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ABSTRACT

A carbon tax has been widely discussed as a way of reducing fossil fuel use and mitigating climate change, generally in a static framework. Unlike standard goods that can be produced, oil is an exhaustible resource. Parts of its price reflects scarcity rents, i.e., the fact that there is limited availability. We highlight important dynamic aspects of a global carbon tax, which will reallocate consumption through time: some of the initial reduction in consumption will be offset through higher consumption later on. Only reserves with high enough extraction cost will be priced out of the market. Using data from a large proprietary database of field-level oil data, we show that carbon prices even as high as 200 dollars per ton of CO2 will only reduce cumulative emissions from oil by 4% as the supply curve is very steep for high oil prices and few reserves drop out. The supply curve flattens out for lower price, and the effect of an increased carbon tax becomes larger. For example, a carbon price of 600 dollars would reduce cumulative emissions by 60%. On the flip side, a global cap and trade system that limits global extraction by a modest amount like 4% expropriates a large fraction of scarcity rents and would imply a high permit price of $200. The tax incidence varies over time: initially, about 75% of the carbon price will be passed on to consumers, but this share declines through time and even becomes negative as oil prices will drop in future years relative to a case of no carbon tax. The net present value of producer and consumer surplus decrease by roughly equal amounts, which are almost entirely offset by increased tax revenues.

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There is almost universal agreement amongst economists who write about climate change that the introduction of a carbon tax would be a move in the right direction. The Brookings Institution has a publication entitled “The Many Benefits of a Carbon Tax” (Morris (Adele Morris n.d.)): the New York Times reported that “Republican Group Calls for Carbon Tax” (2/7/17), and the Financial Times noted that “Leading Corporations Support US Carbon Tax” (6/20/17). The Carbon Pricing Leadership Coalition[1] is a coalition of international and national organizations and corporations dedicated to promoting a carbon tax. The thinking behind this is based on Pigou’s work (Arthur Cecil Pigou 1920): the aim is to internalize the external costs associated with the release of greenhouse gases by combustion of fossil fuels. Every environmental economics text sees the internalization of external costs as a necessary step on the road the efficiency. The Pigouvian framework is the default when it comes to thinking about environmental policy. But when it comes to thinking about exhaustible resources, which include all fossil fuels, there is another significant framework, introduced by Harold Hotelling (1931).

The point we are making in this paper is that these two frameworks lead to rather different conclusions when it comes to thinking about the effectiveness of a carbon tax. Pigou emphasizes the impact of a tax on substitution between commodities, in this case between energy sources. Hotelling on the other hand emphasizes the impact of a tax on an exhaustible resource on the time-path of consumption of that resource. It can lead to the substitution from present to future consumption, so that less of the resource is consumed by any date but the same amount is consumed overall. One of the clear conclusions of the Hotelling model of equilibrium in a resource market is that if there is a substitute for the resource - think of renewable energy - available at a price in excess of the marginal extraction cost of the resource, then all of the resource will be consumed eventually, and a carbon tax can only change this under rather stringent conditions. Carbon taxes appear less clearly beneficial in the Hotelling framework than in the Pigouvian.

Ultimately, section 4 takes our model to data. As we briefly argue below, a carbon tax will make coal consumption unprofitable and hence eliminate CO_2 emissions. However, the effect on oil is less clear. We focus on the oil market, which includes large scarcity rents and is easily traded globally. We study the effect of a carbon tax using proprietary data on the cost structure of oil fields from Rystad Energy’s UCube product and publicly available data on oil consumption from the Energy Information Agency.

The oil market by itself is interesting, as recent estimates have argued consuming all oil

[1] www.carbonpricingleadership.org

would use up the entire carbon budget that is left to keep the world within 2°C warming (Richard J. Millar, Jan S. Fuglestvedt, Pierre Friedlingstein, Joeri Rogelj, Michael J. Grubb, H. Damon Matthews, Ragnhild B. Skeie, Piers M. Forster, David J. Frame & Myles R. Allen 2017). Scarcity rents for oil are so high that only few oil fields will drop out of the market for moderate carbon taxes. For example, a carbon tax as high as $200 will eliminate only 4% of oil production. An oil field becomes no longer profitable if the extraction costs exceed the backstop (or choke) price minus the carbon tax. Lowering the backstop price (e.g., cheaper renewables) is equivalent to a carbon tax and might be used in combination with a carbon tax. About three quarters of tax will initially be passed on to consumers, but this incidence declines over time and even becomes negative as oil consumption is shifted from the present to the future under a carbon tax, decreasing the price of oil by the end of the century compared to a case without a tax. This makes the political economy of a global carbon tax difficult, as the costs are highest on immediate users. In present value discounted terms, producers and consumers roughly split the cost of a carbon tax, i.e., they face similar declines in surplus. The limited response in cumulative oil consumption implies that almost all losses in consumer and producer surplus are offset by higher tax revenue. Net exporters of oil are predicted to see welfare declines, while net importers see welfare increases.

These empirical results are a direct result of exhaustible resource models. After a brief literature review in section 1 we review the underlying theory in section 2. We start in section 2.1 with a basic model in which we explore the impact of a carbon tax on the time pattern of use of a fossil fuel facing competition from a renewable energy source which is a perfect substitute and is available at a price in excess of the marginal extraction cost of the fuel, and show that one of two outcomes must hold: either the tax has no impact on cumulative consumption of the fossil fuel, though it does delay it; or it prevents any consumption of the fuel at all. The two energy sources will never be used simultaneously. We then (section 2.2) modify the model to reflect the fact that the renewable resource is only an imperfect substitute for the fuel. In this case we find that the fossil fuel and the renewable resource are used simultaneously, but the earlier basic conclusion still holds: a tax will either stop the consumption of the fuel altogether, or merely delays it. Section 2.3 looks at the consequences of introducing fixed costs in the extraction of fossil fuels, as well as variable costs. In this case a carbon tax may lead to a reduction in the total consumption of fossil fuels because the net revenues from their sales no longer offer an adequate return on the investment in the fixed cost. In section 2.4 we consider the more realistic, yet also more complex, case of multiple grades of the fossil fuel differing in their extraction costs. Here we find that a rise in a carbon tax may delay the consumption of the less expensive grades and eliminate from the market altogether the more expensive grades, thereby reducing greenhouse gas emissions. In section 2.5 we look at the case of a fossil fuel whose extraction costs today are a function of cumulative extraction to date, a framework that leads to conclusions similar to those of section 2.4: total extraction may be reduced. The overall conclusion is that there are two dimensions to the impact of a carbon tax: delaying the consumption of fossil fuels, and eliminating expensive fuels (expensive in either fixed or variable costs) from the market. Only the latter reduces greenhouse gas emissions, and in some cases only the former mechanism will be effective. In section 3 we extend our model to consider the impact of a cap and trade system on emissions from fossil fuels (an approach based on the ideas of Coase (Ronald Coase 1960) about the role of property rights in controlling externalities), and show that by fixing the allowable quantity it attains the objective of reducing emissions, but even modest quantity reductions imply a steep permit price. If permits are auctioned off and not grandfathered, it has the effect of expropriating the scarcity rents associated with exhaustible fossil fuels.

1 Literature Review

The impact of taxation on the pattern of resource use was discussed in the 1970s by Partha Dasgupta & Geoffrey Heal (1979) and Parth Dasgupta, Geoffrey Heal & Joseph Stiglitz (1980) using the Hotelling framework. These papers pre-date concerns about climate change and greenhouse gases, and focused on the impact of taxation on the time pattern of resource use in a continuous-time infinite-horizon competitive equilibrium. There was no specific discussion of a carbon tax, with the focus being on sales and profits taxes and depreciation and depletion regimes. These papers showed that, to quote, "there exists a pattern of taxation which can generate essentially any desired pattern of resource usage" (Dasgupta, Heal & Stiglitz 1980). In other words, an appropriate system of taxation can produce any time pattern of use of a fossil fuel. But in all of these patterns, all of the fuel will be used up: cumulative use, and so emissions, will thus be the same in all. Only their distribution over time will differ from one case to the other. This is consistent with our finding that in the basic Hotelling model a carbon tax can change the time pattern of fuel use but not alter the total use and therefore not alter cumulative greenhouse gas emissions.

A later literature on the "green paradox" (Hans-Werner Sinn 2015, Hans-Werner Sinn 2012, Michael Hoel 2012, Michael Hoel 2010, Sven Jensen, Kristina Mohlin, Karen Pittel &

Thomas Sterner 2015, Robert Cairns 2012) asks whether policies that are intended to reduce greenhouse gas emissions could in fact have the opposite effect: could they actually promote emissions? The literature arrives at a positive conclusion, noting that an expectation of rising taxes on fossil fuels will lead to an increase in the rate at which they are used (Sinn 2012). This is consistent with earlier findings: Dasgupta Heal and Stiglitz find that "...the effects of tax structure on patterns of extraction are critically dependent on expectations concerning future taxation." They show that a sales tax that rises over time will lead to more rapid use of an exhaustible resource, and vice versa, which is essentially the green paradox.

Reyer Gerlagh (2010) distinguishes between weak and strong green paradoxes: the weak paradox occurs when policies increase near-term carbon emissions, but not total emissions. The strong paradox is used for cases when total emissions are increased. In the models considered in this paper there are no strong green paradoxes, and weak ones occur only if there is an increase in the tax rate over time. Carbon taxes either have no impact on total emissions or reduce them. Rick van der Ploeg & Cees Withagen (2010) and Rick van der Ploeg & Cees Withagen (2015) show that the anticipation of a drop in the price of renewable energy may also generate a green paradox, encouraging the more rapid use of fossil fuels. Hoel (2012) considers a model in which the cost of extraction of a fossil fuel depends on the cumulative extraction to date using the formulation of Geoffrey Heal (1976), and shows that in this case a carbon tax can reduce total greenhouse gas emissions. This is analogous to our results in sections 2.4 and 2.5, where we consider multiple grades of a fossil fuel differing in their extraction costs.

2 Model

2.1 Basic Model

There is a stock $S_0 > 0$ of a fossil fuel, selling at a market price p_t at date t in a competitive market. Its marginal extraction cost is constant at $m > 0$ and its price p_t is given by

$$p_t = h_t + m + \tau \tag{2.1}$$

where τ is a per unit tax rate that must be paid on sales of the fuel. This is a carbon tax, meaning that it is calculated from the carbon released when the fuel is burned: it does not depend on the value of the product. h_t is the scarcity rent or Hotelling rent on the fuel, or its net price after extraction and paying the tax, and we know that in a competitive market equilibrium this will rise exponentially at the prevailing interest rate r (Dasgupta & Heal 1979, chapter 6). Hence

$$p_t = h_0 e^{rt} + m + \tau \tag{2.2}$$

In addition to the fossil fuel there is a renewable resource available in unlimited amounts at a marginal and average cost of $R > m$. This is a perfect substitute for the fossil fuel (it is a "backstop technology" in the terminology of Dasgupta & Heal (1979)), so that if the fuel is consumed we must have

$$p_t \leqq R \tag{2.3}$$

Demand for the fuel is given by the demand function $D(p_t)$. We are interested in the competitive equilibrium dynamics of prices and demand for the fuel, and how these are affected by the carbon tax. We know that the market price of the fuel will rise exponentially away from $m + \tau$ at rate r, as given in (2.2), and that $p_t = h_0 e^{rt} + m + \tau \leqq R$ if the fuel is sold.

Proposition 1. *Assuming perfect substitutability between the fossil fuel and renewable energy, a dynamic competitive equilibrium with a carbon tax τ, $m + \tau < R$, is characterized by the equations (2.4) and (2.5). These determine the initial rental rate h_0 and the date T at which $p_t = R$ and the fossil fuel is exhausted. There is no interval of time over which the fossil fuel and the renewable energy source are both used. If the tax rate is raised to $\tau' > \tau$, $m + \tau' < R$, then the above remains true so that total fossil fuel consumption is not changed. Such a tax increase decreases the initial rental rate h_0 and increases the date T at which the fossil fuel is exhausted. If the tax is so high that $m + \tau > R$ then the fossil fuel is never consumed.*

Proof. For all markets for the fuel to clear it is necessary and sufficient that the time T at which $p_t = R$ and the initial Hotelling rent h_0 satisfy the following two equations:

$$\int_0^T D(p_t)\, dt = \int_0^T D\left(h_0 e^{rt} + m + \tau\right) dt = S_0 \tag{2.4}$$

and

$$p_T = h_0 e^{rT} + m + \tau = R \tag{2.5}$$

Equation (2.4) tells us that demand equals supply cumulatively over time, and equation (2.5) tells us that the price of the fuel never exceeds that of the renewable energy source and becomes equal to it just as the total amount of the fossil fuel is used up. Continuity of the price over the transition from the fossil fuel to the renewable energy source is necessary for competitive equilibrium: if there were a jump in price sellers would withhold supply in anticipation of capital gains, meaning that the path with a jump was not an equilibrium. These two equations can be solved for the two unknowns h_0 and T, the initial resource rent and the date at which the resource is exhausted and the economy transits to renewable energy. Equation (2.5) gives

$$h_0 = (R - m - \tau)\, e^{-rT} \tag{2.6}$$

and we can use this in equation (2.4) to solve for T.

It is clear that as long as $m + \tau < R$ the competitive equilibrium will involve a period $[0, T]$ during which only the fossil fuel is consumed and then a period from T onwards during which only renewable energy is used, and that over the interval $[0, T]$ all of the fossil fuel will be consumed.

An alternative is that the tax τ is so high that $m + \tau > R$, in which case the fossil fuel will never be consumed.[2] Hence we conclude that a carbon tax either delays consumption of the fossil fuel but does not change total cumulative consumption, or alternatively reduces the consumption of the fossil fuel to zero. There is no intermediate case in which the tax reduces the total consumption of the fossil fuel but not to zero.

We can use (2.6) in (2.4) to get

$$\int_0^T D\left([R - m - \tau]\, e^{r(\tau - T)} + m + \tau\right) = S_0 \tag{2.7}$$

and from this we can compute comparative statics with respect to the tax rate τ. It is clear from this that $\partial T / \partial \tau > 0$ and from (2.6) that $\partial h_0 / \partial \tau < 0$, as asserted in the proposition. This means that an increase in the carbon tax rate will extend the economic life of the fossil fuel, reducing its consumption rate at any date, and will reduce the rent it earns at all dates. $\square$

There is a simple intuition behind this result. Suppose to the contrary that at time T we have $p_T = R$ and $\int_0^T D(p_t)\, dt < S_0$, so that a stock of unsold fuel remains. Its price is now constant so that the rate of return to holding it is zero. But agents will only hold this stock if it offers a return equal to the available elsewhere - r - so the stock will be dumped on the market, meaning that the market was not originally in equilibrium. Hence there cannot be a market equilibrium in which stocks of the fossil fuel remain unsold, as long as

[2] See also Hoel (2012) for a discussion of this case: he refers to such a tax as a "high tax."

$m + \tau < R$. If the reverse inequality holds then the fuel is valueless and stocks will never be purchased in the first place. Provided that the marginal extraction cost plus tax is less than the price of the renewable energy source, all of the fossil fuel will be consumed, as it will always be profitable to extract and sell it. No change in the tax rate - as long as it satisfies the condition $m + \tau < R$ - will alter this. Another way of thinking about this is that with a normal produced good, a tax would reduce the net price received by the maker and reduce output along the supply curve. With an exhaustible resource there is no supply curve: the resource is there whatever the price and is profitable as long as $m + \tau < R$.

2.2 Imperfect Substitutability

Given what we observe in the world around us, the results above seem surprising: we see both renewable energy and fossil fuels in the market at the same time, rather than the abrupt switch from one to the other that the model predicts. There are several possible reasons for this discrepancy. Principal amongst them is that we have assumed that fossil fuels and renewable resources are perfect substitutes, so that demand switches completely from one to the other as the ordering of their prices changes. In reality this is not the case: renewable energy is intermittent, which is a disadvantage relative to fossil energy, but is clean, producing no pollutants that damage the local environment and no greenhouse gases. Because of these factors we can imagine situations where renewable energy is used even if it is more expensive (situations where there is a need to reduce local pollution, or to reduce greenhouse gas emissions) and conversely situations where a fossil energy such as natural gas is used even though it is more costly (for example gas is used to back up intermittent renewable energy). To try to capture these possibilities, we now modify the demand for fossil fuels to show that it depends not only on its own price p_t but also on the price of renewable energy R: $D(p_t, R)$, $\partial D / \partial R > 0$. This admits the possible co-existence of both energy sources in the market simultaneously, with demand transferring from one to the other as the price difference changes. We assume the demand function to have a "choke price" $\bar{p}(R)$ such that demand for the fossil fuel falls to zero when its price reaches $\bar{p}(R)$. So $D(\bar{p}(R), R) = 0$. Obviously, the choke price depends on the price of the substitute. In the previous analysis $\bar{p}(R) = R$. Clearly we expect that $\bar{p}(R)$ is increasing in R.

It is still the case that in equilibrium the price of the fossil fuel will be given by 2.2, with the Hotelling rent rising exponentially at the interest rate. For all markets for the fuel to clear it is now necessary and sufficient that the time T at which the price of the fuel equals its choke price, $p_T = \bar{p}(R)$, and the initial Hotelling rent h_0 satisfy the following two equations:

$$\int_0^T D(p_t)\,dt = \int_0^T D\left(h_0 e^{rt} + m + \tau\right) dt = S_0 \tag{2.8}$$

$$p_T = h_0 e^{rT} + m + \tau = \bar{p}(R) \tag{2.9}$$

These equations are the same as 2.4 and 2.5 except that the price of the renewable resource has been replaced by the choke price, a function of the price of the renewable resource.[3] As in the earlier case, these two equations have two unknowns, h_0 and T, and can be solved for these.

This framework leads to similar conclusions to the previous one, except that the transition from the fossil fuel to the renewable resource is now smooth rather than abrupt.

Proposition 2. *Assuming imperfect substitutability between the fossil fuel and renewable energy reflected in the demand function $D(p_t, R)$ with choke price $\bar{p}(R)$, a dynamic competitive equilibrium with a carbon tax τ, $m + \tau < \bar{p}(R)$, is characterized by the equations 2.10 and 2.11. These determine the initial rental rate h_0 and the date T at which $p_t = \bar{p}(R)$ and the fossil fuel is exhausted. If the tax rate is raised to $\tau' > \tau$, $m + \tau' < \bar{p}(R)$, then the above remains true so that total fossil fuel consumption is not changed. If the tax is so high that $m + \tau > \bar{p}(R)$ then the fossil fuel is never consumed.*

Proof. For all markets for the fuel to clear it is necessary and sufficient that the time T at which $p_t = \bar{p}(R)$ and the initial Hotelling rent h_0 satisfy the following two equations analogous to 2.4 and 2.5:

$$\int_0^T D(p_t, R)\,dt = \int_0^T D\left(h_0 e^{rt} + m + \tau, R\right) dt = S_0 \tag{2.10}$$

$$p_T = h_0 e^{rT} + m + \tau = \bar{p}(R) \tag{2.11}$$

The rest of the argument is as in Proposition 1, except that it is now possible that the fossil fuel and renewable energy are used simultaneously. □

The important point here is that even with imperfect substitutability and the co-existence of both products in the market, a carbon tax will not affect the total cumulative consumption of the fossil fuel. The intuition is exactly as before. Renewable energy may be substituted for the fossil fuel, but this will merely spread out the consumption of the fuel over time and

[3] Depletion of the fuel before its choke price is reached is inconsistent with profit-maximization.

will not reduce total consumption. We can also show, as in Proposition 1, that an increase in the tax rate will increase T and lower the initial rent h_0.

2.3 Fixed Costs of Extraction

So far, we have assumed that all the costs of extracting the fossil fuel are variable costs, with a marginal extraction cost of $m > 0$. Suppose in addition that there is a fixed cost $F > 0$ that must be incurred before the fuel can be extracted at a marginal cost of m. This could be the cost of finding and developing an oil or gas field, a cost that in practice can be substantial. Could this alter our conclusions?

In this case the fuel will only be produced if the price is high enough to cover the tax, extraction cost and fixed cost. The time path of the fuel price will still be given by 2.2, so now we require that

$$\int_0^T (p_t - m - \tau)\, dt = \int_0^T h_0 e^{rt} \geq F \tag{2.12}$$

Market clearing conditions are still given by equations 2.10 and 2.11, and the constraint 2.12 introduces the possibility that an increase in the tax rate could make it impossible to satisfy the constraint 2.12. Integrating 2.12 gives

$$e^{rT} \geq \frac{rF}{h_0} + 1 \tag{2.13}$$

and in this inequality F and r are exogenously given and T and h_0 are given by market clearing equations 2.10 and 2.11. It is clear that these values of the variables and parameters need not satisfy 2.13. The introduction of fixed costs in the extraction technology therefore gives another mechanism via which a carbon tax might prevent the extraction of the fossil fuel, but once again if the fuel is extracted at all then it will all be extracted. If there is an initial tax rate at which extraction is profitable - i.e. 2.13 is satisfied - but after extraction has begun the tax is increased to a point where this is no longer true, extraction will continue provided that $m + \tau < \bar{p}(R)$.

2.4 Multiple Grades of Fossil Fuel

Another case of interest is that of multiple sources of the fossil fuel, with different extraction costs. Suppose we modify the model of section 2.1 so that there are I different fuel sources each with marginal extraction cost m_i and let them be numbered in increasing order of extraction costs, so that $m_1 < m_2 < m_3 < ..... < m_I$ and further assume that $m_I < R$ so all are less expensive than the renewable resource. (Others will never be used and can be neglected.) The initial stock of the $i - th$ fuel is $S_{i,0}$. The competitive equilibrium outcome is that there exist dates $T_i,\ i = 1, 2, ...I,\ T_i < T_{i+1}$, and initial rents $h_{0,i},\ i = 1, 2, ..., I$ such that for all i,

$$p_{i,t} = m_i + \tau + h_{i,0}e^{rt},\ T_{i-1} \leq t \leq T_i \tag{2.14}$$

and

$$\int_{T_{i-1}}^{T_i} D\left(p_{i,t}\right) dt = S_{i,0} \tag{2.15}$$

So each grade of fuel i is used over the interval $T_{i-1} \leq t \leq T_i$ and is used only during this interval and is used up by the end of this interval. The least expensive fuel is used up first and the most expensive last (Dasgupta & Heal 1979, page 172 section (iii)). This reference also shows that the price moves continuously so that

$$p_{i,T_i} = m_i + \tau + h_{i,0}e^{rT_i} = p_{i+1,T_i} = m_{i+1} + \tau + h_{i+1,0}e^{rT_i}\ \forall i \tag{2.16}$$

and we must have the last price of the fuel equal to that of renewable energy:

$$p_{I,T_I} = R \tag{2.17}$$

In this case the impacts of a carbon tax are essentially the same as before: provided that $m_i + \tau < R$, a tax increase will merely delay the consumption of the fossil fuel, but will not alter cumulative consumption. However if there are many grades of fossil fuel with different costs, it is possible that the more expensive of them have costs close to R, in which case a tax increase could lead to $m_j + \tau > R$ for some grade j, in which case fuel of grade j will not be produced and cumulative emissions will fall. Because of the existence of multiple grade of fuel we no longer have the earlier all-or-nothing impact of a tax rise: it can now lead to the elimination of some but not all of greenhouse gas emissions by pushing out of the market the more costly fossil fuels.

Clearly we can combine the results of proposition 2 of section 2.2 on imperfect substitutability with those of this section to consider the effect of taxation when there are multiple grades of fossil fuel, all of which are perfect substitutes for each other but imperfect substitutes for renewable energy, as in section 2.2. Because the different grades are perfect substitutes for each other, they must sell at the same price, which means that only one can be on the market at any time. As in section 2.2 there is a choke price $\bar{p}\left(R\right)$ for the fuel (the same for all grades as they are perfect substitutes). Now we have an equilibrium in which different grades of the fuel are exhausted sequentially from least to most expensive, with the use of some of them overlapping with that of the renewable energy source. So an equilibrium is characterized by dates T_i, $i = 1, 2, ...I$, $T_i < T_{i+1}$, and initial rents $h_{0,i}$, $i = 1, 2, ..., I$ such that for all i,

$$p_{i,t} = m_i + \tau + h_{i,0}e^{rt},\ T_{i-1} \leq t \leq T_i \tag{2.18}$$

and

$$\int_{T_{i-1}}^{T_i} D\left(p_{i,t}\right) dt = S_{i,0} \tag{2.19}$$

and continuity of prices with the last price of the fuel being its choke price:

$$p_{i,T_i} = m_i + \tau + h_{i,0}e^{rT_i} = p_{i+1,T_i} = m_{i+1} + \tau + h_{i+1,0}e^{rT_i}\ \forall i,\ p_{I,T_I} = \bar{p}\left(R\right) \tag{2.20}$$

In this case the tax will lead to lower emissions at any date and to lower emissions in total over time if it displaces one or more of the expensive grades of the fuel.

2.5 Extraction-Dependent Costs

The last case we will look at is that of a fuel whose extraction cost is a function of cumulative extraction to date. The motivation for such an assumption is clear: there are many grades of the resource that vary in extraction costs, and the lowest cost grades, those that are easiest to extract, are removed first, driving up costs as extraction increases. This is similar to the case considered in the last section, except that the problem is formulated in a continuously variable framework and there is an explicit dependence of current costs on past extraction, implying that current policies can alter future costs and this needs to be considered in deciding how much to extract now. We assume that the resource extraction at date t is given by $E_t \geq 0$, and that cumulative extraction is denoted $z_t = \int_0^t E_\kappa d\kappa$. The total amount of the resource is $\hat{z}$, so $z_t \leq \hat{z}$. As before R denotes the cost of a renewable substitute for the resource. Extraction costs at time t, c_t, are given as follows:

$$c_t = g\left(z_t\right),\ g\left(z_t\right) \leq R:\ c_t = R,\ g\left(z\right) > R:\ g'\left(z\right) = \frac{dg}{dz} > 0 \tag{2.21}$$

So the cost of extraction is given by the increasing function $g\left(z\right)$ as long as it is less than the cost of the renewable resource and after that only the renewable resource is used. This is the formulation used in Heal (1976), and also in Hoel (2012), who also studies the effect of a carbon tax in this framework, focusing on the consequences of a tax that changes over time.

In a competitive equilibrium there are potentially two regimes: in the first the resource is extracted and its extraction cost is less than or equal to the cost of the renewable resource, which is not used, and in the second the resource is either exhausted (the case when $g(\hat{z}) \leq R$) and only the renewable resource is used, or alternatively the cost of the resource exceeds that of the renewable resource and again only the latter is used. The first regime will exist as long as $g(0) < R$.

As before let the carbon tax rate be τ, so that the total cost of bringing the resource to market is $c(z_t) = g(z_t) + \tau$. Let p be the market price of the resource and p_o the price of a generic output good produced from the resource. Then we can establish the following

Proposition 3. *The market price of the resource in the first regime satisfies the following equation*

$$\frac{\dot{p}}{p} = \delta\left(\frac{p-c}{p}\right) + \frac{\dot{p}_o}{p_o}\frac{c}{p} \tag{2.22}$$

Proof. An extension of the proof in (Heal 1976). □

This proposition has a simple interpretation. The resource price rises at a rate which is a weighted average of the discount rate and the rate at which the output price is increasing, where the weight on the discount rate is the fraction of the price made up of rent and the weight on the rate of change of the output price is the fraction of price made up of costs. So if extraction costs are zero we have the pure Hotelling case, and if extraction costs are non-zero but constant, as in section 2.1, the output price is constant and we have the rent rising at the discount rate. The resource price will rise according to this rule until either the resource is exhausted or the price reaches that of the renewable resource and society switches to that: if this happens before resource exhaustion then unused stocks of the resource remain.

In this context the impact of a carbon tax is easily understood: it raises the extraction cost $c(z_t)$. The fossil fuel will cease to be used as soon as its cost including tax exceeds that of the renewable resource, i.e. as soon as

$$c(z_t) = g(z_t) + \tau \geq R \tag{2.23}$$

or

$$z \geq z^* = g^{-1}[R-\tau] \tag{2.24}$$

As g is increasing, so is g^{-1}, so an increase in the tax rate τ may reduce z^* the level of cumulative extraction at which the fossil resource ceases to be competitive. There are two cases: if $g(\hat{z}) + \tau < R$ then the tax has no impact on the amount of the fossil fuel used, as it is not sufficient to raise the extraction cost above the cost of the renewable resource. If however $g(\hat{z}) + \tau > R$ then the tax does reduce total consumption of the fossil resource, setting a bound on cumulative extraction at $\widetilde{z}$, $g(\widetilde{z}) = R - \tau$, $\widetilde{z} < \hat{z}$.

3 Cap and Trade

The widely-considered alternative to a carbon tax is a cap-and-trade (C&T) system, and next we review the operation of such a system in the context of a Hotelling model. We first work with a simplified version of the basic model of section 2.1, and then consider the impact of various refinements. There is a stock $S_0 > 0$ of a fossil fuel, selling at a market price p_t at date t in a competitive market. There is no carbon tax and we take marginal extraction costs to be zero for the moment. Hence the price satisfies $p_t = p_0 e^{rt}$ where the initial price p_0 satisfies

$$\int_0^\infty D\left(p_0 e^{rt}\right) = S_0 \tag{3.1}$$

Consumption of a unit of the fossil fuel emits one unit of greenhouse gas, and an environmental authority imposes a cap of K_0 units on the total cumulative emissions of greenhouse gases. This implies that

$$\int_0^\infty D\left(p_0 e^{rt}\right) \leq K_0 \tag{3.2}$$

This formulation means that permits can be banked, that is carried over freely from one period to the next, so that the constraint is on total cumulative emissions and not on period-by-period emissions. Clearly one of the equations 3.1 and 3.2 is redundant: if $S_0 < K_0$ then the emissions constraint is redundant, and in the more likely case that the reverse is true, namely $K_0 < S_0$, some of the fossil fuel will be left unused and the binding constraint will be that $\int_0^\infty D\left(p_0 e^{rt}\right) = K_0$. In this case the scarcity rent associated with the constraint 3.1 will be zero, but a positive scarcity rent will be associated with the emissions constraint 3.2. So in a market equilibrium, the price of the fossil fuel will be zero but there will be a price for emissions permits. As such permits are an exhaustible resource, their price will move exactly as the price of such a resource. Letting the permit price be r_t, this will satisfy $r_t = r_0 e^{rt}$ and $\int_0^\infty D\left(r_0 e^{rt}\right) = K_0$. The key point to understand here is that the presence of a binding cap on emissions from the fossil fuel reduces the rent on the resource to zero and all of the rent is now captured by the permit price. So the agency that auctions permits now captures all of the scarcity rent that previously accrued to the resource owners. Financially speaking, the resource has been fully expropriated.

Now suppose that as in section 2.1 there is a positive cost $m > 0$ to extracting the fossil fuel. In the absence of a cap and trade system, Proposition 1 would hold, and the rent on the resource would rise at the interest rate, with the stock of the resource being exhausted at exactly when the price first equals that of the backstop technology if there is one. But if as in the previous paragraph there is a cap and trade system with the cap on emissions tight enough that not all of the fossil fuel can be consumed, matters are again more complex. Letting r_t be as before the price of a permit at time t, in selling a unit of fossil fuel at time t the owner incurs costs of m to extract it and r_t to buy a permit, so that her cost is $m + r_t$. Permits are as before an exhaustible resource, so that their price will rise at the interest rate, so that the resource seller's costs move over time as $m + r_0 e^{rt}$, where the initial permit price r_0 will as before be chosen so that $\int_0^\infty D\left(r_0 e^{rt}\right) = K_0$. Once again the scarcity rent on the fossil fuel is reduced to zero and is replaced by the scarcity value of the emission permits, so again the fuel is effectively expropriated.

If there is heterogeneity in extraction cost m_i among reserves (section 2.4), owners of the cheaper reserves will retain some of their rents, as the price of the permit is given by reserve owner who is on the margin between producing or not producing. As we will show in the empirical section below, the convexity of the marginal cost curve implies that a modest reduction in cumulative oil consumption would expropriate a significant share of the scarcity rents.

Finally, we consider a more complex case: above the emissions permits were infinitely bankable, that is could be used at any point in time. In reality permits generally have a finite life, so we analyze the outcome in this case. To be precise, we assume that the environmental authority issues two sets of permits: one set are valid from time zero to time T, and the others from T onwards forever. Permits issued at time zero lose all value at time T, and cover in total K_0 units of emissions. The permits issued at date T cover a total of K_T units of emissions. We will take the marginal extraction cost to be zero, so that $m = 0$. Let q_t^* be the competitive equilibrium consumption of the fuel at date t in the absence of any policy interventions, i.e. with no cap and trade system or tax, and let $Q_0^T = \int_0^T q_t^* dt$, $Q_T^\infty = \int_T^\infty q_t^* dt$. We will for the moment take it that $K_0 = \infty$, and $K_T < Q_T^\infty$, so that there is no constraint on emissions from zero to T and the cap on emissions after T is less than would be consumed on the competitive path from that date onwards. In this situation, what is the competitive path of consumption (and emissions) from zero to T, assuming that all players in the market at date zero are aware of the cap that comes into effect at T? The total amount of fuel available for consumption over $[0, T]$ is $S_0 - K_T$ and the competitive path is one on which just this amount is consumed over that time period. So the price path $\tilde{p}_t$ satisfies

$$\int_0^T D\left(\tilde{p}_0 e^{rt}\right) dt = S_0 - K_T \tag{3.3}$$

($\tilde{p}_0$ is the only unknown in this equation, which we assume to have a solution.) In this case the amount left at time T is exactly equal to the cap under the C&T system and the price of the fuel post-T will rise at the interest rate as in a competitive equilibrium. There will be a drop in consumption and a jump in the price at T, which will be fully anticipated but will not give rise to arbitrage as no fuel can be transferred from before to after T because of the cap.

Now suppose that $K_0 < S_0 - K_T$ so that the solution we have just described is not permitted. In the earlier period $[0, T]$ the permit constraint is binding, not the resource constraint. In this case the resource price will be zero and the permit price will be positive. Permits for the period $[0, T]$ are an exhaustible resource over that period, and their competitive price will rise at the interest rate from 0 to T from an initial level such that the stock K_0 of $[0, T]$ permits is just exhausted at T. Once again, the C&T system transfers value from the resource market to the permit market. After T the emissions constraint is again binding, as $K_T < S_0 - K_0$, so that again the price of the resource is zero and all scarcity rent is captured in the permit market.

4 Numerical Analysis: Extraction Costs and Tax Rates

We now simulate the effect of a carbon tax on long-term oil consumption and prices. Earlier studies have used short-term variation in the price ratios between natural gas and coal to estimate the reduction in CO_2 emissions from the electricity sector as prices rise and found a very inelastic short-term elasticity (Joseph A. Cullen & Erin T. Mansur 2017). Similarly, imperfect competition in the railway market might imply that not all the cost of a carbon tax will be passed on to coal purchases (Louis Preonas 2019). Our paper focuses on long-term implications of a carbon tax, abstracting from market imperfections in the oil market. We also abstract from short-term influences, e.g., political unrest or demand shocks. For example, Soren T. Anderson, Ryan Kellogg & Stephen W. Salant (2018) have shown that once an oil field is set up for production, it is often costly to halt production, violating one of the assumptions of the classical Hotelling model that oil can be produced at any time. Development of new wells respond to prices, but production of existing wells does so to a lesser degree. This can lead to different short-term dynamics. Since we are interested in the optimal exploration path over the next 100 years under various carbon taxes, we abstract from these short-term influences.

To get a sense of the empirical significance of our analysis and understand the impact of a carbon tax on fossil fuels, we need to know how much CO_2 each type of fuel releases when burned. Table 1 gives this data for coal, gas and crude oil. For one metric ton of coal (MT), one million BTU of gas (MMBTU), and one barrel of oil (BBL), it shows how much CO_2 is emitted when this is burned.[4] There is a range of estimates for how much CO_2 will be released when one barrel of oil is burned. It depends on the exact composition of the fuel and the process by which it is burned. We give the baseline number underlying the Canadian carbon tax. The table also gives the current US price in dollars, and the amount that a \$50 carbon tax would raise per unit of the fuel.

Looking at the numbers in Table 1, it is very clear that the effect of a \$50 carbon tax is potentially much greater in relative terms on coal than on oil: for coal the tax is \$143 per metric ton of coal, while the current price is around \$50. The tax is almost three times the current price. The tax on natural gas is \$2.65 million BTU, while the wholesale price that is just under \$3, i.e., the tax almost equals the price. For oil, however, the tax is about \$17.6 per barrel and the market price around \$65, i.e., the tax equals around a third of the current price.

All three of these fuels are exhaustible resources, so that the earlier analysis is applicable to all of them. Whether reserves drop out of the market depends on the price of the backstop or choke price, whichever is lower. We therefore need to assess whether a carbon tax will increase the MEC - regarding the tax as a part of the MEC - to the point where it is unprofitable to extract the resource. For coal, adding a \$50 carbon tax would roughly quadruple the current price, very likely deeming it uncompetitive, especially relative to natural gas. For natural gas, the answer depends on the circumstances. It is widely assumed in the oil and gas industry that most gas producers are losing money at the current price of \$3 per MMBTU, implying that average costs exceed \$3, though the marginal costs of

[4] The exact carbon content depends on the composition of the fuel. We quote some estimates to highlight the order of magnitude. For gas see https://www.eia.gov/tools/faqs/faq.php?id=73&t=11, for coal see https://www.eia.gov/coal/production/quarterly/co2_article/co2.html, and for gasoline see https://www.canada.ca/en/department-finance/news/2018/10/backgrounder-fuel-charge-rates-in-listed-provinces-and-territories.html

gas are generally low. One source gives operating costs as 34% of total costs for an average shale gas field, and if this field is breaking even at $3 then we have an operating or marginal cost of $1.[5] In those few cases in which gas is an unintended byproduct of oil production ("associated gas"), one could make an argument that the gas effectively has a zero marginal cost. About 20% of US gas is associated gas[6]. Gas prices in Europe tend to be much higher, as they used to be in the US before the shale boom. Some natural gas might still be used even under carbon tax, but the transportation cost are higher than for oil and hence the market seems to be more regional.

Oil is an interesting case study. The world price (the price of Brent marker crude) is in the mid $60s per barrel, and the US marker crude, West Texas Intermediate (WTI) is in the high $50s (as of 6/28/2019). A $50 carbon tax would imply a per-barrel charge that is roughly one third of the current price. The commodity is easily tradable, and hence the basic Hotelling framework of one global market applies.

4.1 Oil Market

Our empirical simulation of optimal oil extraction over time requires three important inputs: the marginal extraction cost of various oil field (producer side), the price of the backstop technology or choke price (R in the modeling sections above), and the demand function (demand elasticity).

For the production side, we use the proprietary data from Rystad Energy, a prominent source of micro-level data set of various oil fields around the globe. For example, it has recently been used by John Asker, Allan Collard-Wexler & Jan De Loecker (2019) to study the misallocation of oil production around the world. The data set gives estimates for roughly 15,000 discovered and 27,000 undiscovered oil "assets"' around the world. An asset is the smallest geographic scale in the data. For example, portions of an oil field can be owned by different firms, and each one of the owners will be listed as separate asset. Importantly for us, Rystad gives estimates of a breakeven price for each asset. For discovered oil fields, this only includes the variable operating cost as marginal cost, as investments in exploration and development are sunk. For undiscovered assets, it does include these costs, as initial investments are required to access these assets.[7]

[5] http://www.insightenergy.org/system/publication_files/files/000/000/067/original/RREB_Shale_Gas_final_20170315_published.pdf?1494419889

[6] See https://www.forbes.com/sites/judeclemente/2018/06/03/the-rise-of-u-s-associated-natural-gas/#73e287c04bd7

[7] More precisely, Rystad models production by each asset in future years. It assumes that oil prices are rising 2.5% per year. Rystad estimates extraction cost for all future periods, and in case for undiscovered assets, the exploration and development cost, which are sunk and not included for producing assets. Future

Figure 1 shows the supply curves for these two categories of crude oil, those already discovered and in operation are shown in dark blue, and those not yet discovered but presumed to exists in light blue. We focus first on the assets already discovered and in operation. The supply curve becomes essentially vertical at a cost of around \$65 and a quantity of just under 1 trillion barrels. Annual global oil consumption is about 36 billion barrels, so the world has about 30 years of oil available at an MEC of \$65 or less.

There are roughly an additional 0.8 trillion barrels available in undiscovered crude oil. These tend to be higher cost. As modeling section 2.4 has shown, the optimal extraction path should first extract the cheaper oil fields, while more expensive ones are developed later. Estimates by Rystad list resources with cost up to \$250 per barrel as viable for future extraction, suggesting the backstop price R is roughly four times the current price. In our simulation, we therefore assume in our baseline that $R = 250$.

We follow James D. Hamilton (2009, Table 3) for the demand function and use a baseline long-term elasticity of -0.6, the average long-term elasticity given in the table, assuming iso-elastic demand curves. In sensitivity checks in Appendix Figure A1 we use the range of long-term elasticities that were listed in Hamilton (2009), ranging from -0.21 to -0.86. The elasticity has implications on the timeline of prices and quantity consumed, but not the total amount of oil that will be extracted, which only depends on the extraction cost, carbon tax, and the cost of the backstop technology.

Combining the three data sets allows us to construct the optimal extraction profile over time. We follow the theory of reserves with heterogenous cost of section 2.4. We know that the most costly reserves will be used last and that the price in the final period has to equal the cost of the backstop $R = 250$. This allows us to solve the problem backwards, going from the mostly costly to the least costly reserves (which will produce first in time). We use a daily time step.[8] Rents have to rise at the rate of interest for reserves with the same marginal cost. Once reserves of a particular quality (marginal cost) are exhausted, the price stays continuous, but the rent $h()$ jumps discontinuously by the difference in marginal extraction cost. The exact steps of this backward analysis are given in Appendix section A1.

There is one free parameter in our simulations. The parameter α of the iso-elastic demand function $q_t = \alpha p_t^{\eta}$. Once we fix the parameter, we simulate the problem backwards to obtain estimates for both the equilibrium price p_{2019} and quantity q_{2109}. We iterate over α to match current global consumption at 100 million barrels a day. Since we have two equilibrium

costs are discounted to the present using a 10% interest rate. The breakeven price is the current price that makes an asset profitable.

[8]For simplicity every year is assumed to have 365 days.

outcomes but only one parameter, there is an implicit test of the other parameter assumptions of the model: they should give us a price p_{2019} that matches the current equilibrium price. For our baseline model, i.e. a demand elasticity of -0.6, interest rate of $r = 0.03$ and backstop price of $R = 250$, the equilibrium price of 63.22 closely aligns with current market price of oil. Using parameters from the literature gives results that are internally consistent. On the other hand, if we choose the lower bound of the elasticities $\eta = -0.21$, the simulated price of 80.42 seems too high, while the upper bound of the elasticities $\eta = -0.86$, the simulated price of 52.69 seems too low.[9]

The baseline case showing the price and production path is shown as short dashed line (carbon tax = 0) in Figure 2. The dashed red line shows the increasing price path over time, rising from 63.22 a barrel to 250 when the price equals the backstop price in the final period in the year 2097, at which point the production quantity, shown in blue, falls to zero. Demand after 2097 would only come from the backstop technology (i.e., renewables). Alternative scenarios for carbon taxes ranging from \$50 to \$400 per ton of CO_2 are added as well. Higher taxes are shown in a darker shade of blue and red as shown in the legend. Not surprisingly, a carbon tax raises the price in 2019, as a portion of it is passed on to consumers. The higher price for consumers implies lower production, while the lower price for producers (consumer price minus the tax) lower resource rents $h()$ to producers. These lower resource rents now rise at the rate of interest, implying that oil prices grow more slowly than in the baseline case under no carbon tax. Interestingly, there is a point towards the end of the century when prices under the carbon tax become lower than in the baseline case without a carbon tax. The reason is that the carbon tax shifts some of the production from the present to later periods, implying a lower equilibrium price and higher production quantity. As shown in the theoretical section, the lifetime can be extended under a carbon tax, i.e., the final period will be 2100 under a \$50 carbon tax, and 2107 under a \$400 carbon tax, w3hen production again falls to zero.

The relative change in prices is shown in Figure 3. It plots the share of the carbon tax that is passed on to consumers at each point in time by comparing consumer prices under a particular carbon tax (the color coding corresponds to the price path in Figure 2) to the price path without a carbon tax. This share is initially fairly high (between 70-80% in 2019), but declines continuously as oil prices under the new equilibrium path rise more slowly than under no carbon tax. The ratio eventually becomes negative towards the end of the 21st

[9] There might of course be other combinations of α, r, R that give pairs for (p_{2019}, q_{2019}) that are consistent with the current market outcome, but we find it reassuring that the parameters from the literature seem to align with the current equilibrium.

century when oil prices fall below the level they would have been without a carbon tax. In summary, the carbon tax will initially be passed through to consumers, leading to an immediate increase in oil prices, but the passthrough declines over time and even becomes negative in later years. The cost of a carbon tax would hence be felt most significantly right away, while future generations would even see a decline in prices.

The resulting reduction in quantity extracted is shown in Figure 4. The color coding again corresponds to various quantity paths in Figure 2. The figure shows the cumulative reduction in oil use up to a given year. Since production initially declines, the curves show how cumulative extraction declines, i.e., the y-values are negative. However, prices under the carbon tax rise at a slower rate and hence the production decline becomes less over time. As a result, the cumulative savings start to level off. Towards the end of the century, when prices under a carbon tax are lower than under the counterfactual of no carbon tax, some of the cumulative reductions will be offset through higher production, i.e., the curve bends upward. Finally, the carbon tax extends the lifetime beyond 2097, the last year of extraction under no carbon tax. The curves hence show an almost linear upward trend for the additional years of production, which offset the majority of the initial cumulative savings. For example, a significant carbon tax of \$200 would decrease cumulative emissions by 13% in 2080, but these savings are offset through a prolonged production period. By the end, only 4% of the cumulative emissions are avoided. We find that the reallocation of current consumption into future periods in not only a theoretical concern, but empirically relevant.

Cumulative savings are small as the combined supply curve in Figure 1 is very steep. Any oil field will eventually be extracted under a carbon tax as long as the marginal extraction cost plus the carbon tax falls below the backstop price. In other words, only oil fields with a marginal cost higher than the backstop price minus the carbon tax will find it no longer profitable to extract oil. The convexity of the supply curve implies that as the carbon tax increases, the number of oil reserves that become no longer profitable increases non-linearly. This is shown in Figure 5. Carbon taxes that have been proposed in the past (up to \$100 a ton of CO_2) are projected to have very small reductions in cumulative oil use. For example, a \$100 tax reduces emissions by 1.6%. On the other hand, increasing the tax from \$500 to \$600 would reduce emissions by an additional 30%. Significant emission reductions are required if the world is to comply with the Paris Climate Agreement. The cumulative emissions are 200GT of carbon (Millar et al. 2017), which is equivalent to roughly 2.1 trillion barrels of oil.[10] So if the world were to use all of the 1.8 trillion barrels of oil, it would have almost

[10]200 GT of carbon are equivalent to 733 billion tons of CO_2 given the atomic mass of carbon (12) and

entirely used up the carbon budget. This does not count emissions from coal and natural gas, methane, etc. Meeting the Paris target can only be achieved if oil consumption is significantly reduced.

We present sensitivity checks under different demand elasticities in Appendix Figure A1. Note how the overall emission changes do not depend on the demand elasticity, but the time path does. A larger demand elasticity leads to temporarily larger cumulative emissions reductions as the per-period consumption drops, but these are again offset through a further extension of the time period when the resource is used. For example, under a demand elasticity of -0.86 (right column), the cumulative emission reductions under a \$200 carbon tax reach 20% instead of the 13% in our baseline using an elasticity of -0.6, but in the end only 4% less of the oil is consumed in both cases. The demand elasticity is not an important driver of our overall results.

One other important lever that we have held constant in our analysis so far is the price of the backstop R. If this backstop price becomes lower (e.g., as renewables become cheaper and storage becomes available), it would be equivalent to a carbon tax. Recall that fields will be extracted if marginal cost are less than $R - \tau$. Increasing the tax τ or decreasing R have equivalent effects. Each \$1 tax per ton of CO_2 implies a tax of roughly 35cents per barrel, so a reduction of $R = 250$ to $R = 145$ for $\Delta R = 105$ is equivalent to an additional \$300 carbon tax. For example, a \$100 carbon tax as well as lowering the backstop from $R = 250$ to $R = 145$, would be equivalent to a \$400 carbon tax. There are hence alternative scenarios that would combine a carbon tax with investments in alternative energy to decrease $R - \tau$.

4.2 Welfare Effects

We have argued that only a sizable carbon tax, or a carbon tax with advances in alternative energy that lower the cost of the backstop R have the potential to meaningfully lower oil consumption. What are the welfare consequences of various taxes? Below, we only count the direct welfare impacts in the oil market, not counting the externality reduction through limiting greenhouse gas emissions. In principle, the carbon tax should be set to equal the social cost of carbon. We are interested in the ramifications for consumers and producers on top of that. We highlight that aggregate welfare impacts are limited even without the benefit of CO_2 reductions. Figure 3 has shown that while consumers initially feel a significant price increase, over time much of the tax is paid by producers.

oxygen (16). Using the estimate from Table 1 that each barrel of oil is emits 0.35tons of CO_2, the equivalent amount of oil is 2.1 trillion barrels.

Table 2 presents the net present value of various scenarios. The first row states again the cumulative amount of oil that will be extracted under various carbon taxes. It is simply the sum of all future extraction shown in Figure 2. The next three rows present producer surplus, consumer surplus, and tax revenue, all in net present value terms again assuming a discount rate of 3%. Producer surplus is the difference between the price in each period and the extraction cost as given by Rystad (recall that for undiscovered assets these include cost for exploration and development). Our backward solution gives us how much will be produced by each asset on each day over the next 100 years as well as the price. This allows us to take the simple difference and discount it. Consumer surplus is the area under the iso-elastic demand curve between the current price and the backstop of $R = 250$, i.e., the surplus to consumers from having lower energy prices than under the backstop.[11] We use quantity and price information from Figure 2, calculate the surplus under the iso-elastic demand curve, and discount it to 2019 with a interest rate of 3%. Finally, tax revenue is the quantity consumed times the carbon tax rate, again discounted to the present.

First, note how for moderate carbon tax rates, e.g., up to \$100, the overall welfare impacts are limited to at most 1.5%. This is the flip side of the fact that a carbon tax up to \$100 does not significantly reduce overall emissions, i.e., there is limited deadweight loss from taxation (again, not counting externality reductions). The roughly equal losses to producer and consumer surplus are offset by increased tax revenue. For example, a \$100 carbon tax reduces producer surplus by 15 trillion, consumer surplus by 14 trillion, but increases tax revenues by 26 trillion, for a net surplus loss of less than 3 trillion.

Second, a carbon tax of \$500 would reduce carbon emissions by just under 30%, but expropriate most of the producers and consumer surplus. The reason is that the supply curve for oil is fairly flat for the first two thirds of oil reserves and hence producers find it still profitable to extract oil at much lower oil prices. At the same time, consumer prices (producer prices plus the tax) increase enough to also eliminate most of the consumer surplus. Combined producer and consumer surplus collapses from 144 trillion to 25 trillion, i.e., by more than 80%. This is again offset by 91 trillion in tax revenue. The flat initial supply curve implies that significant reductions in oil use are only possible when most of the consumer and producer surplus is wiped out.

We next split producer surplus changes by country in Table 3. The reduction in producer surplus is not proportional but depends on the cost structure of each country. For example, Saudi Arabia is not only one of the biggest producers, but also has really low production

[11] The formula for consumer surplus for the iso-elastic demand function is $\frac{\alpha}{1+\eta}[250^{1+\eta} - p^{1+\eta}]$

cost, resulting in high producer surplus. A carbon tax of \$200 would eliminate 38% of that surplus. On the other hand, the same carbon tax would eliminate more than 50% of Canada's surplus, as the country extracts oil from high-cost tar sands, and a comparable reduction in price hence implies a large relative reduction in rents.

Since oil demand will likely shift significantly between countries in future years, e.g., a higher share will be consumed by developing countries, an analysis of consumer surplus by country for all future years is beyond the scope of this paper as we would have to simulate the shift in consumption. Instead we present an analysis for 2016, the last year for which the Energy Information Administration is providing data for most countries at the time of writing. Table 4 list the 25 countries with the highest decrease in overall surplus under a \$50 carbon tax, while Table 5 gives the 25 countries with the highest gains. All numbers are in billion dollars. Effects on producer surplus are split into two components. Column (1) gives the revenue effect, by multiplying the current production of each country by the decline in producer price that would result from the \$50 carbon tax. The carbon tax will drive a wedge between producer and consumer prices. While producer prices fall, consumer prices increase and hence demand will decrease. The drop in demand has to be matched by a drop in production. We present two counterfactuals: the first shown in column (2a) scales down the production of each country by the same relative aggregate drop in production, eliminating the reserves with the highest marginal cost in *each country*. On the other hand, column (2b) eliminates the production of the most expensive reserves *around the world*. For example, Saudi Arabia is a low-cost producer and hence would keep its production unchanged, while high-cost producers like Canada would reduce output by a higher ratio that the global reduction in output.

Consumer surplus changes are given in column (3), assuming the same iso-elastic demand function with an elasticity of -0.6 in each country and using 2016 consumption quantities as given by EIA. Column (4) is the tax revenue of each country, assuming that it is proportional to domestic consumption after the carbon tax is imposed, i.e., it assumes that each country imposes the same carbon tax on consumption and it is not imposed by producing countries. Columns (5a) and (5b) give the combined impact of producer surplus, consumer surplus, and the tax revenue. The difference between (5a) and (5b) is whether the producer surplus component (2a) or (2b) are used, respectively.

Intuitively, the biggest losers in Table 4 are countries that are net exporters of oil, e.g., Saudi Arabia. The drop in producer surplus is no longer offset by an increase in tax revenue, which occurs where oil is consumed. On the flip side, winners in Table 5 are generally net importers of oil, e.g., Japan, China and Germany. The increase in tax revenue more than offsets the decrease in consumer and producer surplus.[12] The tables also clearly show the high cost producers, e.g., Canada and Brazil. The producer surplus loss in column (2b) is much higher as most of a country's reserves should be shut down when the globally most expensive reserves are used to balance the implied demand reduction, while column (2a) reduces each country's output proportionally. Tables 4 and 5 is to stress that the aggregate impacts mask spatial heterogeneity.

4.3 Comparison to Recent Carbon Taxes

Some regions (e.g., British Columbia) or countries (Denmark, Finland, Sweden) have established carbon taxes. Several studies have argued that these taxes have led to significant reductions in CO_2 emissions. For example, Brian Murray & Nicholas Rivers (2015) find that a modest carbon tax of $30 per ton of CO_2 has reduced emissions by 5-15%, while Boqiang Lin & Xuehui Li (2011) find mixed results for Scandinavian countries. Finland seems to have significantly reduced its emissions, while other countries do not see significant drop in emission, likely due to the fact that some emission intensive sectors are exempt.

These studies only look at partial regulation of small subset of the global economy. Their results are not at odds with ours. A partial regulation of a country might indeed reduce emissions of that country as firms in that countries shift away from energy as input to other factors or become more efficient. These partial regulations are not expected to have a sizable effect on global emissions and have the ramification we consider here: feedback on the optimal price and extraction path of an exhaustible resource. These considerations arise when a global carbon tax was to be imposed. Our study focuses on such a global carbon tax. There is a catch 22: overall emissions are only meaningfully impacted if all major emission sources are regulated, but if we regulate them all, it would have ramifications on the extraction path that we emphasize.

5 Conclusions

In a static one-period framework a carbon tax is an obvious Pigouvian policy response to the global warming problem. However, the replacement of fossil fuels by alternatives will

[12] As previously mentioned, we used consumption quantity for 2016, the latest year for which EIA published demand estimates around the world at the time of writing. The United States have since become a net exporter.

play out over several decades, which is long enough for intertemporal substitution to come into play. This is what is emphasized by the Hotelling model of extractive resource markets: equilibrium is a dynamic process not a static state. As a result, the effects of taxes are not immediately obvious. Taking the dynamics of resource use into account shows that a carbon tax may act in two ways: it can delay the consumption of a fossil fuel, leading to lower emissions of greenhouse gases at any date but the same emissions cumulatively over time. Alternatively, it may force a fossil fuel out of the market and so reduce total emissions and lead to the replacement of fossil by renewable energy. There are cases in which both of these effects will be seen, in particular the case where there are multiple grades of fossil fuel with varying extraction costs. In practice we can expect to see both effects of a carbon tax, with the balance between the two depending on how much fossil fuel is selling for a price close to its backstop price. The latter effect is where a carbon tax will reduce fuel consumption and greenhouse gas emissions, and seems to be especially relevant for coal, which would be phased out under a carbon tax. The effect on crude oil is less clear. The remaining oil reserves are large enough that their use would release almost as much as CO_2 as the remaining carbon budget that would keep the world within 2°C. If other greenhouse gas emissions (natural gas use, methane emissions, agricultural uses, etc) are added, it becomes clear that staying within 2°C requires a reduction in oil use as well.

Applying our framework to empirical micro-level data on the MECs of crude oil suggests that a carbon tax would need to be much larger than is commonly suggested to have a significant impact on oil consumption. A carbon tax of \$100 would only reduce cumulative oil emissions by 1.6%. Some of the initial reductions in oil use are offset through an extended time of consumption. Around 70-80% of the tax will initially be passed on to consumers, but the passthrough is declining in time and even becomes negative in later years as the tax shifts oil consumption from the present to the future. In net present value terms, consumer and producer surplus in the oil market decline by equal amounts, most of which is offset by carbon tax revenues. Global welfare impacts in the oil market are limited: a carbon tax of \$100 reduces surplus in the oil market by less than 1.5%, not counting the externality of oil use. Given the convexity of the oil supply curve, significant reductions in oil use can only be achieved if most producer and consumer surplus are taxed away.

Another important lever when regulating oil consumption is the price of the backstop R. If this backstop price becomes lower (e.g., as renewables become cheaper and storage becomes available), it would be equivalent to a carbon tax. Recall that fields will be extracted if marginal cost are less than $R - \tau$. Increasing the tax τ or decreasing R have equivalent effects. The result that the marginal reduction in oil use is highly convex in the carbon tax, implies equivalently that a carbon tax together with a lower backstop price (e.g., cheaper renewables) will decrease carbon emissions much more than either of the two policy levers by itself.

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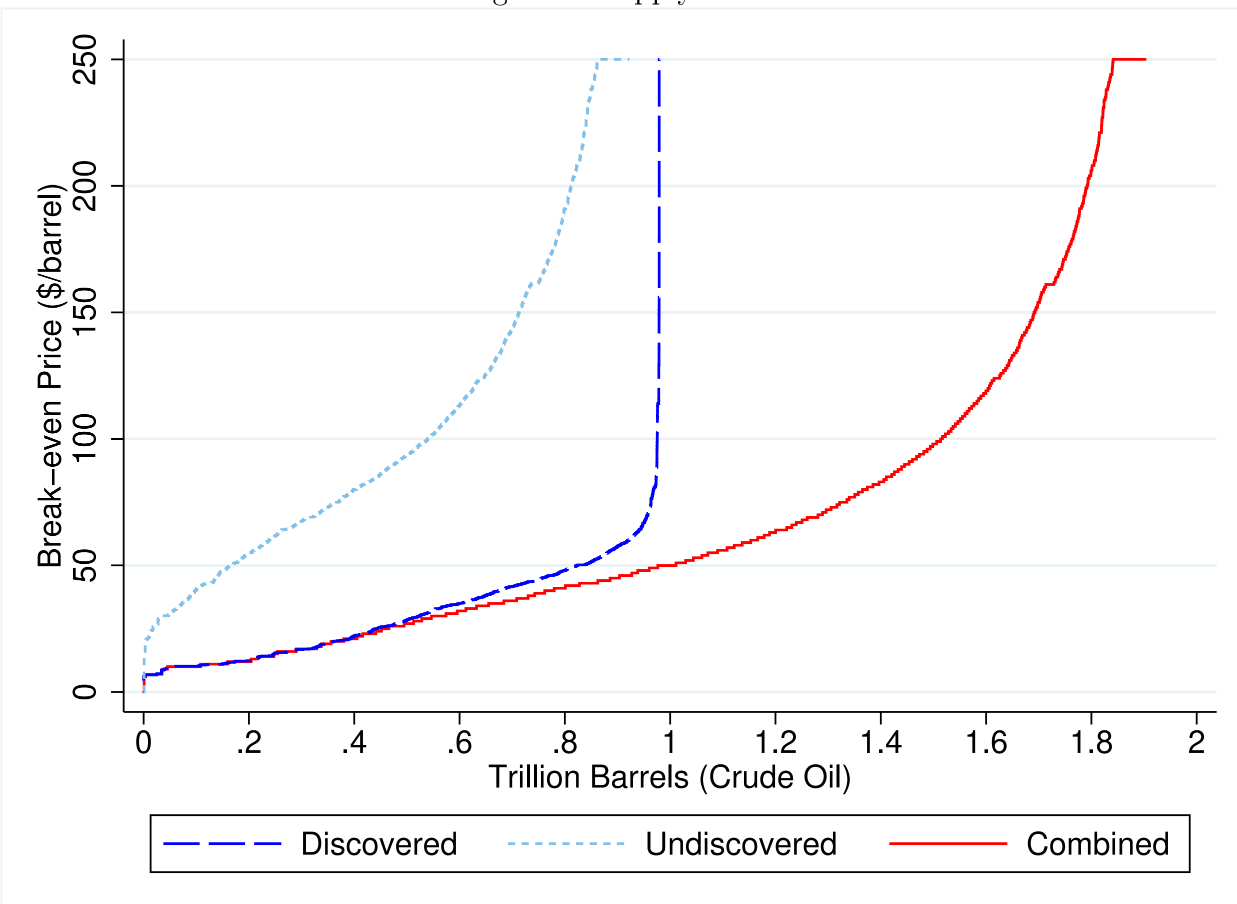
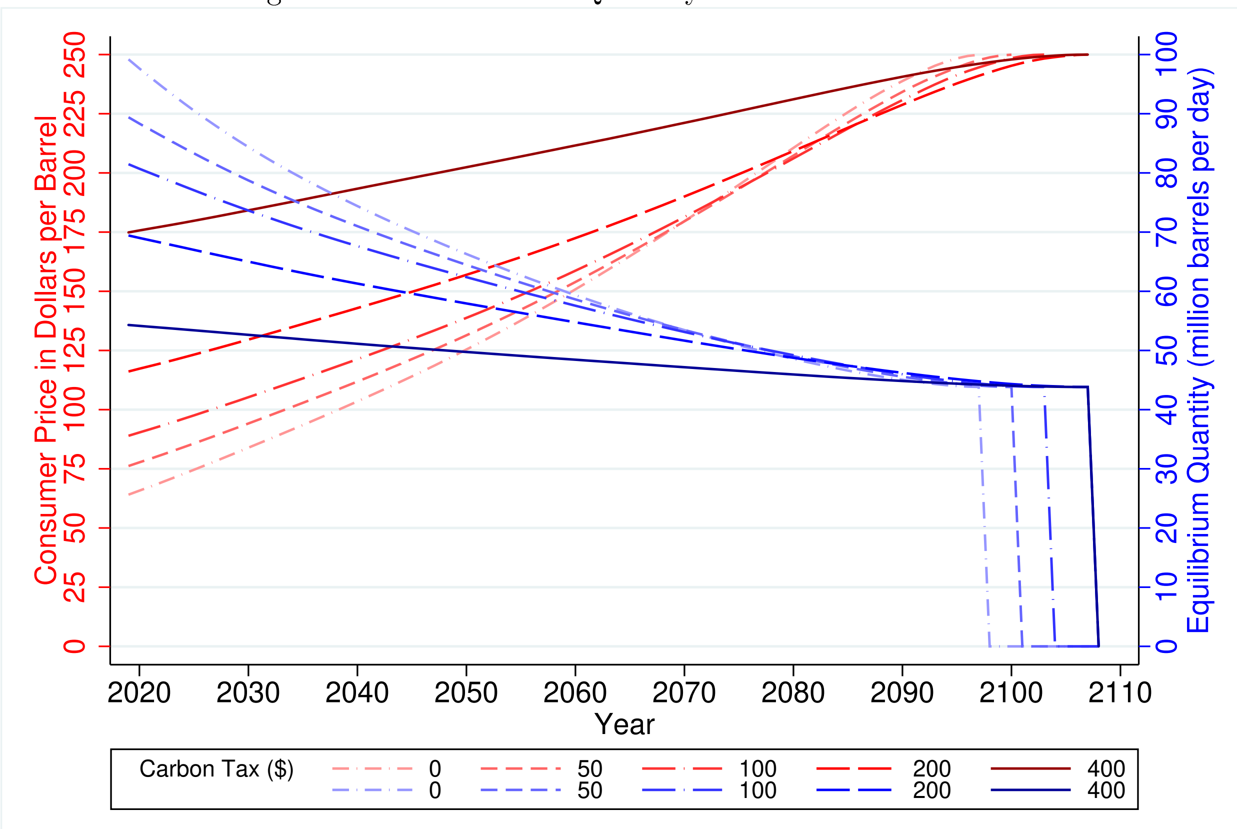
Figure 1: Supply Curve



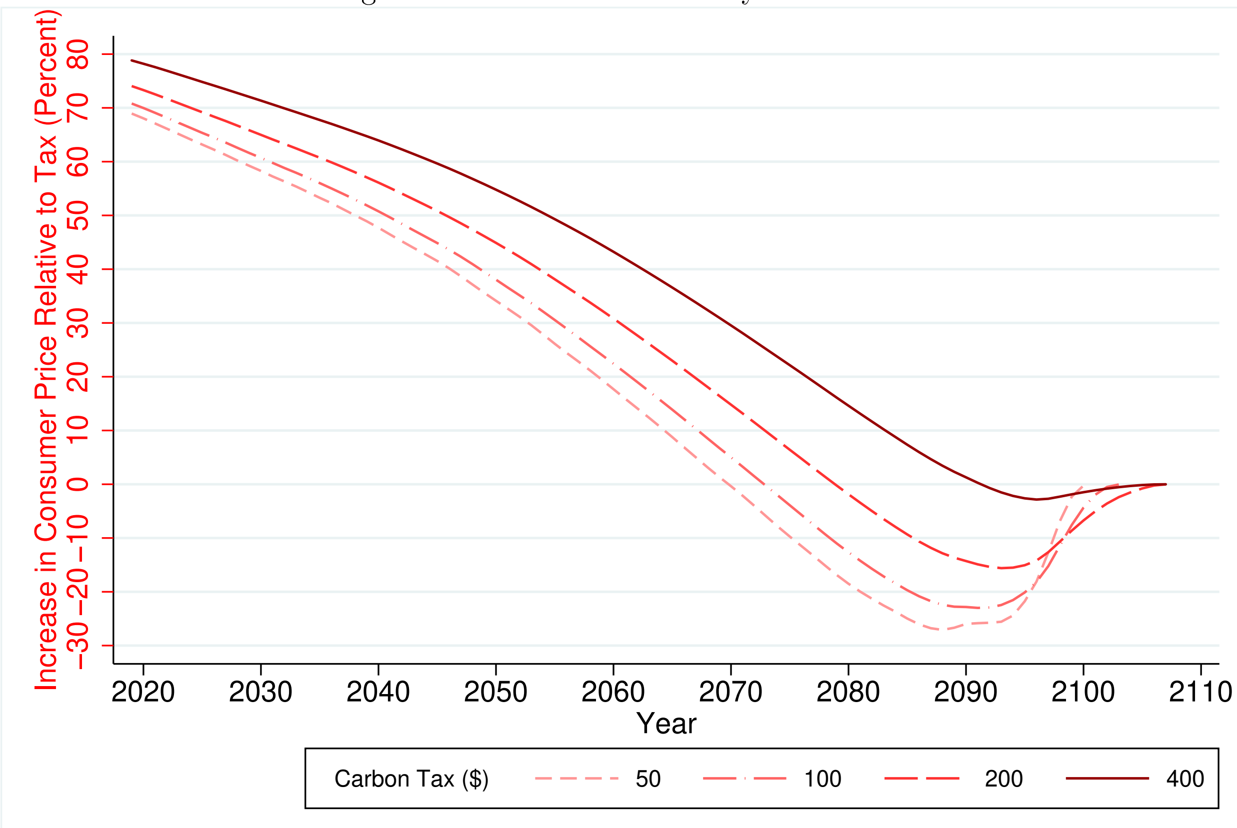
Notes: Figure displays the supply curve for crude oil using data for all discovered (dark blue) and undiscovered (light blue) reserves. The red line combines the two. Break-even price for producing fields do not consider sunk exploration and set-up cost, while they are included for fields that need to be developed first. Supply curves order fields from least to highest cost. The horizontal axis shows cumulative reserves.

Figure 2: Oil Prices and Quantity Consumed Over Time



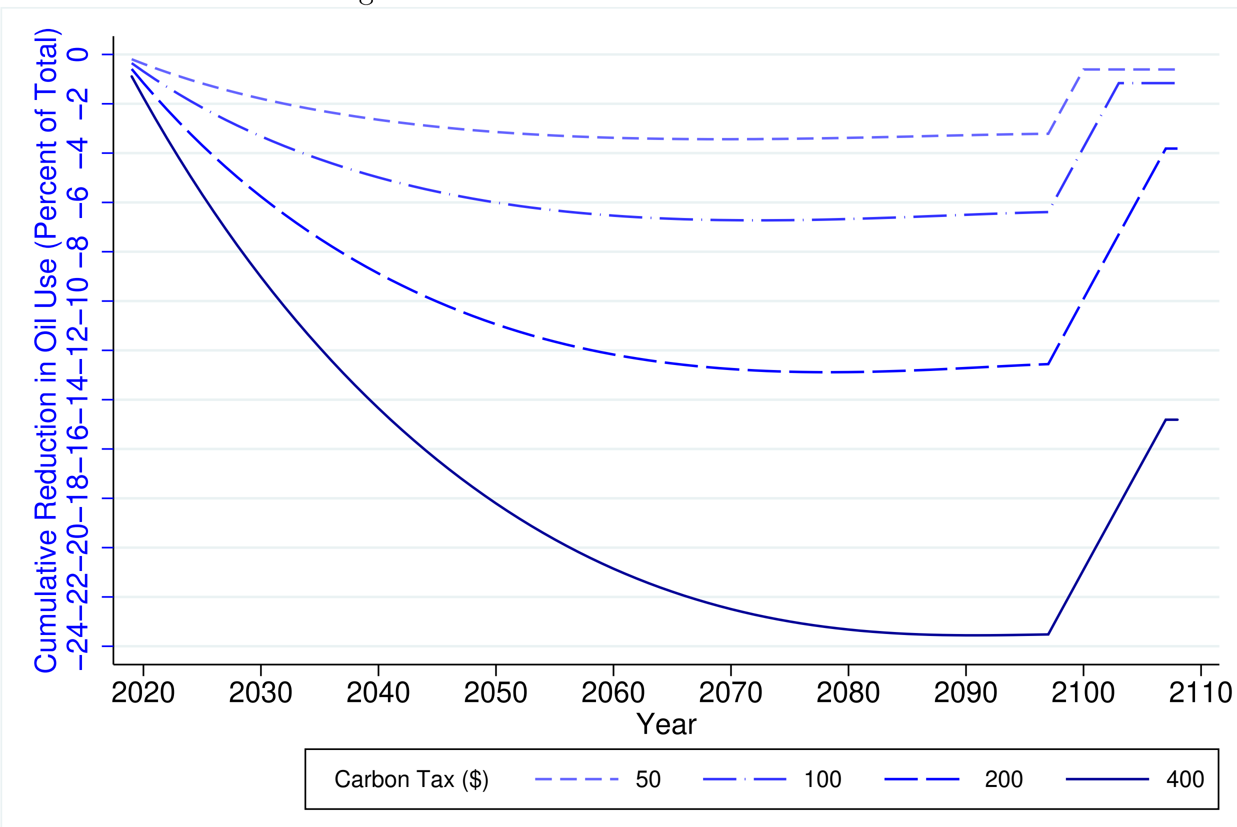
Notes: Figure displays oil prices faced by consumers (producer prices plus the carbon tax, displayed as red lines) as well oil consumption (blue lines) over time. Different shades indicated carbon taxes ranging from 50 to 400 dollars per ton of CO_2. A carbon tax of \$1 per ton of CO_2 implies a surcharge of 0.84 cents per gallon of gasoline or 35 cents per barrel of oil.

Figure 3: Share of Tax Paid by Consumers



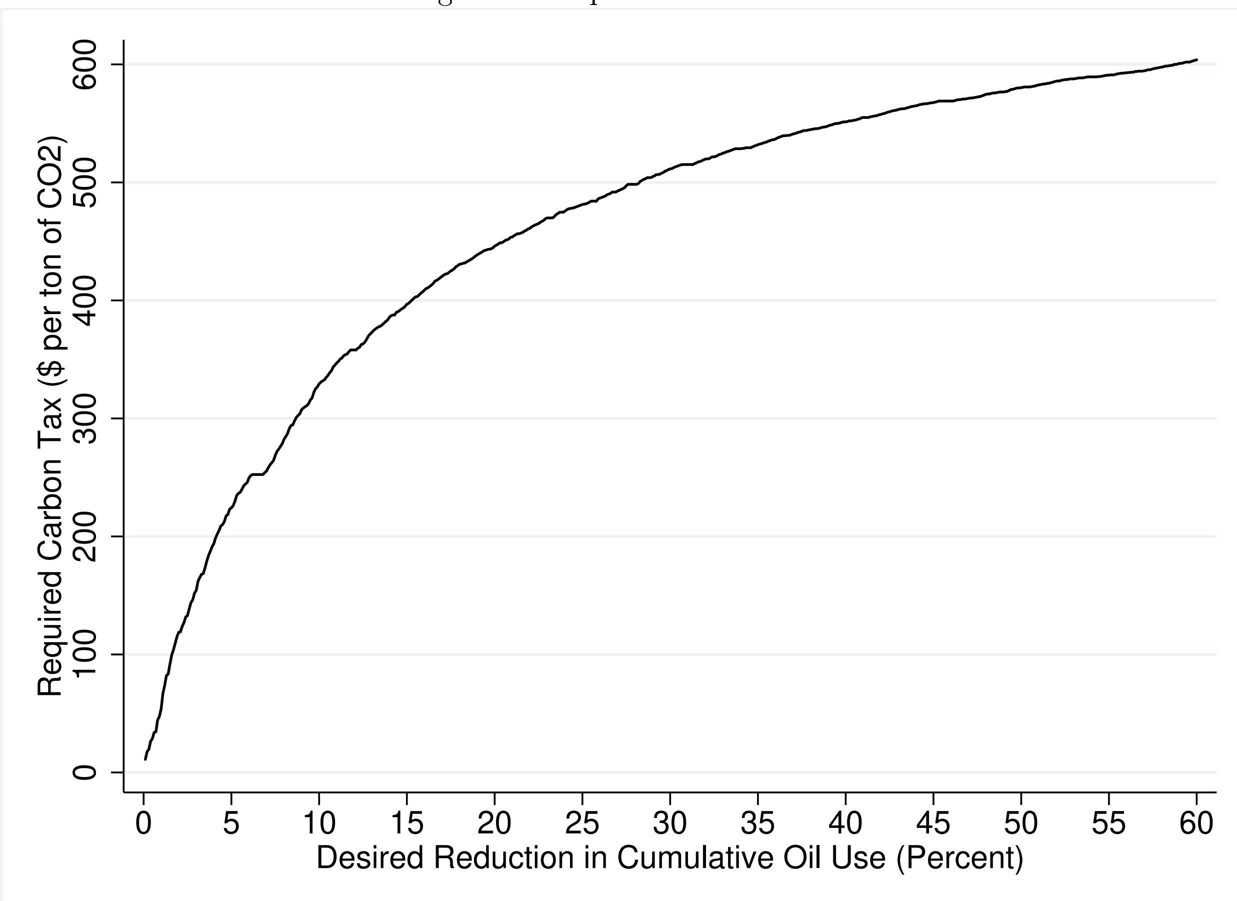
Notes: Figure displays the share of the carbon tax that is paid for by consumers, i.e., how much oil prices will be higher at each point in time in Figure 2 compared to the case without a tax. Since a carbon tax reallocates some of the oil consumption to future years, the share can be negative when oil prices will be lower than they would have been without a tax. Different shades indicated carbon taxes ranging from 50 to 400 dollars per ton of CO_2. A carbon tax of \$1 per ton of CO_2 implies a surcharge of 0.84 cents per gallon of gasoline or 35 cents per barrel of oil.

Figure 4: Cumulative Reduction in Oil Use



Notes: Figure displays the cumulative reduction in oil up to that point in time. As shown in Figure 2, a carbon tax will initially decrease oil consumption and hence lower cumulative use. Around 2080, oil prices will be lower under a carbon tax than they would have been without a tax, leading to a reversal in cumulative oil use. Finally, a carbon extends the time period of oil use beyond 2097, which will offset some of the saving in earlier years as shown by the uptick in the graph. Different shades indicated carbon taxes ranging from 50 to 400 dollars per ton of CO_2. A carbon tax of $1 per ton of CO_2 implies a surcharge of 0.84 cents per gallon of gasoline or 35 cents per barrel of oil.

Figure 5: Required Carbon Tax



Notes: Figure displays the required carbon tax ($ per ton of CO_2) for various desired reductions in cumulative oil use over all future years.

Table 1: Carbon Tax and Cost of Various Fuels

Fuel	**Units**	**CO_2 Emissions (mt per fuel unit)**	**Current Price ($ per fuel unit)**	**Carbon Tax ($ per fuel unit)**
Coal	mt	2.86	50	143
Gas	mmbtu	0.053	3	2.65
Oil	bbl	0.35	60	17.6

Notes: Table translates a uniform carbon tax of $50 per ton into cost for various fuels. The first column lists the fuel type, the second column the common unit in which the fuel is measured: metric tons (mt), millon BTU (mmbtu), or barrels (bbl). The third column shows the CO_2 emissions in metric tons for each unit of a fuel. The fourth column gives the current average price, while the last column shows the cost of a $50 carbon tax on each unit of fuel.

Table 2: Simulated Cumulative Effects over all Future Years

Carbon Tax (Dollar per ton of CO2)	0	10	30	50	100	200	400	500	600
Oil Reserves Used (Billion Barrels)	1842	1840	1832	1824	1812	1765	1560	1321	756
Producer Surplus (Trillion Dollars)	57.36	55.70	52.53	49.53	42.77	31.81	16.89	11.31	5.41
Consumer Surplus (Trillion Dollars)	86.77	85.46	82.80	80.07	73.03	58.29	28.38	14.43	3.35
Tax Revenue (Trillion Dollars)	0.00	2.85	8.39	13.71	26.16	47.78	80.43	91.24	86.32
Total Surplus (Trillion Dollars)	144.13	144.02	143.71	143.32	141.96	137.88	125.71	116.98	95.09

Notes: Table gives the value of all future global oil consumption, producer surplus, consumer surplus and tax revenues. Top header list the carbon tax, ranging from 10 to 600 dollars per ton of CO_2. The first row of the Table gives total oil consumption over all future years. The remaining rows give the discounted net present value using a discount rate of 3 percent. Producer surplus is the rent (price - marginal extraction cost), consumer surplus is the area under the demand curve from the curent price to the backstop price of 250 dollars per barrel. Tax revenue is the quantity consumed times the carbon tax.

Table 3: Discounted Net Producer Surplus over All Future Years

Carbon Tax	0	10	30	50	100	200	400	500	600
Saudi Arabia	10.06	9.81	9.34	8.90	7.89	6.24	3.92	2.97	1.80
United States	6.56	6.36	5.96	5.59	4.76	3.41	1.61	0.93	0.23
Russia	4.69	4.54	4.27	4.01	3.42	2.48	1.22	0.73	0.21
Iran	3.88	3.78	3.59	3.40	2.99	2.31	1.34	0.96	0.52
Iraq	3.74	3.65	3.48	3.31	2.93	2.32	1.47	1.14	0.72
UAE	2.63	2.57	2.45	2.33	2.08	1.66	1.08	0.84	0.54
China	2.48	2.41	2.27	2.13	1.83	1.34	0.65	0.39	0.12
Canada	2.43	2.35	2.20	2.05	1.73	1.20	0.52	0.27	0.06
Brazil	2.36	2.28	2.13	1.99	1.67	1.15	0.45	0.22	0.05
Kuwait	2.24	2.18	2.08	1.99	1.77	1.41	0.89	0.69	0.44
Venezuela	1.62	1.57	1.46	1.37	1.15	0.80	0.32	0.15	0.02
Mexico	1.52	1.47	1.39	1.30	1.12	0.81	0.39	0.24	0.09
Kazakhstan	1.42	1.38	1.31	1.24	1.08	0.82	0.45	0.30	0.13
Norway	0.83	0.80	0.76	0.71	0.62	0.45	0.23	0.15	0.06
Australia	0.80	0.78	0.74	0.69	0.60	0.45	0.23	0.14	0.05
Libya	0.71	0.69	0.65	0.62	0.53	0.40	0.21	0.13	0.06
Nigeria	0.69	0.67	0.63	0.59	0.49	0.35	0.14	0.08	0.02
Algeria	0.45	0.43	0.40	0.38	0.32	0.22	0.09	0.05	0.01
India	0.43	0.42	0.40	0.38	0.33	0.25	0.14	0.09	0.04
Azerbaijan	0.42	0.41	0.38	0.36	0.31	0.23	0.12	0.08	0.03
United Kingdom	0.39	0.38	0.36	0.33	0.28	0.21	0.10	0.05	0.01
Somalia	0.36	0.35	0.32	0.30	0.24	0.15	0.03	0.01	0.00
Angola	0.35	0.33	0.31	0.29	0.24	0.16	0.07	0.04	0.01
Indonesia	0.32	0.31	0.29	0.27	0.23	0.16	0.08	0.05	0.02
Argentina	0.31	0.30	0.28	0.26	0.22	0.15	0.06	0.03	0.01

Notes: Table breaks the global producer surplus of all future oil production (second row of Table 2) by country and lists the 25 countries with the highest surplus under no carbon tax (column 1). Producer surplus is the rent (price - marginal extraction cost), discounted at 3 percent discount rate and given in trillion 2019 US dollars. Subsequent columns give the surplus under various carbon taxes ranging from 10 to 600 dollars per ton of CO_2.

Table 4: Change in 2016 Surplus from 50 Dollar Carbon Tax - 25 Biggest Losers

	$\Delta_{ProducerSurplus}$			Δ_{CS}	Δ_{Tax}	**Overall**	
	(1)	(2a)	(2b)	(3)	(4)	(5a)	(5b)
Saudi Arabia	-20.61	-19.54	0.00	-13.97	19.10	-35.02	-15.48
Russia	-20.00	-18.03	-0.41	-15.36	21.00	-32.38	-14.76
Iraq	-8.71	-8.64	-0.04	-3.62	4.96	-16.01	-7.41
Iran	-6.88	-6.38	-0.11	-7.63	10.43	-10.46	-4.19
Kuwait	-5.49	-5.51	0.00	-1.52	2.08	-10.43	-4.93
UAE	-6.05	-5.57	0.00	-3.79	5.18	-10.23	-4.66
Canada	-7.08	-3.61	-23.22	-10.45	14.30	-6.85	-26.46
Venezuela	-4.04	-3.07	-6.31	-2.53	3.46	-6.18	-9.42
Angola	-3.31	-2.31	-2.14	-0.56	0.77	-5.41	-5.24
Norway	-3.13	-1.90	-1.80	-0.91	1.25	-4.70	-4.60
Mexico	-4.20	-3.16	-0.81	-8.68	11.87	-4.17	-1.82
Kazakhstan	-2.69	-1.92	-1.65	-1.37	1.88	-4.11	-3.84
Nigeria	-2.78	-1.54	-1.50	-1.81	2.48	-3.65	-3.62
Algeria	-2.11	-1.96	-0.00	-1.81	2.48	-3.40	-1.45
Brazil	-4.85	-2.85	-10.82	-12.62	17.26	-3.05	-11.02
Azerbaijan	-1.51	-1.23	-0.20	-0.41	0.56	-2.58	-1.55
Oman	-1.78	-0.75	-1.06	-0.77	1.06	-2.24	-2.55
Colombia	-1.66	-1.08	-3.26	-1.51	2.06	-2.18	-4.36
Qatar	-1.27	-1.09	-0.24	-0.73	0.99	-2.09	-1.25
Ecuador	-1.06	-1.01	-0.00	-1.10	1.50	-1.67	-0.66
Libya	-0.77	-0.67	0.01	-0.94	1.29	-1.09	-0.42
Congo	-0.58	-0.36	-0.36	-0.07	0.10	-0.91	-0.91
Argentina	-0.96	-0.83	-0.05	-3.00	4.10	-0.69	0.09
Malaysia	-1.12	-0.62	-1.40	-2.99	4.10	-0.64	-1.42
Equatorial Guinea	-0.33	-0.22	-2.02	-0.02	0.03	-0.54	-2.34

Notes: Table gives the effect of a US$50 carbon tax for the most recent year in which EIA list consumption data: 2016. It separates overall surplus change into changes in producer surplus, consumer surplus, and tax revenues raised. Column (1) gives the change in revenue from a price decline holding output constant $q_{i0}(p_p - p_0)$. Column (2a) gives the change in producer surplus from a constant proportional change in quantity produced by all countries. Columns (2b) replicate (2a) but no longer require a proportional reduction in every country but instead retires the fields with the highest cost in the entire world. Column (3) gives the change in consumer surplus assuming a common demand elasticity of -0.6 using a countries consumption from EIA. Tax revenues are given in column (4), which are simply the after-tax consumption times the tax rate. Overall effects of proportional production adjustments are given in columns (5a), which is the sum of (1), (2a), (3), and (4). Overall effects when the globally most costly fields are retired are given in columns (5b), which is the sum of (1), (2b), (3), and (4). All numbers are in billion US$.

Table 5: Change in 2016 Surplus from 50 Dollar Carbon Tax - 25 Biggest Winners

	$\Delta_{ProducerSurplus}$			Δ_{CS}	Δ_{Tax}	**Overall**	
	(1)	(2a)	(2b)	(3)	(4)	(5a)	(5b)
Peru	-0.08	-0.01	-0.33	-1.04	1.42	0.29	-0.03
Ukraine	-0.03	-0.03	-0.00	-1.03	1.41	0.32	0.34
Israel	-0.00	-0.00	0.00	-0.94	1.28	0.34	0.34
Austria	-0.03	-0.03	0.00	-1.13	1.55	0.36	0.39
Morocco	-0.00	-0.00	0.00	-1.16	1.59	0.43	0.43
Greece	-0.01	-0.01	0.00	-1.25	1.71	0.45	0.45
Chile	-0.00	-0.00	0.00	-1.49	2.04	0.54	0.54
Pakistan	-0.12	-0.12	-0.00	-2.35	3.22	0.63	0.74
Philippines	-0.01	-0.00	-0.04	-1.81	2.48	0.65	0.61
Poland	-0.04	-0.03	0.00	-2.46	3.37	0.84	0.87
South Africa	-0.00	-0.00	0.00	-2.71	3.70	0.99	0.99
Turkey	-0.10	-0.09	0.00	-3.99	5.45	1.28	1.37
Australia	-0.31	-0.02	-0.66	-4.68	6.40	1.39	0.76
United Kingdom	-1.56	0.54	-3.52	-6.70	9.16	1.45	-2.61
Netherlands	-0.04	-0.01	-0.03	-4.14	5.66	1.48	1.46
Taiwan	-0.00	-0.00	0.00	-4.15	5.68	1.52	1.52
Thailand	-0.31	-0.16	-0.64	-5.51	7.53	1.55	1.07
Italy	-0.15	-0.04	-0.10	-5.23	7.16	1.74	1.68
Spain	-0.00	-0.00	-0.02	-5.46	7.46	2.00	1.98
France	-0.03	-0.02	-0.11	-6.99	9.56	2.52	2.43
Germany	-0.09	-0.09	0.00	-10.17	13.90	3.55	3.64
India	-1.34	-1.04	-0.37	-18.79	25.70	4.53	5.20
United States	-15.95	-10.00	-12.22	-83.27	113.87	4.65	2.43
China	-7.79	-5.94	-16.49	-54.10	73.99	6.15	-4.40
Japan	-0.01	-0.01	0.00	-16.96	23.19	6.21	6.22

Notes: Table gives the effect of a US$50 carbon tax for the most recent year for which EIA list consumption data: 2016. It separates overall surplus change into changes in producer surplus, consumer surplus, and tax revenues raised. Column (1) gives the change in revenue from a price decline holding output constant $q_{i0}(p_p - p_0)$. Column (2a) gives the change in producer surplus from a constant proportional change in quantity produced by all countries. Columns (2b) replicate (2a) but no longer require a proportional reduction in every country but instead retire the fields with the highest cost in the entire world. Column (3) gives the change in consumer surplus assuming a common demand elasticity of -0.6 using a countries consumption from EIA. Tax revenues are given in column (4), which are simply the after-tax consumption times the tax rate Overall effects of proportional production adjustments are given in columns (5a), which is the sum of (1), (2a), (3), and (4). Overall effects when the globally most costly fields are retired are given in columns (5b), which is the sum of (1), (2b), (3), and (4). All numbers are in billion US$.

A1 Empirical Deviation of Equilibrium

The iso-elastic demand function is $q_t = \alpha p_t^\eta$ and the inverse demand function is $p_t(q_t) = \left[\frac{\alpha}{q_t}\right]^{\frac{-1}{\eta}}$

The final price will either be the backstop or the choke price, whichever one is lower. We call this R. Since we are solving the problem backwards, we start with $p_T = R$ and solve for prices p_t backward for $t < T$ until all reserves are extracted. The final step of this backward simulation gives the most current price and quantity, i.e., p_{2019}, q_{2019}.

Our baseline model uses a demand elasticity of $\eta = -0.6$, the average estimate of long-term elasticities in the literature (Hamilton 2009, Table 3), and sets the interest rate $r = 0.03$. We adjust the constant α of the demand function so the demand at the start of extraction process (the end of the backward simulation, i.e., corresponding to 2019) matches the observed demand quantity of 100 million barrels per day. In a first step we solve the below algorithm repeatedly until the simulated quantity we obtain from the backward simulation $\widehat{q_{2019}}$ deviates at most 0.001 from 100, i.e., falls within $[99.999, 10.001]$. We do this by adjusting α upward if the q_{2019} is too low and vice versa until convergence occurs. Specifically, we multiply the old α by $\frac{100}{\widehat{q_{2019}}}$.

Below are the steps how we solve the problem backwards: We use the results from the section on heterogenous extraction cost (section 2.4), which showed that the cheapest reserves will be extracted first and the most expensive last. Our backward induction hence starts with $i = I$ (most expensive reserves) down to $i = 1$ (cheapest reserves). Recall that $t = T_i$ is the time when all reserves of quality i are extracted. Since cheapest reserves are extracted first, we get $T_i < T_{i+1} < T_I$. The carbon tax is τ.

Looping over reserves $i = I, I-1, I-2, \ldots, 1$:

1) By the continuity of prices the final price for reserves i will be R. Start at step (1a) below

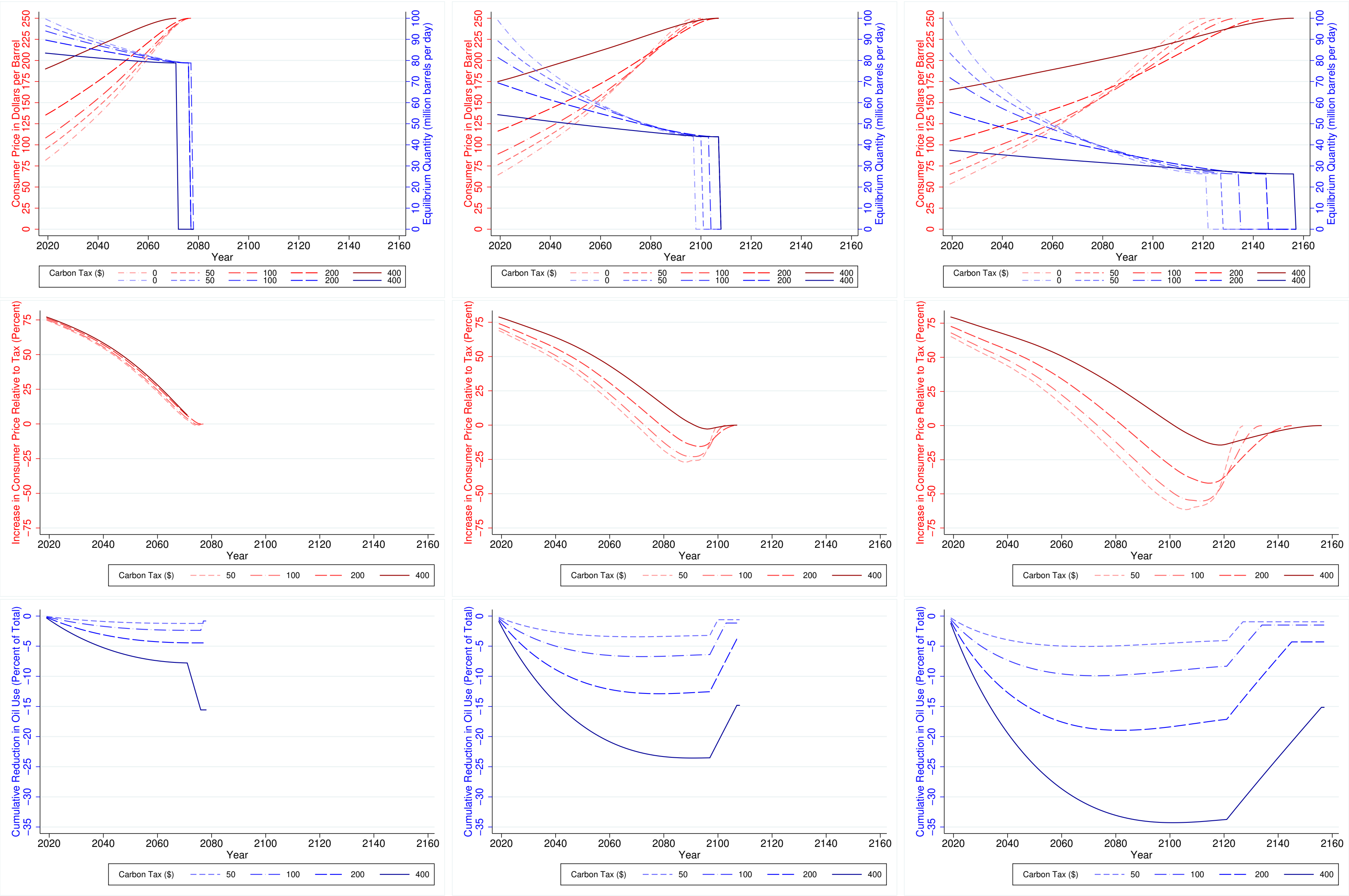
1a) If $i = I$: For the final reserve when we get $p_{T_I} = m_I + \tau + h_I(T_I)$. This can be solved for $h_I(T_I) = R - m_I - \tau$. Go to step 2.

1b) If $i < I$: For all but the final reserve we get by the continuity of prices that at the time when reserves i are exhausted, the final price equals the new starting price of the next reserves, or $p_{T_i} = m_i + \tau + h_i(T_i) = m_{i+1} + \tau + h_{i+1}(T_i)$. This can be solved for $h_i(T_i) = h_{i+1}(T_i) + m_{i+1} - m_i$.

2) The resources rents $h_i(t)$ have to rise at the rate of interest. Since we are solving backwards in time we get $h_i(t < T_i) = h_i(T_i)e^{-rt}$ and hene prices $p_t = m_i + \tau + h_i(t) = m_i + \tau + h_i(T_i)e^{-rt}$ and quantity consumed $q_t = \frac{\alpha}{p_t^\eta}$. We solve this on a daily time step $t = \frac{1}{365}$ and add up the daily demands until all reserves with marginal cost m_i are used up. Keeping note of the number of daily time steps Δt we know that $T_{i-1} = T_i - \Delta t$ The remaining demand that could not be satisfied on the last day when reserves i are exhausted is carried over to the next reserve quality $i-1$. If $i > 1$ go back to step (1b) and decrease i by one, otherwise go to step (3)

3) This gives us the extraction time for reserves $i = 1 \dots I$ and T_I. We renormalize time so that the current price / consumption are labeled p_{2019}, q_{2019}

Figure A1: Oil Prices and Quantity Consumed Over Time



Notes: Figure shows sensitivity analysis of Figures 2 (top row), Figure 3 (middle row) and Figure 4 (bottom row). The baseline is shown in the middle column using a demand elasticity of -0.6, while left column uses an elasticity of -0.21 and the right column an elasticity of -0.86. Different shades indicated carbon taxes ranging from 30 - 200 dollars per ton of CO_2. A carbon tax of $1 per ton of CO_2 implies a surcharge of 0.84 cents per gallon of gasoline or 35 cents per barrel of oil.