Assessing the Economic Effects of Environmental Regulations: A General Equilibrium Approach

Richard Rogerson*

Princeton University

February 2013

Abstract

I describe standard macroeconomic methods for assessing the effects of policy on allocations and welfare. I then embed a version of a benchmark industry equilibrium model into an otherwise standard version of the one sector growth model and describe how this setting provides a useful structure for the analysis of environmental regulations that impact on one particular sector but which might reasonably have important aggregate effects.

---

*This research was supported by a grant from the Environmental Protection Agency. An earlier version was presented at the conference "The Employment Effects of Environmental Regulation" held in Washington DC in October 2012. I would like to thank Kerry Smith, Charles Brown, Tim Kehoe, as well as other conference participants for useful comments. The views expressed in this article are those of the author and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

1. Introduction

Evaluating the effects of policy or regulation on allocations and welfare is a key goal of applied economic analysis. The methods that are used to evaluate these effects differ across studies and areas. One approach emphasizes the use of explicit economic models in which the primitives–preferences, technologies and endowments–are rigorously specified and equilibrium allocations are derived from these primitives. The analysis of specific policies or regulations then requires the analyst to specify the details of the policy or regulation, and solve for the new equilibrium that would emerge in the presence of the policy or regulation. Because the structure includes an explicit description of preferences, one can evaluate the welfare effects in an internally consistent way. I will refer to this as the structural approach to policy evaluation.

This paper discusses the application of the structural approach in the context of studies that seek to evaluate the economic consequences of policies or regulations that are motivated by environmental concerns. I begin the paper by describing two distinct benchmark models that are commonly used for structural policy analysis. The first of these is the one sector neoclassical growth model, and the second is an industry equilibrium model. The simple one sector growth model and its many variants are routinely used to evaluate policy questions in both the macroeconomic and public finance literatures. The one sector neoclassical growth model is particularly well suited to the assessment of policies which are aggregate in nature (that is, policies that apply to all firms, or all households). This is routinely the case in the analysis of either macroeconomic policies or tax policies.

Another important property of this model in the context of these types of analyses is that it is explicitly general equilibrium, so that one can trace out the full extent of the impact of these policies on the overall economy.

If most environmental policies shared this property of being "aggregate" in nature, then the one sector growth model would be a suitable framework for implementing the structural approach. However, many environmental regulations are targeted at specific industries rather than the whole economy. The second model that I describe is a partial equilibrium model of a specific industry. In contrast to the one sector growth model which focuses on aggregate economic outcomes, this model emphasizes establishment level dynamics in investment and labor decisions and how they influence establishment level growth dynamics, including the process of entry and exit. By offering a rich description of heterogeneity at the establishment level and the choices made by establishments, this class of models seems well suited to studying the effects of very specific regulations that interact with these various decisions and the heterogeneity that exists among establishments. However, while offering a rich partial equilibrium setting, this framework does not allow one to assess the aggregate effects on the economy, or put somewhat differently, does not allow one to address the extent to which the impacts on the directly affected industry are propagated to the rest of the economy through general equilibrium effects.

Having described each of these two approaches and illustrated how simple versions of them can be used to carry out structural evaluations of policy in the context of environmental regulations, I then describe a hybrid model that combines the two approaches into a tractable framework. Specifically, it allows one to build a rich model of the particular industry while at the same time embedding it into the structure of the one sector growth model. Connecting this hybrid model to the data is effectively the same as connecting the two benchmark models to the data, and I show that solving for steady state equilibria in the hybrid model can be done in a particularly simple fashion. While I carry out my discussion in the context of some very simple prototype models in order to maximize transparency, I discuss how these models can be enriched along many dimensions. The key output is a framework that can simultaneously be used to connect to a large set of industry specific details in the affected industry and trace out potential general equilibrium effects and permit a consistent evaluation of welfare effects.

An outline of the paper follows. In Section 2 I describe the simple one sector growth model and describe how it could be used to evaluate an environmental regulation that was applicable to the entire production sector. In particular, I describe one method for calibrating the model and then quantitatively evaluate how a stylized environmental regulation affects both allocations and welfare, both in the long run (across steady states) and including short run transition effects. I emphasize that the same method can be applied independently of whether the regulation affects labor market outcomes, that is, one does not need to make any special adjustments to the welfare calculations depending on what happens in the labor market. Section 3 describes a benchmark industry equilibrium model, discusses how one might calibrate it to specific industry data, and then quantitatively evaluates three different types of regulations in the context of a numerical example that captures some generic features of establishment dynamics. Although I do this in the context of a very simple benchmark model, a key message is that evaluating many components of environmental regulations will typically require that the model being used incorporates a rich set of features. Finally, Section 4 develops the hybrid model that combines the two benchmark models. A key feature of the model is that it allows for a flexible specification in terms of how the directly affected industry interacts with the rest of the economy, both in terms of its relative size and the degree to which its output is either complementary or substitutable with economic activity in the rest of the economy. After developing the model I describe how steady state equilibrium can be easily calculated in the model and evaluate one prototype policy to illustrate some features of the model and emphasize a few basic messages. Section 5 concludes.

2. Benchmark I: Aggregate (One Sector) Analysis

In this section I illustrate how a benchmark aggregate model–the one sector neoclassical growth model–is commonly used for policy analysis, and in particular how macroeconomists use it to evaluate the welfare cost of policies. Of particular interest is that the analysis allows for policies to affect aggregate labor market outcomes and as a result the welfare analysis takes labor market effects into account.

2.1. Model

Here I describe a simple version of the representative agent one sector neoclassical growth model that serves as the benchmark model for modern macroeconomic analysis. I emphasize that what I am describing here is the simplest version of this model. One can extend the model along any number of dimensions to yield a much richer model. But this simplest version will serve as the best way to illustrate the general method that I describe, since this method is easily transferred to richer specifications of the model. Also, for now I abstract from any considerations that might serve to provide a welfare improving role for environmental regulations. I will add such considerations later on in this section when we consider the effects of a specific regulation.

There is a representative household that is infinitely lived, with preferences given by:

$$\sum_{t=0}^{\infty} \beta^t u(c_t, 1 - h_t)$$

where c_t is consumption in period t, h_t is the fraction of the time endowment that is devoted to market work, $0 < \beta < 1$ is a discount factor and U is the period utility function. There is an aggregate production function that uses capital (k_t) and labor (h_t) services to produce output (y_t) according to a constant returns to scale production function $F(k_t, h_t)$:

$$y_t = F(k_t, h_t).$$

Output can be used for either consumption or investment (i_t):

$$c_t + i_t = y_t$$

and the economy's capital stock evolves according to:

$$k_{t+1} = (1 - \delta)k_t + i_t$$

where $0 < \delta < 1$ is the depreciation rate. The economy begins period 0 with some initial capital stock, denoted by $\hat{k}_0$. In the subsequent analysis I will assume standard regularity conditions on utility and production functions.[1]

2.2. Equilibrium

If one is going to ask how policy affects outcomes in the economy one has to adopt some notion of how outcomes are determined, i.e., one has to adopt some notion of equilibrium. As is standard in the macroeconomic literature, we will study a competitive equilibrium, though one can certainly consider alternatives.[2] I will say a little bit about one alternative later on in which wages are set at a level that is "too high" relative to the competitive equilibrium.

[1] Note that I abstract from both population growth and technological progress in this specification. As is well known, one could inlcude this in the original specification, but then assuming that the specification is consistent with balanced growth, a change of variables effectively removes the growth associated with these forces, effectively reducing the model to the specification that I study.

[2] It is easy to extend the model to allow for a continuum of intermediate goods producers who produce differentiated products and behave as monopolisitic competitors. Such a specification is common in the macroeconomics literature that emphasizes price or wage stickiness. See, for example, Christiano, Eichenbaum and Evans (2005).

I note that one can formulate the equilibrium with households owning capital and renting it to firms, or alternatively with firms accumulating capital that they use in production, and households owning the capital stock indirectly through their ownership of the firm. The two formulations are equivalent in terms of equilibrium allocations, so it does not matter for substantive analysis. I will focus on the formulation in which households own capital and rent it to firms each period. I will also consider what is referred to as a sequence of markets equilibrium, in which we envision the economy evolving through time with a small set of markets opening each period. In particular, in each period there will be a market for current output, in addition to factor markets for both capital and labor services. The price of output can be normalized to one in each period, with the prices for labor and capital services denoted by w_t and r_t respectively. The one period ahead interest rate is implicitly given by $r_{t+1} - \delta$.

With this formulation an equilibrium is defined as a list of sequences $\{c_t^*\}$ $\{h_t^*\}$ $\{k_t^*\}$ $\{i_t^*\}$ $\{y_t^*\}$ $\{w_t^*\}$ and $\{r_t^*\}$ such that the quantities solve the household's lifetime utility maximization problem taking prices as given, production choices maximize profits taking prices as given and markets clear.

For future purposes it will be useful to have expressions that characterize equilibrium allocations. For the economy as currently described the competitive equilibrium will necessarily be Pareto efficient and so one can obtain expressions for the equilibrium allocations by solving an appropriate Social Planner's problem. But since we will also be interested in solving for the equilibrium in the presence of distortions, it is useful to have a method that works even when the equilibrium allocation is not Pareto efficient. Here I sketch this method.

The household problem can be written as:

$$\max \sum_{t=0}^{\infty} \beta^t u(c_t, 1-h_t)$$

$$\text{s.t. } c_t + k_{t+1} - (1-\delta)k_t = w_t h_t + r_t k_t,\ c_t \geq 0,\ k_t \geq 0,\ 0 \leq h_t \leq 1,\ k_0 \text{ given}$$

With standard regularity conditions it is sufficient to consider interior solutions for c_t, k_t and h_t. Letting λ_t be the Lagrange multiplier for the period t budget equation, the first order conditions for c_t, h_t and k_t are:

$$\beta^t u_1(c_t, 1-h_t) = \lambda_t \tag{2.1}$$

$$\beta^t u_2(c_t, 1-h_t) = \lambda_t w_t \tag{2.2}$$

$$\lambda_{t-1} = \lambda_t (r_t + 1 - \delta) \tag{2.3}$$

Taking the ratio of equation (2.1) at time t and $t+1$ and using equation (2.3) gives:

$$\frac{u_1(c_t, 1-h_t)}{\beta u_1(c_{t+1}, 1-h_{t+1})} = r_t + (1-\delta) \tag{2.4a}$$

And taking the ratio of equations (2.1) and (2.3) gives:

$$\frac{u_2(c_t, 1-h_t)}{u_1(c_t, 1-h_t)} = w_t \tag{2.5}$$

The profit maximization problem of the firm gives the standard first order conditions:

$$F_1(k_t, h_t) = r_t$$
$$F_2(k_t, h_t) = w_t$$

Substituting from the firm's first order conditions into equations (2.4a) and (2.5) and using the market clearing condition, we have that an equilibrium allocation must satisfy:

$$\frac{u_1(c_t, 1 - h_t)}{\beta u_1(c_{t+1}, 1 - h_{t+1})} = F_1(k_{t+1}, h_{t+1}) + (1 - \delta) \tag{2.6}$$

$$\frac{u_2(c_t, 1 - h_t)}{u_1(c_t, 1 - h_t)} = F_2(k_t, h_t) \tag{2.7a}$$

$$c_t + k_{t+1} = F(k_t, h_t) + (1 - \delta)k_t \tag{2.8}$$

in addition to the initial condition plus a transversality condition. Equilibrium prices can be inferred once knows equilibrium quantities directly from the firm's first order conditions.

We will also be interested in a steady state equilibrium for this economy. In the steady state all prices and quantities are constant over time, so we simply look for solutions to equations (2.6)-(2.8) that are constant (and so do not necessarily satisfy the initial condition). That is, we look for values k^*, h^*, and c^* that solve:

$$\frac{1}{\beta} = F_1(k^*, h^*) + (1 - \delta)$$

$$\frac{U_2(c^*, 1-h^*)}{U_1(c^*, 1-h^*)} = F_2(k^*, h^*)$$

$$c^* = F(k^*, h^*) - \delta k^*$$

As is well known, starting from an arbitrary positive initial condition, the equilibrium allocations will converge to their steady state values, so if one is considering an economy that has been operating for some amount of time, it is natural to focus on the steady state allocation as a starting point for how the economy will respond to changes moving forward in time.

2.3. Policy and Welfare Analysis

This model (and its various extensions) are routinely used in the macroeconomics literature to assess the effects of various fiscal policies on allocations and welfare.[3] Given the motivation for this paper, I describe the general method of analysis in this literature for the case of a policy which although highly stylized, has an interpretation that is relevant in the context of environmental policy. Specifically, consider a policy that is unexpectedly enacted and adopted in a particular period, that we will for convenience think of as period 0. The policy requires that each unit of capital must be augmented with an additional piece of equipment to lessen the extent of a certain kind of emission that is released during the production process. This additional capital has zero marginal product from the perspective of producing output. In particular, I assume that in order to satisfy the regulation,

[3] There are far too many examples to cite, but two examples are Lucas (1990), who analyzes capital taxation, and Prescott (2004) who analyzes labor taxation. While I study a version of the growth model with infinitely lived agents, the same methods can be used to study models with overlapping generations. See, for example, Auerbach and Kotlikoff (1987).

a firm that uses k_t units of capital services will only have $(1-\lambda)k_t$ units of capital from the perspective of capital services used in production. That is, in terms of producing output, a fraction λ of a firm's capital stock is not productive. Note that from the perspective of analyzing the aggregate effects of regulation, with a particular focus on how labor market implications enter into the analysis, an interesting feature of this policy is that it indirectly increases the demand for labor in the sense that the economy needs to produce the additional (but unproductive) capital.

As I noted earlier, when I originally described the model I abstracted from any elements that might give rise to a welfare role for environmental regulation. A simple way to extend the analysis to give a role for such policy is to posit a period utility function of the form:

$$u(c_t, 1-h_t) - d(P_t)$$

where P_t is a measure of the aggregate amount of pollutants in the environment in period t and d is a function that captures the disutility associated with these pollutants. There would be another set of relations that describe the relationship between the current stock of pollutants and current and past production decisions, including both the volume of production and the nature of how the production took place. The fact that production decisions influence the aggregate level of pollutants implies the presence of an externality that gives rise to possible welfare benefits from various sorts of regulatory policies.

Several clarifying remarks are in order. First, note that I have assumed that the externality enters into the utility function in a separable fashion. I have assumed this not because it is necessarily warranted, but rather in order to justify the type of "partial" analysis that I will focus on. I use the word "partial" to refer to a separation between the costs and benefits of environmental regulation. To be sure, if one is interested in analyzing optimal environmental policy then one must necessarily consider both the costs and the benefits simultaneously even if the economic and environmental elements enter into utility functions in a separable fashion. However, my goal is to examine a method that can be used to evaluate the economic costs of specific regulations without presuming the ability to measure the benefits that would also result. If the environmental effects did not enter preferences in a separable fashion then one cannot assess the economic costs without knowing exactly how the environmental impacts enter, as changes in pollutants would then influence the economic decisions and these interactions could affect the assessments of these costs. All of this is simply to say that I will adopt a narrow focus of assessing the economic costs of particular regulations, and the above assumptions are simply one way to rationalize such a narrow focus. But to the extent that one is prepared to take a stand on how the environmental factors actually enter into preferences, the methods that I describe can certainly be applied. That is, I could alternatively assume that the period utility function is of the form:

$$u(c_t, 1 - h_t, P_t)$$

and specify some explicit relationship between past and present production decisions and current pollution. Having specified these relationships I could carry out the exact same exercise that I describe below for the separable case. One could also allow for an effect of the level of pollutants on health, which could show up as an increase in the amount of discretionary time that individuals have, allowing for both more leisure time and more time devoted to work.

In assessing the effects of this policy on allocations and welfare it is natural to assume that the economy is initially in the steady state equilibrium that corresponds to the situation in which there is no environmental regulation, at which time the regulation is introduced without any prior anticipation. Assessing the consequences of the introduction of this policy requires solving for the new equilibrium that will result, starting from the initial condition that the economy starts in the no-regulation steady state.

Some notation will be useful. I will use c_U^* to denote steady state consumption in the economy prior to the enactment of the regulation, and will use c_R^* to denote the steady state level of consumption that results after the regulation has been enacted, and similarly for other variables. By assuming that the economy starts in the unregulated steady state at time 0 when the regulation is announced and enacted, we are assuming that the initial capital stock, k_0 is equal to k_U^*. In the absence of the adoption of the regulation, the economy would have continued to be in the unregulated steady state, so that this allocation would have persisted each period moving forward. But given that the regulation was adopted, the economy will have a new equilibrium that we denote by sequences $\{c_t^R\}\{h_t^R\}\{k_t^R\}\{i_t^R\}\{y_t^R\}\{w_t^R\}\{r_t^R\}$.

We can follow the same procedure that we previously used to derive conditions to characterize the equilibrium allocations in the absence of the regulation to derive expressions that characterize the equilibrium in the presence of the new regulation. In fact, nothing changes from the first order conditions that we derived from the household optimization problem. There is, however a change in the firm's conditions for profit maximization. Specifically, on account of the new regulation, a firm that rents k_t units of capital will only have $(1-\lambda)k_t$ units of capital that are used to produce output, with the remaining units used to reduce emission of pollutants. As a result, the firm's first order conditions now become:

$$\begin{aligned} (1-\lambda)F_1((1-\lambda)k_t, h_t) &= r_t \\ F_2((1-\lambda)k_t, h_t) &= w_t \end{aligned}$$

Following the same procedure as above and substituting these conditions into the expressions that we derived from the household's first order conditions gives: equilibrium will satisfy:

$$\frac{u_1(c_t^R, 1-h_t^R)}{\beta u_1(c_{t+1}^R, 1-h_{t+1}^R)} = (1-\lambda)F_1((1-\lambda)k_{t+1}^R, h_{t+1}^R) + (1-\delta)$$

$$\frac{u_2(c_t^R, 1-h_t^R)}{u_1(c_t^R, 1-h_t^R)} = F_2((1-\lambda)k_t^R, h_t^R)$$

$$c_t^R + k_{t+1}^R - (1-\delta)k_t^R = F((1-\lambda)k_t^R, h_t^R)$$

Note that in the last equation only a fraction $(1-\lambda)$ of the capital stock is useful in producing output, but that investment includes both the productive capital and the capital that is used to reduce emissions.

The new steady state equilibrium allocations will be values k^*, h^*, and c^* that solve:

$$\frac{1}{\beta} = (1-\lambda)F_1((1-\lambda)k_R^*, h_R^*) + (1-\delta)$$

$$\frac{u_2(c_R^*, 1-h_R^*)}{u_1(c_R^*, 1-h_R^*)} = F_2((1-\lambda)k_R^*, h_R^*)$$

$$c_R^* = F((1-\lambda)k_R^*, h^*) - \delta k_R^*$$

Solving for the equilibrium allocations following the adoption of the regulation serves to address the issue of how the regulation will affect allocations. But what about the welfare effects, or, more specifically given my narrow focus, what about the welfare effects net of environmental benefits? The literature often distinguishes between two different notions. One notion is to compare the original steady state outcome that existed prior to the policy change with the new steady that emerges after the policy change. Loosely speaking, if we wanted to compare how the policy affects an individual who is born into the original steady state with someone who is born into the future steady state, then this comparison is relevant. But if we want to assess how the adoption of the policy will affect the welfare of those who are around at the time of the policy change then it is important to study not just the long run consequences but also the transition to the new steady state. The second notion of welfare change will take into account not only the new steady state allocation that is achieved but also the nature of the transition path to the new steady state.

In each case the welfare criterion is conceptually the same, with the only difference being that one of them includes the period of transition. In words, our measure of welfare is the fractional change in per period consumption in the original steady state that would make the representative household indifferent between staying in the original steady state and moving to the new equilibrium. In the case of steady state welfare comparisons we only compare the two steady state allocations. In the other case we evaluate the utility after the regulation using the entire time series in the post-adoption period. More formally, if we let Δ^S be the change in welfare associated with comparing only the two steady state outcomes then it is defined by:

$$u((1+\Delta^S)c_U^*, 1-h_u^*) = u(c_R^*, 1-h_R^*).$$

And if we let Δ^T be the change in welfare taking into account the transition path to the new steady state, it is defined by:

$$\frac{1}{1-\beta}u((1+\Delta^T)c_U^*, 1-h_u^*) = \sum_{t=0}^{\infty}\beta^t u(c_t^R, 1-h_t^R).$$

By way of interpretation, note that if one of these measures of welfare change is equal to .01, it means that individuals would be willing to give up 1% of their consumption forever in order to stay in the original steady state.

This measure of welfare change has three appealing properties. First, it is firmly connected to the utility functions of the individuals in the economy. Second, it offers a value that is easy to interpret quantitatively. And third, it does not require any auxiliary assumptions to implement. For example, although the setting that I have described above has the property that the initial steady state allocation is Pareto efficient and as a result the steady state equilibrium prices do reflect certain marginal valuations, exactly the same welfare criterion can be applied if we had instead assumed that the original economy had some other distortion so that the original allocation was not efficient. At the same time it is important to note that there is nothing unique about this particular welfare measure. One could have instead scaled up the allocation of both consumption and leisure to produce a different but conceptually similar measure.

Given an economy with heterogeneous consumers, one can apply the same concept at the aggregate level given any weighting scheme for individual utilities, and one can also apply it at the level of each individual in the economy to study the distribution of welfare gains and losses.

2.4. Calibrating the Model

In order to illustrate the methods discussed in the previous subsection it will be useful to consider a quantitative example. This requires choosing function forms and parameter values. Here I describe a standard procedure in the macroeconomics literature for making these choices. I note that the methods that I describe later on do not depend in any way on how one chooses to calibrate the model; for present purposes this should just be seen as one set of choices.

I begin with functional forms. We need to choose functional forms for the production function and the period utility function. It is standard in the macroeconomics literature to assume that the aggregate production function is Cobb-

Douglas:

$$y_t = k_t^\theta h_t^{1-\theta},$$

though more general specifications are sometimes used.

A commonly imposed requirement that influences the set of possible period utility functions is that the preferences be consistent with balanced growth in the presence of technological progress. Assuming that we also want to require strict concavity of the utility function, this imposes that the period utility function be either of the form:

$$\log c_t + v(1 - h_t)$$

if preferences are separable between consumption and leisure, or of the form:

$$\frac{1}{1-\sigma}[c_t v(1 - h_t)]^{1-\sigma}$$

where v is a strictly positive, strictly increasing, strictly concave function and the parameter σ is strictly positive. This still permits quite a range of functions, but for purposes of illustration I will use as my benchmark the commonly used specification of:

$$u(c_t, 1 - h_t) = \alpha \log c_t + (1 - \alpha) \log(1 - h_t).$$

However, to illustrate more generally how labor market effects operate I will also consider a slightly more general period utility function that does not necessarily lie in the set of balanced growth preferences:

$$u(c_t, 1-h_t) = \alpha \frac{c_t^{1-\sigma}-1}{1-\sigma} + (1-\alpha)\log(1-h_t)$$

Having specified functional forms, we now have to choose parameter values. Given the functional form choices, there are 4 parameter values to assign in the benchmark setting (in the more general case considered we also need to assign a value to σ): θ, δ, α, and β. While there are a few variations on how to choose these parameters, the ultimate values are quite similar, so I just describe one procedure. The value of θ is chosen to match the observed time series average for the share of income going to capital, which is around .30. In steady state, the value of the real interest rate, which is also the real return to capital, is given by $(1/\beta) - 1$. Studies typically target an annual value of 4%, which is in between the observed real returns on a safe asset like treasury bonds and the average real return on risky assets such as equity. The value of δ is chosen so that the ratio of investment to output in the steady state is equal to its time series average, typically taken to be around .20. Finally, the value of α is set so that the fraction of available discretionary time that the representative household devotes to market work matches the average of this value in the population of individuals who are 16 and older, or sometimes between the ages of 16 and 65. A typical value is .33.

Given the above targets and interpreting a period to be one year, standard values for parameters would be $\theta = .30$, $\beta = .96$, $\delta = .08$ and $\alpha = .3644$. Note that in calibrating the model to these targets I have abstracted away from taxes. One can easily incorporate these and apply the same calibration procedure, though the values of some parameters will be affected. In the case of the slightly more general class of preferences that do not force utility from consumption to be logarithmic, one must set a value for the preference parameter σ, but conditional on that choice one can adopt the same procedure as above to set values for the other values. The only parameter value that is affected is α.

2.5. An Example

In this section I present some quantitative results to illustrate the method just discussed in the context of the regulatory policy that I described earlier. I will consider five different values of the parameter λ that serves to parameterize the extent of the regulation. I begin by presenting the results for steady state effects and then consider the transition effects as well.

2.5.1. Steady State Effects on Allocations

Using the calibrated values from the previous subsection and having utility from consumption be logarithmic (i.e., $\sigma = 1$), Table 1 shows how regulations characterized by different values of λ affect the relative steady state values for each of several values, in addition to the implied steady state welfare change.

Table 1

Steady State Effects of Regulation: $\sigma = 1$

	$\lambda = 0$	$\lambda = .01$	$\lambda = .02$	$\lambda = .03$	$\lambda = .04$	$\lambda = .05$
k_R^*/k_U^*	1.00	.996	.991	.987	.983	.978
h_R^*/h_U^*	1.00	1.00	1.00	1.00	1.00	1.00
y_R^*/y_U^*	1.00	.996	.991	.987	.983	.978
c_R^*/c_U^*	1.00	.996	.991	.987	.983	.978
w_R^*/w_U^*	1.00	.996	.991	.987	.983	.978
h_R^*/h^*	0.00	.002	.004	.006	.008	.010
Δ^S	0.00	$-.004$	$-.009$	$-.013$	$-.017$	$-.022$

Readers who are familiar with real business cycle models will probably note that the regulation that I am considering is equivalent to making capital services less efficient, and that since with a Cobb-Douglas technology all technological change is equivalent to neutral technological change, the results in Table One are identical to those that one would get if we instead considered a permanent decrease in aggregate TFP by the fraction $1-(1-\lambda)^{\theta}$. In particular, this regulation serves to lower total accumulation of capital, and capital, output, consumption and wages all decrease by the same percentage relative to the original steady state. Steady state hours do not change, since the defining feature of preferences that are consistent with balanced growth is that hours of work do not respond to permanent changes in TFP.

The reader may at first find it curious that output and total capital decrease by the same amount, given that productive capital decreases by even more than total capital. This is reconciled by noting that although the percent drop in effective capital is larger than the percent drop in total capital, capital's share in output is less than one, so that output does decrease by less than the percent change in productive capital.

The second row from the bottom in the table reports the fraction of total labor that is used to produce the equipment that is used to reduce emissions rather than produce output. Even though there is no change in total hours worked across the two steady states, there is a change in how labor is allocated. Moreover, note that although there is no change in the amount of total hours worked, there is a decrease in wages across the two steady states. An important message is that when considering labor market effects it is not sufficient to focus on total hours of work or total employment. Had it not been for the change in wages, the implied welfare losses would have been much smaller.

Because hours do not change across the two steady states it is easy to infer the implied welfare change, since it is simply the percent change in consumption. The welfare losses are roughly linear in the size of the regulation over the region that is studied in the table. To the extent that any effects that have a welfare loss of 1% or greater are viewed as quite large in the macro literature, the table shows that this type of aggregate regulation can generate quite sizable losses in welfare net of environmental factors. Although the regulation I consider is a very stylized one and the model is a simple benchmark, it serves to illustrate that regulations that impact firm level capital stocks on the order of one percent or more, if sufficiently broad in scope so as to affect most of the economy, can have sizeable aggregate effects.

In the case just studied, there was no change in aggregate hours worked. This was due to the utility function that was used. Given a specific interest in incorporating labor market changes into the welfare analysis of regulatory changes it is perhaps of interest to consider an alternative specification in which there are also steady state effects on aggregate labor. Table 2 repeats the analysis of Table One except that in the calibration it is assumed that the utility from consumption takes the form of $c^{.5}$, i.e.,, that $\sigma = .5$.

Table 2

Steady State Effects of Regulation: $\sigma = .5$

	$\lambda = 0$	$\lambda = .01$	$\lambda = .02$	$\lambda = .03$	$\lambda = .04$	$\lambda = .05$
k_R^*/k_U^*	1.00	.994	.987	.981	.974	.967
h_R^*/h_U^*	1.00	.998	.996	.993	.991	.989
y_R^*/y_U^*	1.00	.994	.987	.981	.974	.967
c_R^*/c_U^*	1.00	.994	.987	.981	.974	.967
w_R^*/w_U^*	1.00	.996	.991	.987	.983	.978
h_R^*/h^*	0.00	.002	.004	.006	.008	.010
Δ^S	0.00	$-.005$	$-.009$	$-.014$	$-.018$	$-.023$

As in the previous case, the steady state features proportional declines in capital, output, and consumption, though these declines are now slightly larger than in the previous case. The reason for this is that there is now a decrease in hours worked across the two steady states, with the extent of the decrease an increasing function of λ. Note that the change in wages is the same as in the previous case. Also note that to first order, the welfare effects are the same. In the previous case there was no change in hours of work and a decrease in consumption relative to the initial steady state, whereas in this case the drop in consumption is larger but there is now an increase in leisure. The key point here is that one does not need to do anything special in applying this method depending upon whether the policy affects steady state hours of work. A very simple message that this example illustrates is that one should not identify changes in labor with changes in welfare; as just noted, the welfare effects in the two cases are basically the same even though the effects on labor are quite different.

2.5.2. Effects Including Transitions

As noted earlier, if one wants to understand how the change in regulation will affect those individuals who are currently living in the economy, abstracting from effects along the transition path could lead to a misleading picture of the nature of the changes. As a practical matter it is typically more demanding to carry out analyses of transition paths than it is to simply compute steady states. Beyond this, I would argue that transition paths are much less robust than steady state effects, to the extent that there are many details that could affect the nature of transitions without affecting the final steady state that is reached. For example, if there are any anticipation effects associated with the introduction of a regulation, this could affect the transition, but assuming the regulation is permanent and individuals come to realize that it is, then anticipation effects at the time of adoption will not influence the final steady state. Also, model features such as adjustment costs can affect transitions without affecting steady states. With these types of considerations in mind it is quite useful to know how important the transition effects might be. If they tend to be very close to the steady state effects then perhaps these additional complications can be dispensed with. Of course, there is no reason to think that the answer will not be context dependent. But in this section I examine this issue in the context of the adoption of the regulation that we studied in steady state in the previous section.

Solving for transition dynamics in the one-sector growth model is relatively straightforward. I do it using a shooting algorithm. Because the regulation that I am considering as an example is equivalent to a permanent reduction in TFP, there are theoretical results that tell us that the paths for capital and consumption starting from an arbitrary initial condition will be monotone and converge to the new steady state. In Figures one through three I show the transition paths for capital, consumption and hours over the first 25 years of the transition for the case in which $\lambda = .05$ and $\sigma = 1$, i.e., utility that is logarithmic in consumption.

A few properties are worth noting. First, convergence happens quite rapidly. Although the capital stock is initially more than 2% higher than its eventual steady state value, after only five years it is less than 1% away. Consumption is effectively never more than 1% higher than its steady state value, and after five years it is less than one half of one percent from its steady state value. And hours are never more than one half of one percent from their new steady state value. While consumption and capital decrease monotonically to their new steady state values, hours is increasing. The reason for the latter is that the relatively high initial value

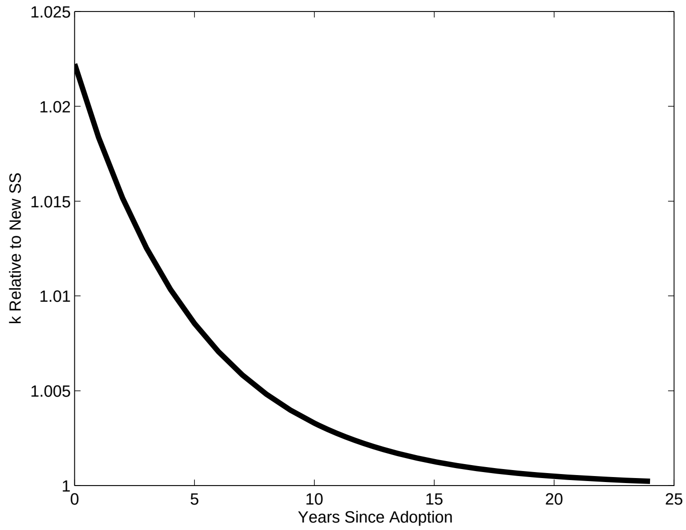

Figure 1: Transition Path for Capital

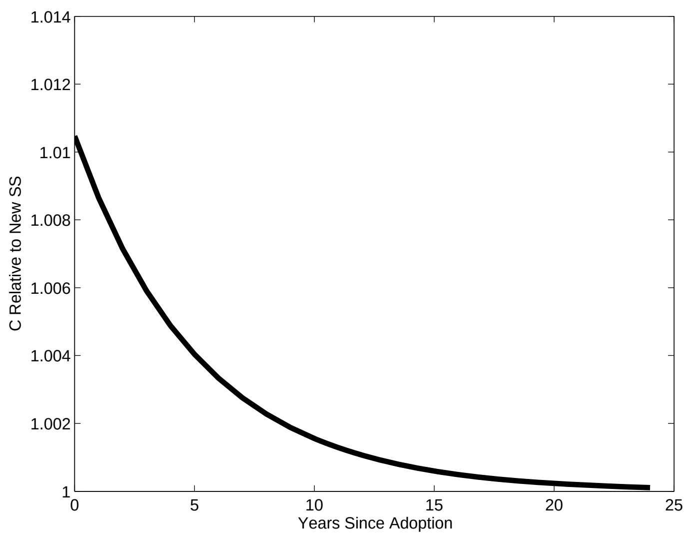

Figure 2: Transition Path for Consumption

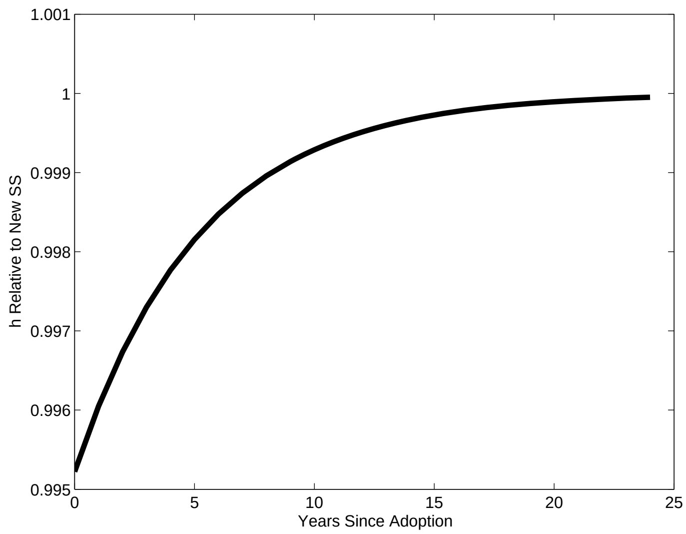

Figure 3: Transition Path for Hours

of capital implies that there is less desire to work due to intertemporal substitution effects. As capital decreases towards its new steady state value the interest rate increases to its steady state level and so do hours. While these transition dynamics are well known to economists who work with the one-sector growth model, it is worth pointing out that the initial decrease in hours immediately following the adoption of the regulation does not reflect any sort of "disequilibrium" in the labor market, that is, this decrease is part of an efficient response in the economy. As I briefly discuss later, one could introduce additional features into the analysis, such as wage rigidities and various sorts of adjustment costs that reflect the lack of skill transferability or search frictions, some of which may serve to amplify the initial decrease in hours worked. But the mere presence of a decline in hours worked is not by itself evidence of these additional features.

From a welfare perspective, note that during the transition there is higher consumption and leisure relative to the eventual steady state allocation, so that steady state welfare losses will exaggerate the extent of the losses that include the transition period. In fact, the welfare change that includes the transition path turns out to be $-.019$ as opposed to the value of $-.022$ when only considering the steady state. I conclude that the transition is not of first order importance in assessing welfare effects in this context. Table 3 reports the two different welfare changes for the case of $\sigma = 1$ and the five different values of λ.

Table 3

Welfare Effects: Steady State and Transition

	$\lambda = .01$	$\lambda = .02$	$\lambda = .03$	$\lambda = .04$	$\lambda = .05$
Δ^S	$-.004$	$-.009$	$-.013$	$-.017$	$-.022$
Δ^T	$-.0037$	$-.0075$	$-.011$	$-.015$	$-.019$

The main message from the table is that the effects of including the transition in this case is relatively small. This reflects the fact that the economy is never that far from its new steady state, and that after five years the allocations are all quite close to their new steady state values.

2.6. Discussion and Extensions

The goal of this section has been to lay out a benchmark macroeconomic model, describe how it is typically used to evaluate the welfare effects of policy, and then illustrate this in the context of one example of a highly stylized environmental regulation that affects the entire economy. I have tried to emphasize that the example studied here was purposefully simplified in order to best illustrate the general method. However, I think it is worth noting just a few of the many ways of interest in which the analysis could be extended.

In the spirit of the growth model I have assumed a putty-putty technology, in the sense that in the initial period of the regulation, some of the preexisting capital stock will actually be converted from being used to produce output to being used to reduce emissions. One could reasonably argue that a putty-clay formulation would be more natural, so that the equipment used to reduce emissions needs to be produced rather than converted. One might also consider the possibility that there are some sorts of adjustment costs associated with trying to increase the scale of production of this equipment too rapidly. And in view of these issues, it might be of interest to consider some sort of a gradual adoption process for the regulation, or even a grandfather clause for preexisting capital. All of these types of features can be incorporated somewhat readily and do not require any conceptual changes in the basic methodology. While these types of considerations might not have much impact of the steady state outcomes, they could matter for the effects during the transition period.

One could also consider situations in which the initial equilibrium has very different features. In particular, one could assume that wage setting practices in the labor market result in a level of the real wage that is higher than the competitive equilibrium level, so that hours worked in equilibrium do not correspond to the efficient level. One could then repeat the analysis in this setting, though one would need to make some assumption about how the regulation would influence wages, if wages are not determined by demand and supply. But again, the method outlined above can be equally well applied in this case as well. Related to this, one could assume that there is some sort of rigidity in wages that influence the transition dynamics from one steady state to another. As a result the transition might involve a reduction in hours if wages do not fall sufficiently fast.[4] This would increase the size of the welfare losses associated with the transition dynamics.

Lastly, consistent with the earlier discussion, one could potentially incorporate effects of lower pollution in a non-separable fashion if there were sufficient information available to guide such a specification. For example, if lower pollution promotes health and thereby enhances the enjoyment of leisure time or makes workers more productive at work by reducing the incidence of sickness, then such effects can be incorporated.

3. Benchmark II: Industry Analysis

In this section I lay out a partial equilibrium model that serves as a useful starting point. The model I describe here is a simple version of the industry equilibrium model of Hopenhayn (1992).[5] Melitz (2003) developed a variant of this model which has become the workhorse model used in international trade for thinking about the effects of trade policy. Ryan (2012) uses a version of this model to

[4] See the recent paper by Shimer (2013) for an analysis of how extreme wage rigidity can affect the transition dynamics.

[5] This type of analysis is also closely related to the span of control model analyzed in Lucas (1979).

study the effects of regulation on the cement industry. The model will give rise to a stationary (or steady state) equilibrium in which the aggregate behavior of the industry is constant over time, at the same time that the industry exhibits a rich set of dynamics at the establishment level, with establishments growing, shrinking, exiting and entering. As a result the model is both sufficiently rich to connect with key facts about establishment dynamics at the micro level while also permitting one to focus on industry aggregates. The model that I describe below should be viewed as the simplest prototype within a broad class of models. That is, it is possible to extend the model that I describe below to allow for a much richer set of features. I note some of these extensions later in this section, but from the perspective of exposition, I feel it is best to work with the simplest model within this class.

3.1. Model

I consider an industry consisting of many individual establishments that produce a homogeneous product. (The analysis can easily be modified to the case of firms that produce differentiated products.) The industry faces a time invariant inverse demand curve for its output given by $P(Y_t)$, where Y_t is the amount of output produced by the industry in period t.[6]

The unit of production in the industry is a plant. Each plant i has a production function:

$$y_{it} = z_{it} f(k_{it}, h_{it})$$

[6] We could easily allow for trend growth in demand but since it will not play any role in the analysis that follows I have abstracted from this feature.

where f is a strictly increasing and strictly concave function, k_{it} is input of capital services, h_{it} is input of labor services, and z_{it} is idiosyncratic plant level productivity. The fact that the function f is strictly concave implies that there is an efficient scale at the plant level and is critical in this framework to generate a non-degenerate distribution of plant sizes.[7] The idiosyncratic plant level productivity term z_{it} is assumed to be stochastic. This will allow the model to capture the large volume of job reallocation that occurs across establishments within an industry. (See, for example Davis. Haltiwanger and Schuh (1996)). In the differentiated product version of this model one could achieve this type of reallocation through either changes in relative productivity or changes in the relative demand for the differentiated products coming from changes on the consumer side. For our purposes there is no loss in generality by having all of these changes induced by changes in productivity. I will assume that the cdf for next period's shock z_{it+1} given today's realization z_{it} is given by a cdf $\Phi(z_{it+1}; z_{it})$. We will assume that the cdf has a mass point at 0 and that 0 is an absorbing state. Thus, receiving a draw of zero will be identified with exit. In many applications one might suspect that endogenous exit is an important channel of response to changes in regulations, and in a later subsection I describe how to endogenize exit by allowing for a fixed per period operating cost. But for present purposes the analysis is much more transparent with exit modeled as an exogenous process. Labor and capital services

[7] If we instead considered the model with differentiated products then we could have constant returns to scale in the production technology at the plant level, and the curvature needed to produce a non-degenerate plant-size distribution could instead by achieved by having curvature in preferences via imperfect substitutability of the differentiated products. Melitz (2003) adopted this type of specification in his analysis.

can be rented in competitive factor markets with time invariant prices w and r respectively. Because the analysis in this section is explicitly partial equilibrium, the maintained assumption is that changes within this industry have no effect on the factor prices that firms in this industry face.

We also allow for entry into the industry. The entry process works as follows. Each period there is an unlimited number of potential entrants. In order to enter in period t a potential entrant must pay a nominal cost c_e. After paying this cost, the entrant will receive an initial draw for its idiosyncratic productivity that is a draw from a distribution with cdf $\Upsilon(z)$. These draws are assumed to be iid across entrants, so that the expected quality of new entrants is independent of the amount of entry. If a potential entrant pays the entry cost in period t it begins operation in that same period with productivity given by its draw from the distribution described by $\Upsilon(z)$. Beyond the initial period, the idiosyncratic productivity of a new entrant will evolve according to the same stochastic process described previously.

We assume that firms discount future profits using the interest rate R.

3.2. Steady State Industry Equilibrium

I focus on the steady state equilibrium in this industry. The key feature of a steady state equilibrium is that industry output and hence the price will be constant over time. As noted above, although aggregates will be the same from one period to the next in a steady state equilibrium, there will be a lot of change at the microeconomic level, consistent with what we see in the actual data.

Let P^* denote the steady state equilibrium price in this industry. Because our analysis is partial equilibrium, this is the only endogenous price in the model. So finding a steady state equilibrium for this model requires that we find the value P^*. Consider the profit maximization problem faced by an individual establishment in the steady state equilibrium that has current productivity z. This plant could be either a plant that produced last period and has received its new shock for the current period, or a plant that was created last period, with z being its initial draw from the distribution. Its current period profit maximizing behavior is static: it is optimal to choose quantities of labor and capital today so as to maximize current period profit net of factor costs, since choices made today have no impact on future profits. The resulting profits will be a function of $P^*$and z, which we define by:

$$\pi(P^*, z) = \max_{k,h} \; \{P^* z f(k, h) - wh - rk\}$$

Let $V(z, P^*)$ be the value function for an establishment with current productivity z in steady state equilibrium when the output price is P^*.The Bellman equation for this value function is:

$$V(z, P^*) = \pi(p^*, z) + \frac{1}{1+R} \int V(z', P^*) d\Phi(z', z) dz'$$

Since $\pi(P^*, z)$ is increasing in P^*, it is easy to show that $V(z, P^*)$ is also increasing in P^*.

Now consider the entry decision. The expected return to entry net of entry costs is given by:

$$-c_e + \int V(z, P^*) d\Upsilon(z)$$

Since $V(z, P^*)$ is increasing in P^* it follows that the expected return to entry is also increasing in P^*. Given our assumption of an unlimited number of potential entrants, in equilibrium it must be that the net return from entering is not positive. Additionally, if there is entry in the steady state equilibrium, then the net return from entering must equal zero. It follows that if there is entry (and hence exit) in the steady state equilibrium, then P^* must be such that:

$$-c_e + \frac{1}{1+R} \int v(z, P^*) d\Upsilon(z) = 0$$

Because entry and exit are robust features in the data, we will focus on parameterizations such that there is entry and exit in the steady state equilibrium. Having determined P^* we now also know the level of output in the steady state equilibrium. Note that we pinned down P^* by requiring that the net return to entry is zero. This implies that all potential entrants are indifferent about entering. In steady state there is a constant flow of entrants. The steady state size of the industry will be increasing in this volume given that we are fixing P^* and that the exit rate is exogenous. We will determine the volume of entry by requiring that the amount of entry be such that the steady state size of the industry generate the right amount of output given that the price must be P^*. We next describe how to compute this level of entry. To do this it is useful to introduce one additional piece of notation. Assume that there is a mass of incumbents with distribution over z

values described by a measure $\mu(z)$. If we follow this group for one period, they will get new draws for z next period, and some of them will receive draws of zero and exit. The resulting measure of these establishments one period later will be denoted by $T\mu$. An important property of this operator is that it is homogeneous of degree one, i.e., if we double the mass of incumbents today, we will have double the mass of remaining firms tomorrow.

Suppose that there was a unit mass of entry in each time period. Then in the resulting steady state distribution the mass of firms of exactly age 0 will be given by the unity and because of the law of large numbers they will be distributed according to the cdf $\Upsilon(z)$. Denote the resulting measure by $\mu_0(z)$. In steady state, we can also determine the measure of establishments that are exactly one year old–since these would be the establishments who began one year earlier and did not exit after one year. This measure, which we denote by μ_1 will simply be equal to $\mu_1 = T\mu_0$.Continuing in this fashion we can trace out the measure of z's for each cohort in the steady state, and they are given by repeated applications of T to the distribution μ_0. Given that we know the measure of establishments over z's for each cohort in the steady state, we can also compute the amount of output produced by each cohort in the steady state. In particular, letting $Y_j(1)$ denote the amount of output produced by the cohort of age j in the steady state when there is a unit mass of entry in each period, we have that:

$$Y_j(1) = \int y(z, P^*)\mu_j(dz)$$

where $y(z, P^*)$ is the optimal output level for an individual establishment that has current productivity z if the steady state price in equal to P^*. Total output is then given by

$$\sum_{j=0}^{\infty} Y_j(1)$$

This is an infinite sum. It will be finite if establishments are exiting fast enough, so that the mass of establishments of older ages goes to zero sufficiently rapidly. If this does not happen, then there does not exist a steady state equilibrium for the economy. We will assume that exit happens sufficiently fast that a steady state equilibrium does exist, so that the sum is finite. Denote the value of this sum by $Y(1)$. It follows that this is the amount of output that would be produced in the steady state equilibrium if the output price were $P^*$and there was a unit mass of entry in each period. While we know that the steady state price must equal P^* assuming that there is entry in the steady state, we know that the steady state output consistent with this price is given by $Y^* = D^{-1}(P^*)$. As we noted before, the operator T is homogeneous of degree one. It follows that if we had entry of mass 2 in each period, steady state output would be $2Y(1)$. It follows that the amount of entry that occurs in the steady state equilibrium is given by $Y^*/Y(1)$. This completes the algorithm for finding the steady state equilibrium.

3.3. Policy Analysis and Welfare Effects

There are various types of regulations that we might consider in the context of this model. For example, if a regulation requires that plants buy more expensive capital equipment in order to cut down on some pollutant, this could be captured as an increase in the per unit cost of capital services, or as a need to use capital services beyond what is required to simply produce a given amount of output. A regulation which requires more documentation and studies prior to authorizing new start-ups can be modeled as an increase in the entry cost c_e. A third policy is one that requires a fixed per-period cost of compliance, perhaps associated with additional monitoring. While each of these cases operates through slightly different channels, they have a great deal in common in terms of the nature of their effects.

To provide continuity with the analysis in the previous section, I begin by considering a regulation that requires firms to purchase additional capital to reduce the amount of emissions that they produce. In particular, assume that the policy implies that if an establishment hires k_{it} units of capital that a fraction λ of this capital will be used to reduce emissions with only a fraction $(1-\lambda)$ being actively used for production.

It follows that the value of $\pi(z, P^*)$ will decrease for any given values of its arguments. This implies that at the old equilibrium price, the net expected return to entering will be negative, so that the equilibrium price must be higher. This in turn implies that output must be lower. The higher value of P^* will change the optimal size of an establishment conditional on its value of z. If this effect is positive, and since exits are exogenous, the only way that output can be lower in the steady state is if the mass of entry in the steady state is lower. If the effect on establishment level output is negative, then the effect on entry is ambiguous.

Alternatively, consider a regulation that makes entry more costly, perhaps by requiring additional documentation or impact studies up front. Although this has no direct effect on $\pi(z, P^*)$ for given values of its arguments, this policy will also lead to an increase in P^* via the free entry condition, since the cost c_e has increased. This increase in P^* will necessarily increase optimal establishment size in this case, since there is no impact on the production function. It follows that entry must decrease. Similarly, if there is an increase in a per period compliance cost, this also reduces profits at the original equilibrium price, implying that the price must increase and that entry must decrease. One of the key messages that this simple qualitative analysis serves to communicate is the importance of the entry margin in bringing about adjustment to the new equilibrium.

Next we consider the issue of assessing the welfare cost associated with these types of policies. Unlike the analysis in the previous section, there is no utility function that is specified as part of this industry equilibrium analysis. Standard practice for computing welfare in this framework would be to take the area under the demand curve as a measure of the value of the industry's output, plus any profits accruing to firms, less the cost of any inputs that are used to produce output. That would include the resource costs associated with entry. Changes in this measure across steady states would give us the appropriate steady state change in welfare. Implicitly, this method assumes that if total employment changes in this industry, there is no direct cost or benefit associated with this change. In this sense, partial equilibrium analyses do not provide an internally consistent method for assessing the welfare costs that might be associated with changes in labor input to the industry being studied.

3.4. Calibration

If one wants to use this model to carry out quantitative evaluations of policy changes then it is necessary to choose functional forms and assign parameter values. Whereas there is widespread agreement on what constitutes a reasonable calibration of the one sector growth model, this is somewhat less true for the industry equilibrium considered in this section. In part this reflects the fact that it is an industry model and different industries can display different patterns of establishment dynamics. Additionally, there are more variants of this model in use, with less agreement as to what constitutes the natural benchmark. Having noted this qualification, here I describe one calibration procedure.

In what follows I will assume that f takes the following form:

$$f(k,h) = k^{\alpha} h^{\theta}$$

where α and θ are both positive and $\alpha + \theta < 1$.

I begin with the stochastic process for idiosyncratic shocks. There are two aspects to this process, one describing the exogenous exit dynamics and the other describing the productivity dynamics conditional on remaining in the industry. I restrict attention to a specification in which z takes values in a finite set with N elements, ordered so as to be increasing. In the examples below, N is 11 and the values are equally spaced on the interval $[1, 4]$. For each value of z I will assume that there is a decreasing function $\phi(z)$ that gives the probability of exit (i.e., a zero productivity draw for next period). In the examples computed below, I assume that the exit rate is decreasing in the value of z, and ranges from .05 to .15, varying linearly in z. With probability $1 - \phi(z)$ the evolution will follow a given stochastic process. Given the simple structure of the benchmark model, i.e., that the profit maximizing choice of inputs is static, it follows that stochastic processes for both factors and output will closely mimic the stochastic process for the idiosyncratic shocks. An AR(1) process in logs is the most common choice for this process:

$$\log z_{it+1} = \rho_z \log z_{it} + \varepsilon_{it+1}.$$

This results in a process for establishment size that exhibits mean reversion. The distribution of the innovations in this process will have a significant impact on the nature of the steady state distribution of establishment sizes. A common choice is to assume that these innovations are distributed according to a normal distribution, implying that the steady state establishment size distribution will resemble a log normal distribution. It is well known that this distribution does not have as much mass in the upper tail as is found in the data, and choosing the innovations to come from a Pareto distribution would help with this issue, though normal is the more common choice in the literature. In the calculations that I carry out I assume a very simple process that captures the spirit of the above process. For any interior value of z, I assume that with probability .95, productivity will be the same next period as this period. And with probability .025, the productivity will move up or down one position. A the two boundaries I assume that the entire .05 probability reflects the probability of a one step move into the interior of the set.[8]

The second stochastic process concerns the distribution that new entrants draw their initial productivity from. A key observation from the data is that new establishments tend to be small. A richer model might have additional features, such as learning, that influence the size of new entrants, but in this simple model, the average size of new entrants is dictated entirely by their average productivity draw, subject to them choosing to operate. This implies that the mean productivity draw of new entrants must be sufficiently low relative to the steady state distribution of productivity shocks. Subject to meeting this criterion, the distribution does not seem to matter that much. In the calculations that I carry out below I will assume that the distribution is uniform on the three lowest points in the set of idiosyncratic shocks.

The other functional form to specify is the industry inverse demand function. I assume that this relationship exhibits a constant elasticity:

$$P_t = AQ_t^{-\eta}$$

Having specified a particular process on the idiosyncratic shocks, the remaining parameters are the prices r, R and w, the demand parameters η and A, the two technology parameters α, θ, and the cost of entry parameter c_e. Several values can be normalized to reflect a choice of units. The values of A and w can both

[8]See, for example, Hopenhayn and Rogerson (1993) for a calibration procedure that posits an AR(1) process with normal innovations and discusses how to calibrate it using data on job creation and destruction. See also Khan and Thomas (2007) for a model with many additional features and a richer calibration strategy.

be normalized to one with no loss of generality. I will also impose that the steady state price of output, P^* will be equal to one, again as a normalization. As we will see later, this amounts to fixing the units in which the fixed costs are measured. For the results shown below I assume that $\eta = 1$.

If we set a period equal to one year, and make use of the relationship between the interest rate and the depreciation rate and the value of r in a standard growth model (the interest rate is r less the depreciation rate in these models), then setting $R = .04$ would suggest that $r = .12$ as a reasonable choice.

The values for α and θ can be chosen by targeting values for capital's share, labor's share and the residual. There is no definitive estimates of the latter value, though typical calibrations assign a 15% share to this category. Using a $1/3 - 2/3$ split between capital and labor of the remaining 85% yields $\alpha = .255$ and $\theta = .595$. The value of the entry cost is then pinned down by the requirement that the free entry condition is satisfied given all of the other parameter assignments.

Although I have considered a very simple stochastic process for idiosyncratic shocks, the steady state distribution of establishment sizes does match some key features found in the data. For example, the steady state distribution of establishments is heavily skewed towards smaller establishments, at the same time that the majority of employment is accounted for by larger establishments. In the steady state the labor input at the largest establishment is roughly $10,000$ times the labor input at the smallest establishment. If we interpret the smallest establishments as those with one worker, then the three lowest productivity levels would correspond to establishments with less than 20 workers. Roughly 93% of establishments then have less than 25 employees, but these establishments account for less than half of total labor input that is hired by the industry.

Now I consider a few specific policies. Results are shown in Table 4.

Table 4

Effects of Regulation in the Industry Equilibrium Model

	$\%\Delta p$	$\%\Delta E$	$\%\Delta H$	$\%\Delta avg\ h$	$\%\Delta welfare$
capital requirements	2.79	$-.46$	0.00	.47	-2.72
per period compliance cost	1.89	-11.3	0	13.3	-2.20
increased entry cost	1.44	-9.1	0	10.0	-1.43

The first row considers the case of a regulation that requires hiring of additional capital services. Suppose that the policy is such that establishments need to hire an additional 10% of capital to sufficiently lower emissions. The new steady state price turns out to be 2.79% higher, so that output is also 2.79% lower. The change in welfare relative to the initial expenditure in the industry turns out to be -2.72%. Entry, denoted by E, falls by .46%, so that in the new steady state the number of firms falls by the same amount. Average firm size is actually higher by .47% which implies that the effect of the higher price dominates the direct effect of the regulation. This policy produces proportional changes in size across the size distribution, given the nature of the production function. There is no change in aggregate employment due to this policy. I note that there is nothing general about this particular outcome, as it results from the assumption of a unitary elasticity of demand.

The second row considers a policy that introduces a fixed compliance cost for all active establishments. The size of the cost is set at 10% of the average profit level in the original steady state equilibrium. The effects are qualitatively similar to those of the first row, except that the effects on entry and average establishment size are much larger, though offsetting. To gauge the magnitude of the two different regulations, note that in the original equilibrium, capital's share of output is roughly 25% so that a 10% increase in capital costs holding behavior constant would amount to a 2.5% increase in costs. Profits represent 15% of output in the original steady state, so 10% of this represents 1.5% of output. Note that output decreases even though nothing happens to total labor input. This occurs because the increase in average firm size is suboptimal and leads to a decrease in average labor productivity.

The third row considers a 10% increase in entry costs. The qualitative effects are again similar. Note that in the initial steady state, entry costs represent roughly 8.5% of total output, so a 10% increase amounts to roughly a .85% increase in costs.

Since I have not calibrated to a particular industry and a specific regulation, the above values are simply illustrative. But having said this, I think it is fair to say that moderate sized changes in regulations can have sizeable effects on welfare.

3.5. Discussion and Extensions

To facilitate exposition I have focused on the simplest version of an industry equilibrium model that incorporates establishment level dynamics and allows for entry and exit of establishments. However, it is straightforward to extend the model in a number of directions. I note a few of these here. First, it is straightforward to endogenize the exit decision. To do this, assume that in addition to the variable costs associated with hiring labor and capital services there is a fixed cost of operation that any plant incurs, denoted by c_f. An establishment can avoid incurring this fixed cost in period t by exiting, which means ceasing to exist. In particular, a plant is not allowed to avoid the fixed cost by not producing output this period and waiting to see if a better shock is realized next period. The period t value of idiosyncratic productivity is assumed to be observed before a plant makes its decision about whether to continue in operation. One could still maintain some amount of exogenous exit as was the case in the simpler model.

I assumed that the only dimension of heterogeneity was the establishment level TFP shock. One could allow for additional sources of heterogeneity, in terms of fixed costs, technology share parameters etc... One could also enrich the specification of technology in various ways, perhaps allowing for vintage effects that would lead to heterogeneity in technology and perhaps heterogeneity in the extent to which different establishment cause pollution. The literature on establishment dynamics has considered a variety of factors that may be quantitatively important in influencing dynamics, such as different types of adjustment costs, learning effects about technology, learning effects about demand etc... These kinds of effects can easily be incorporated.

While I have listed a number of generic extensions that might be of interest, it is undoubtedly the case that for an applied study of a given industry there are likely to be features of that specific industry which will motivate the inclusion of particular features.

In the above analysis I have focused on steady state effects. One can also consider transition dynamics. In the simple model studied here, the key source of dynamics is the adjustment in the entry process, since this is the only dynamic element in the benchmark model that I studied. In a model with an endogenous exit decision there would also be dynamics in the exit process. There are two basic forms that the adjustment dynamics may take in the examples considered above, all of which served to decrease the profitability of entry and lead to a higher price. One possibility is that the price increases immediately to the new steady state level and there is entry throughout the adjustment process. The other possibility is that the price increases to the new steady state only after some periods. In this case there will be no entry during the period in which the price is below the new steady state price, since entry is only profitable at the new steady state price. As establishments exit the price will increase, eventually reaching the new steady state level and making entry profitable again. While these two types of adjustment seem intuitive, one cannot rule out price paths in which the price oscillates around the new steady state price. Unlike the case of the one sector growth model where transition paths are well understood and have been thoroughly characterized, this is not the case for partial equilibrium industry equilibrium models.

4. A Hybrid Model: Industry Equilibrium Analysis Within An Aggregate Model

In this section I develop a tractable framework that allows one to consider a rich description of the industry (or industries) affected by a specific regulation while simultaneously allowing for an analysis of the potential aggregate or general equilibrium effects that are associated with the regulation. Moreover, the framework lends itself to welfare calculations that are tightly connected to individual preferences and can be applied in a wide range of circumstances.

The essence of the model is to retain the basic structure of the one sector growth model but to allow for multiple intermediate goods sectors. Each intermediate goods sector combines labor and capital to produce its output. The intermediate goods are then combined through another production function into the single final good. The single final good can then be used as either consumption or investment. This type of production structure is popular in macroeconomics in the study of wage and price rigidities, as it retains the tractability of the one-sector growth model while allowing for monopolistic competition among intermediate goods producers, thereby providing a coherent framework for thinking about wage and price rigidities. In the macro literature these models assume that each intermediate good is produced by a single firm. In contrast, the prototype model that I develop here will assume that there are two intermediate goods sectors. One of these will represent the industry which is the prime focus of study given the regulation being considered. The second intermediate goods sector will be the aggregate of all other sectors. While we could treat these two sectors symmetrically in terms of modeling, my benchmark model will impose an asymmetry, with the idea being that the industrial structure is most important in the context of the directly affected industry. So while I will explicitly consider the industrial organization of this sector, and model it in the fashion of the industry equilibrium model from the previous section, the other sector will be captured by an sectoral aggregate production function. While one could also introduce the details of firm level dynamics into the non-regulated sector, it is not clear that this is of first order importance and increases the tractability of the model. The details follow.

4.1. Model

There is a single final good in the economy, and there is a representative household that is infinitely lived, with preferences given by:

$$\sum_{t=0}^{\infty} \beta^t u(C_t, 1 - H_t)$$

where all of the objects are as defined in an earlier section. There are two intermediate goods. The final goods sector combines the two intermediate goods into the final good using a constant returns to scale production function:

$$Y_t = G(Q_{1t}, Q_{2t})$$

where Q_{it} is the input of intermediate i in period t. We will assume that intermediate good 2 is the sector that is directly affected by the regulation that is being considered. A natural choice for the production function G is a constant elasticity of substitution function:

$$G(Q_1, Q_2) = [aQ_1^\gamma + (1-a)Q_2^\gamma]^{1/\gamma}$$

With this choice the parameter a can be used to capture the relative importance of the sector being considered in terms of it share of aggregate value added, and the parameter γ captures the extent to which this intermediate is substitutable with goods or services produced elsewhere in the economy.

As in the one sector growth model, aggregate output can be used for either consumption or investment, but we also assume that this final good is the good that is used in the entry process:

$$C_t + I_t + E_t c_e = Y_t$$

where E_t is the amount of entry in period t and c_e is the cost of entry. The aggregate capital stock evolves as before:

$$K_{t+1} = (1-\delta)K_t + I_t.$$

In the model I develop here I will assume that capital is freely mobile between sectors, so that:

$$K_t = K_{1t} + K_{2t},$$

though it may well be of interest to consider the case in which each sector has its own capital stock and there is no mobility of capital across sectors.

The technology in sector 1 is standard, in that it is represented by a constant returns to scale aggregate sectoral production function:

$$Q_{1t} = F(K_{1t}, H_{1t})$$

where K_{1t} and H_{1t} are inputs of capital and labor in sector 1, respectively.

In contrast, in sector 2 we model production by specifying plant level technologies and allowing for establishment level dynamics driven by idiosyncratic shocks, in addition to entry and exit. The details are the same as those in the previous section, namely a plant level production function $z_{it}f(k_{it}, h_{it})$, idiosyncratic shock process denoted by $\Phi(z_{it+1}, z_{it})$, and entry cost of c_e, which will be measured in units of the final good. New entrants draw their initial productivity shock from a distribution with cdf $\Upsilon(z)$.

As in any general equilibrium model, all firms are owned by the household sector. For the final goods firm and the firm in sector 1 there will be zero profits in equilibrium on account of the constant returns to scale assumption, so there are no effects associated with ownership. For sector 2, given that there are decreasing returns to scale at the plant level, and entry costs, profits will typically be non-zero. Although there is a zero profit condition for entry, this does not imply that the aggregate of cross-sectional profits are zero if the interest rate is positive.

4.2. Equilibrium

Although one can certainly solve for transitional dynamics in this model, as in the last section, my analysis here will focus on steady state equilibria. I will normalize the steady state price of the final good to be equal to unity. A steady state equilibrium will then be characterized by four prices: two factor prices (w and r for labor and capital respectively) and two intermediate goods prices (p_1 and p_2 for intermediate goods 1 and 2 respectively). The relevant quantities in a steady state equilibrium are aggregate consumption and hours worked for the household (C and H), aggregate production quantities in sector 1 (Q_1, H_1, and K_1), aggregate quantities in sector 2 (Q_2, H_2, and K_2) and the volume of per period entry in sector 2 (E). All of the establishment level variables can be computed given these values.

I next show how to solve for this steady state equilibrium. The procedure will draw on the various first order conditions that have been derived previously, so rather than re-derive these conditions I will simply refer to past derivations as needed. To begin, note that the household problem in this model looks exactly like the household problem in the one sector neoclassical growth model, so that it remains true that in a steady state competitive equilibrium we must have:

$$r = \frac{1}{\beta} - (1 - \delta)$$

Profit maximization in the final goods sector and in intermediate sector 1 imply that following standard conditions:

$$
\begin{aligned}
p_1 F_1(K_1, H_1) &= r \\
p_1 F_2(K_1, H_1) &= w \\
G_1(Q_1, Q_2) &= p_1 \\
G_2(Q_1, Q_2) &= p_2
\end{aligned}
$$

where it should be noted that we have used the fact that the price of the final good is normalized to one. Suppose we knew the value of p_2. Because G displays constant returns to scale, marginal products of G depend only on relative factor inputs, so that knowing the value of p_2 implies that we can then infer the value of p_1. Similarly, knowing r/p_1 allows us to infer w/p_1. It follows that we know the values of all prices once we know the value of p_2. However, from our analysis of industry equilibrium in the previous section, we know that the free entry condition imposes a specific relation between r, w, and p_2. In fact, the above procedure implies that w is a decreasing function of p_2. It follows that expected profits net of entry costs are strictly monotone in the conjectured value of p_2, so that checking the free entry condition will allow us to determine all of the steady state equilibrium prices.

Having determined all of the prices, we know determine the allocation of factors across sectors. Given prices that are consistent with free entry, we can determine the steady state outcome within intermediate sector 2 given a unit mass of entry in steady state. This will produce a particular volume of output. As we noted above, the first order condition of the final good firm tells us the value of Q_1 consistent with any value of Q_2. In fact, since the ratio is pinned down, this condition will scale the values of these two outputs proportionally. Knowing this we can infer the amount of aggregate labor and capital being used, and hence also the steady state level of consumption, since we know that investment is exactly equal to depreciation in steady state. Since changing the mass of entry simply scales al quantities up and down, it follows that C and H are being scaled up as we vary E. To determine the equilibrium value of E we simply check the households condition for optimal labor supply. The wage rate is given and as we vary the amount of entry we increase consumption and decrease leisure, so at some scale of operation the marginal rate of substitution between consumption and leisure will be equal to the wage rate.

4.3. Calibration, Policy Analysis and Welfare

Calibrating this model is basically a matter of combining the two calibration procedures documented earlier. Specifically, the details of intermediate sector 2 can be calibrated to capture the key features of establishment dynamics in this sector. And while I have specified a very simple model, all of the extensions which were discussed in the previous section can also be implemented here in order to capture whatever features seem central in the context of the specific industry being studied and the particular policy or regulation being considered. The technology for combining the two intermediate goods is purposefully allowed to be flexible in order to capture the potentially different role of various sectors that one might want sector 2 to represent. Having specified this, sector one will be calibrated to match standard aggregates given the rest of the production structure.

To illustrate the method I adopt the following calibration. For sector 1, we assume a Cobb-Douglas production function with capital share equal to .30. And as in the earlier exercises, we again set the depreciation rate on capital equal to .08. For the production function that combines outputs of the two sectors we assume a constant elasticity of substitution production function:

$$G(Q_1, Q_2) = [aQ_1^\rho + (1-a)Q_2^\rho]^{1/\rho}$$

and will consider a few different settings for both a and ρ to illustrate their role. As earlier, we assume that the period utility function is of the form:

$$\alpha \log c + (1-\alpha)\log(1-h).$$

For the same reason as before, I set $\beta = .96$ in order to generate an annual steady state interest rate of 4%.

For sector 2, I adopt the same specification for functional forms and parameter values as in the previous section. Specifically, I let $f(k,h)$ take the form $f(k,h) = k^{\alpha_2}h^{\theta_2}$, and set $\alpha_2 = .85 * .3$ and $\theta_2 = .85 * .7$ so that capital and labor shares in this sector will be proportional to the capital and labor shares in sector 1, with the difference between that the sum of the exponents is unity in sector 1, and .85 in sector 2.

For the first set of results I will consider the case in which ρ tends to zero so that the production function that aggregates the outputs of the two sectors is Cobb-Douglas. There are three parameters that still need to be set: α, a, and c_e. These are determined by requiring that the steady state match three targets. First, I require that steady state hours worked represent one third of the households time endowment. Second, as a normalization of units for the two different sectoral outputs I require that in the steady state equilibrium the ratio of the two prices is unity. Third, to fix the relative importance of sector 2 in the overall economy I assume that the value of sector 2's output is 10% of the value of sector 1's output. Given that the relative price of the two goods in steady state is unity, this amounts to the condition that steady state output of sector 2 is 10% of the steady state output of sector 1.

Here I briefly sketch the procedure that one can follow to implement the last steps of this calibration. Given a value for ρ, profit maximization in the final good sector implies:

$$\frac{p_2}{p_1} = \frac{(1-a)}{a}(\frac{Q_2}{Q_1})^{\rho-1}$$

This condition can be used to determine the value of the parameter a. Given a value of a, one can then use the individual first order conditions for Q_1 and Q_2 to determine the level of both p_1 and p_2. As is standard in the growth model, and as we derived earlier, the steady state rental rate on capital is connected to the discount factor and the depreciation rate via:

$$r = \frac{1}{\beta} - (1-\delta).$$

Given values for r and p_1, the first order condition for capital in the profit maximization problem for the representative firm in sector 1 pins down the capital to labor ratio in sector 1:

$$p_1 \theta (\frac{k_1}{h_1})^{\theta - 1} = r$$

And knowing the capital to labor ratio implies that the value of the wage can be inferred from the analogous first order condition for labor in sector 1:

$$p_1 (1 - \theta)(\frac{k_1}{h_1})^{\theta} = w$$

At this point, all of the prices have been determined. As in the previous section, given values for all of the prices, one can calculate the expected return to entry in sector 2, as was done in the previous section. Given that the net return to entry must equal zero in equilibrium, this condition is used to pin down the value of the entry cost c_e.

It remains to determine the value of the preference parameter α. This is determined by requiring that total time devoted to work equals to chosen target. Specifically, the previous steps ensured that the net return to entry in sector 2 is zero. It follows that any level of (constant) entry is consistent with this condition. But, higher levels of entry in sector 2 lead to higher levels of steady state output in sector 2, and also in sector 1, since sector 1 output is necessarily ten times the output of sector 2 given the calibration. The values for r and w determined above imply that capital to labor ratios are determined in both sectors. It follows that higher levels of entry will simply increase the total amount of labor. Hence, the amount of entry can be determined by requiring that total labor equals the target. Given the amount of entry, and the volume of labor supplied, one can use the previous information to compute the level of steady state consumption. Given values for steady state consumption, steady state labor, and the wage rate, we can infer the value of α that is consistent with the household's first order condition for labor supply.

Given a calibrated version of the model, we could now introduce various policies as earlier in the paper and compute the effect of these policies on both steady state allocations and welfare.[9] To facilitate comparison with the earlier results in the one sector model I will focus on policies that are interpreted as raising the amount of capital that needs to be hired in sector 2 in order to generate the same level of services from capital. As discussed earlier, one interpretation of such a policy is that firms need to use a more expensive form of capital in order to reduce emissions, and I will parameterize it in the same way as previously, with λ parameterizing the policy.

Table 5 presents results for how this type of policy affects a variety of steady state outcomes both in the benchmark calibration and in three other settings.

[9] One can also compute transition paths from one steady state to another in this type of model, though this is a bit more intensive in terms of computation and is not dealt with in this paper. However, Veracierto (2001) is an early example of a paper that solved for transition dynamics in a model with heterogeneous firms and endogenous entry.

Table 5

Policy Effects in the Two Sector Model Relative to Initial SS

	Benchmark		$Q_2/Q_1 = .20$	$\rho = .25$	$\rho = -.25$
% change in:	$\lambda = .05$	$\lambda = .15$	$\lambda = .85$	$\lambda = .85$	$\lambda = .85$
Y	$-.16$	$-.52$	$-.96$	$-.53$	$-.51$
C	$-.13$	$-.41$	$-.78$	$-.41$	$-.41$
K	$-.26$	$-.81$	-1.46	$-.80$	$-.82$
H	$-.09$	$-.27$	$-.46$	$-.26$	$-.27$
Q_1	$-.04$	$-.13$	$-.25$	$-.02$	$-.21$
Q_2	-1.4	-4.3	-4.44	-5.47	-3.51
h_1	$+.01$	$+.03$	$+.05$	$+.14$	$-.04$
h_2	-1.20	-3.76	-3.47	-4.95	-2.98
p_2/p_1	$+1.30$	$+4.29$	$+4.34$	$+4.29$	$+4.29$
Welfare	$-.11$	$-.36$	$-.61$	$-.33$	$-.38$

The first two columns consider two levels of the policy in the benchmark calibration, one in which the effective capital services in sector two are reduced by 5% and a second policy in which the reduction is 15%. To first approximation, the effects of the larger policy are just a proportionately scaled version of the effects in the smaller policy setting, and so I focus my discussion on the second column. All of the effects are intuitive in terms of their direction. That is, we see that this policy has a negative effect on total output, total consumption, total labor supply and the total capital stock. Turning next to the sectoral effects, we see that output of both sectors decreases, though the decrease in sector 2 is more than an order of magnitude larger. Because the policy directly effects sector 2, making it more costly to produce output in that sector, it is intuitive that sector 2 will experience a greater impact. Loosely speaking, holding factor prices as given, the decrease in efficiency in sector 2 leads to an increase in the relative price in sector 2 from the free entry condition, and this increase in price reduces the demand for sector 2 output, leading to less demand for labor and capital in sector 2. In the partial equilibrium model of the previous section, this is the whole story. But in the general equilibrium model considered here, this excess supply of factors of production creates general equilibrium effects. These general equilibrium effects involve changes in factor prices and factor supplies. These in turn influence the demand for sector 2 output, thereby feeding back into the steady state change in the price of sector 2. The net effect of these is that labor in sector 1 increases by a very small amount, while output of sector 1 decreases. That is, the decrease in overall capital accumulation dominates the effect of there being additional labor allocated to sector 1. Consistent with the effects just described, the price of output in sector 2 increases relative to the price of output from sector 1. Note that in steady state, the rental rate on capital is necessarily determined by the discount factor and the depreciation rate, so all of the adjustment in the capital market occurs on the quantity side.

The final row of the table reports the steady state welfare loss relative to the initial steady state equilibrium. Although the policy has a large effect on inputs and output in sector 2, since this sector is a relatively small part of the overall economy, the overall welfare effect of these changes is much less. While not exactly true, the overall welfare effects are similar in magnitude to the percentage change in output in sector 2 times the share of sector 2 in total output. As we will see shortly, the extent to which this calculation provides an accurate estimate of the overall welfare costs is very much influenced by the extent of substitutability between sector 1 and sector 2 in the production of the final good.

The third column of Table repeats the exercise from the second column except that the model is calibrated so that sector 2 is large relative to sector 1. Specifically, in the benchmark calibration it was assumed that sector 2 was only one tenth as large as sector 1, whereas in the third column it is assumed that sector 2 is one fifth as large as sector 2 in the original steady state equilibrium. Note that this implies that sector 2 is roughly 9% of total output in the benchmark calibration and roughly 17% in the alternative calibration. Perhaps not surprisingly, the third column indicates that the aggregate effects are increased roughly proportionately to the importance of sector 2 in overall economic activity. Interestingly, however, the change in output and labor in sector 2 is not much effected. The reason for this is that the direct effect on sector 2 is independent of the size of sector 2; it is only the general equilibrium effects that are influenced by the size of sector 2.

The final two columns consider values for the elasticity of substitution between the two sectoral outputs on either side of unity. The basic message is that the greater the extent to which sector 1 output can be substituted for sector 2 output, the larger is the reallocation of production away from sector 2 and toward sector 1. However, the effect on aggregates is relatively minor, and the welfare cost is slightly larger if there is less substitutability. An important implication is that the size of the effects on sector 2 is not necessarily a good indication of the overall welfare loss. Specifically, comparing the effects on hours worked in sector 2 between the cases of $\rho = +.25$ and $\rho = -.25$, we see that the decrease is more than one and half times larger when $\rho = +.25$, but that the welfare losses are really quite similar.

4.4. Extensions

Consistent with the earlier analysis, one can consider any number of extensions to the simple prototype that I have described. To the extent that one is concerned about the labor market consequences of dislocation, there are a couple of different features that could be incorporated. One simple feature is to assume that there are labor adjustment costs in the technology, i.e., in addition to the possibility of utility costs associated with moving labor input across sectors. A second, and related possibility is that one could assume that there is sector specific human capital. One could model human capital accumulation in different ways, but one way would be to assume that there is human capital accumulated via a learning by doing technology. One might also want to consider the possibility of sector specific physical capital, as noted earlier. These features might be particularly relevant for understanding transition dynamics. While transition dynamics in this model will be a little bit more complicated than in the simple one sector growth model and I have not explicitly discussed them, it is certainly feasible to compute transition dynamics in this model.

5. Conclusion

The goal of this paper has been to summarize a method that can be used to evaluate the aggregate effects of environmental regulations for both allocations and welfare, with a particular emphasis on contexts which are dynamic and in which labor market effects are present. The approach described here is structural, in the sense that it specifies a given structural model and uses the model to predict how a given change in regulation will affect the equilibrium outcomes in the economy. I have developed a simple hybrid model which amounts to embedding industry equilibrium analysis into an otherwise standard version of the one sector growth model. I argue that this is likely to be a useful framework for assessing environmental regulations that are largely focused on a particular industry, but which at the same time are thought to potentially have important aggregate consequences. The structure I described allows for a rich description of establishment dynamics in the industry of interest, and allows for a fairly flexible yet tractable assessment of the general equilibrium effects.

The focus in this paper has been on describing a general method, rather than in producing a particular assessment of a given policy or regulation. For purposes of transparency in exposition, I have focused on the simplest possible specifications, and considered some fairly generic types of regulations to illustrate the method. But I have also tried to emphasize that the methods described here can be used in much more complex versions of the models that I described. For specific applications this is likely to be important.

An issue that I have not addressed here is the extent to which the methods I have described can offer reliable assessments of the effects of policies. While it is useful to know that the method can accommodate a wide range of specifications, the method will only be useful if one can establish that particular specifications do give reliable answers to questions of interest. This is an issue at the forefront of applied research in macroeconomics and applied economics more generally, and will require that we confront the predictions of specific versions of the model with observed outcomes that result from specific changes in regulation. Developing these models and assessing their reliability is a key issue for future research.

References

Auerbach, A., and L. Kotlikoff. 1987. *Dynamic Fiscal Policy.* Cambridge University Press: Cambridge, UK.

Christiano, L., M. Eichenbaum and C. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." Journal of Political Economy 113: 1-45.

Davis, S., J. Haltiwanger, and S. Schuh. 1996. *Job Creation and Destruction.* The MIT Press: Cambridge, Massachusetts.

Hopenhayn, H. 1992. "Entry, Exit, and Firm Dynamics in Long Run Equilibrium". Econometrica 60: 1127-50.

Hopenhayn, H. and R. Rogerson. 1993, "Job Turnover and Policy Evaluation: A General Equilibrium Analysis". Journal of Political Economy: 101(5): 915-38.

Khan, A., and J. Thomas. 2007. "Inventories and the Business Cycle" An Equilibrium Analysis of (S,s) Policies." American Economic Review 2007.

Lucas, R. 1990. "Supply Side Economics: An Analytical Review." Oxford Economic Papers 42: 293-316.

Melitz, M. 2003. "The Impact of Intraindustry Trade Reallocations and Aggregate Industry Productivity". Econometrica 71(6): 1695-1725.

Prescott, E.. 2004. "Why Do Americans Work So Much More than Europeans?" Quarterly Review of the Federal Reserve Bank of Minneapolis: 2-13.

Ryan, S. 2012. "The Costs of Environmental Regulation in a Concentrated Industry." Econometrica 80: 1019-1061.

Shimer, R.. 2013. "Wage Rigidities and Jobless Recoveries". Working paper, University of Chicago.

Veracierto, M. 2001. "Employment Flows, Capital Mobility, and Policy Analysis". International Economic Review 42(3): 571-95.