Fitted participation stage values	-1.859 (6.718)	3.633 (3.618)	52.019 (47.601)

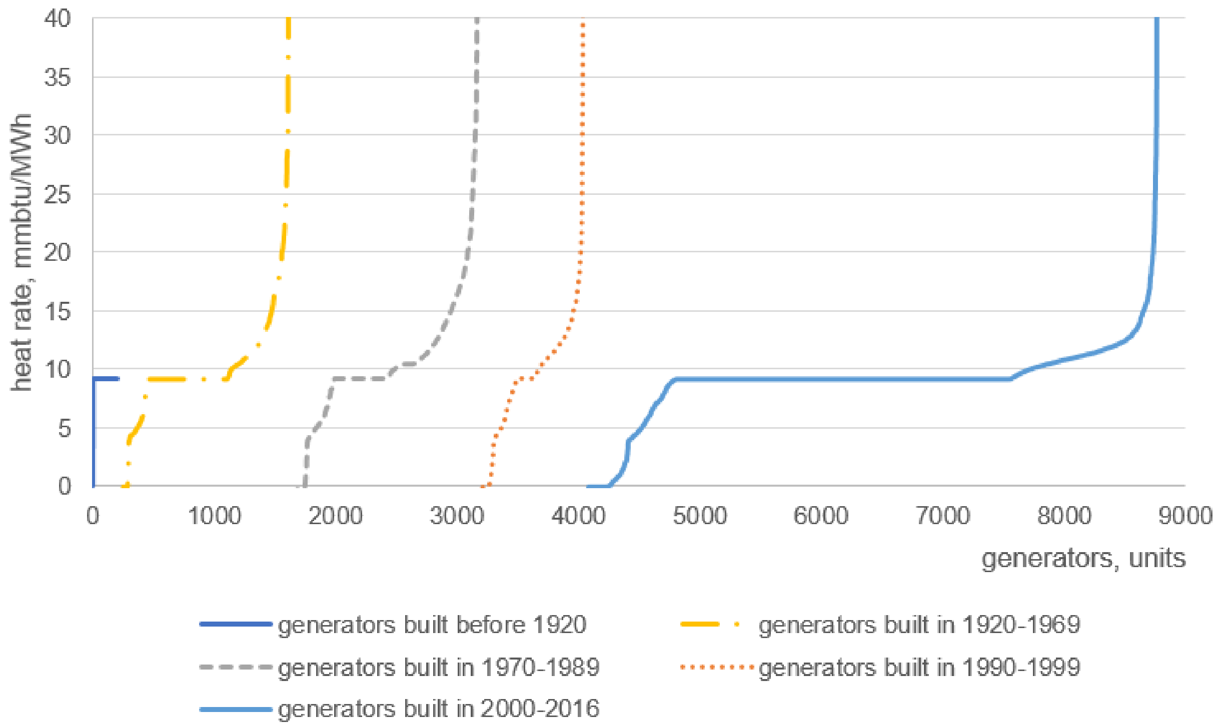
Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance threshold. Output for time dummies is suppressed.

Table 14: The effects of lagged key explanatory variables on Heckman participation decision to build new gas capacity.

Variable	No lag	One-year lag	Two-year lag	Three-year lag
Full specification				
Markup min ($/MWh)	0.002 (0.002)	**0.006**** **(0.002)**	0.004 (0.002)	-8.0E-4 (0.002)
Markup trend	-5.9E-4 (0.006)	-0.009 (0.006)	**-0.008*** **(0.005)**	-0.005* (0.006)
Markup volatility	**-0.011**** **(0.005)**	**-0.014***** **(0.005)**	-0.002 (0.003)	**-0.011** **(0.005)**
Markup max ($/MWh)	4.7E-4 (0.002)	**-0.004*** **(0.002)**	-6.5E-4 (0.002)	0.003 (0.002)
Markup neighbors ($/MWh)	-0.003 (0.002)	-5.2E-4 (0.003)	-6.8E-4 (0.003)	-0.003 (0.003)
Incremental RPS (%)	**7.749**** **(3.080)**	**5.870*** **(3.202)**	4.304 (3.247)	-4.407 (3.500)
RPS adjacent (%)	6.398 (4.660)	**14.461***** **(4.660)**	**9.016**** **(4.317)**	5.252 (4.227)
Gas markup, minimum specification				
Markup gas ($/MWh)	**0.004*** **(0.002)**	**0.005**** **(0.002)**	0.003 (0.002)	**0.002*** **(0.001)**
Incremental RPS (%)	**6.879**** **(2.863)**	**5.379*** **(3.079)**	**6.083*** **(3.314)**	**8.721**** **(3.718)**
RPS adjacent (%)	6.268 (4.072)	**13.800***** **(4.447)**	**12.637***** **(4.411)**	**13.336**** **(5.560)**

Standard errors are in parentheses. Significance levels are denoted by an * for 10%, ** for 5%, and *** for 1% significance threshold. Output for time dummies is suppressed.

Figure 13: Current US generators, split into historical eras and ordered by their inferred heat rates (mmbtu/MWh) from lowest to highest. Eighty percent of all generators have a heat rate close to 10 mmbtu/MWh.



the size of new capacity. The markup, however, does not affect how much capacity is can be shut down so that the new generators are built as long as the electricity supply curve is staircase-shaped.

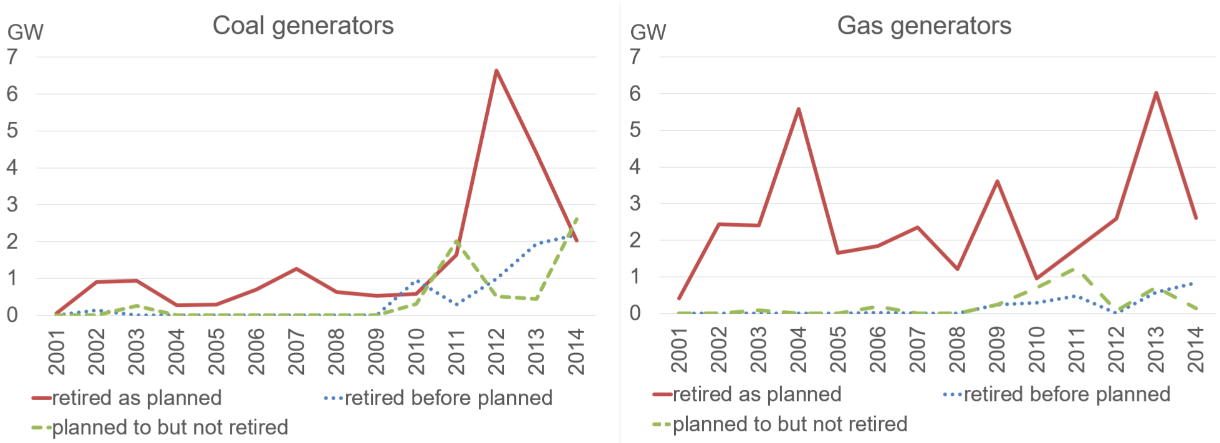
To have a staircase-shaped electricity supply curve, I assume that (1) fuel costs to be equal for all of the generators of the fuel type in a given state and (2) all the generators of the fuel type to produce identical amounts of MWh from a unit of fuel. The ability to convert millions of British thermal units (mmbtu) of fuel into MWh of electricity is a generator's heat rate.

I consider the 12870 generators mentioned in the 2016 EIA-923 Monthly Generation and Fuel Consumption report. For those, fuel consumption in mmbtu and generation in MWh is available. Thus, I infer the heat rates for the generators by observing shipments of fuel and production of electricity. I compare this information to the 20000 generators reported as operable in 2016 in the EIA-860 datafile, where the years of construction are available. In 9000 cases, I establish the connection between the generators in the two forms. I order these generators by heat rate and by era of construction in Figure 13. The survivors or the pre-1970 era are mostly coal generators. Two decades started in 1970 are when nuclear power becomes a prominent electricity source. Construction of nuclear power plants ceases in the 1990s, and coal generation begins to lose its share. The current era is dominated by combined-cycle gas turbines, prolific since 2000, and wind turbine generators.

Heat rates do not change with the year of a generator or across the 25 years in consideration. It is apparent from Figure 13 that 80% of the US generating capacity has a heat rate around 10 mmbtu/MWh. The deviations are caused by either different technology and purpose of a generator (for example, peakers), or increasing/decreasing stocks of fuel on site.

Therefore, the assumption of the staircase-shaped supply curve is valid for the industry.

Figure 14: Retirements of coal and gas capacity



Appendix I Retirements of legacy capacity

Our supply and demand interpretation of the electricity market in Section 2.2 implies that, given an inelastic demand growing at a steady exogenous annual rate of 1% (10 GW) a year, newly constructed generators must the existing capacity in order to enter the market. From the retirements data, I find that the upticks in the retirements of legacy capacity coincide with the developments of a more economical type of gas generator, cheap gas in the 2010s, and increasingly competitive wind turbines.

On average, the US adds 21 GW of new capacity annually. Two events define the history of capacity additions. The first is the introduction of the combined-cycle gas turbines in the early 2000s. CCGT are more efficient than basic gas turbines and can compete economically with coal generators. Second, technological improvements gradually made wind turbines economic going into the 2010s. As the result, in the last decade, the breakdown of new capacity by type has been roughly 50:50 between gas and wind.

The effect of these entrants is evident in the retirement data. I compare the planned and factual retirement dates for every generator for 14 years of EIA-860 reports. For every year, this comparison reveals three types of outcomes: a generator was slated to retire and did so as planned, a generator was retired earlier than planned, and a generator was operational, having missed its retirement date. In Figure 14, every generator appears only once, at its original retirement date, and falls into one of the three categories. There is a surge of retirements of gas generators around 2004, coinciding with the introduction of the CCGT. As gas becomes cheaper and the appeal of wind turbines grows, there is a wave of planned and unplanned retirements of coal generators in the 2010s. This coincidence of new entries and retirements across time suggests that the principles I lay out in Section 2.2 hold in practice.

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Education

PhD, Economics, University of Wisconsin–Milwaukee.

Dissertation title: "Essays on the resource sector, international finance, and environmental policy"

Dissertation committee chair: Rebecca Neumann

BA, Management, St. Petersburg State University of Economics and Finance, 2005.

Research

Academic fields of interest: international finance, open-economy macroeconomics, resource economics.

Research methods: DSGE models, time series, Kalman filter.

Working papers:

- "Long-term implications of oil discoveries for international saving in a DSGE model."

- “The effects of a carbon tax on new electricity generators in the US.” (jointly with Laura Grant)
- “Where are America’s shale oil benefits?”

Teaching Experience

Lecturer, Department of Economics, **University of Wisconsin–Whitewater**. 2018–2019

ECON 245: Business Statistics. Spring 2019 (two sections)

ECON 202: Principles of Macroeconomics. Fall 2018 (two sections)

Visiting Instructor, Department of Economics, **The University of Tampa**. 2017–2018

ECO 205: Principles of Macroeconomics. Fall 2017, Spring 2018 (seven sections total)

Adjunct Lecturer, Department of Economics, **Milwaukee Area Technical College**, 2015–2017

ECON-195: Economics. Fall 2016, Spring 2016, Fall 2015 (four sections total)

ECON-202: Principles of Macroeconomics. Fall 2016

Graduate Teaching Assistant, Department of Economics, **University of Wisconsin–Milwaukee**, 2011–2015

ECON 100: Introduction to Economics. Spring 2015

ECON 301: Intermediate Microeconomics. Fall 2014, Fall 2013

ECON 302: Intermediate Macroeconomics. Spring 2014

ECON 103: Principles of Microeconomics. Spring 2013

ECON 454: International Trade Theory. Fall 2012

ECON 351: International Economics. Spring 2012, Fall 2011, Spring 2011