# Would Hotelling Kill the Electric Car?[⋆]

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**Abstract**

Did oil companies collude to kill the electric car? If so, would this behaviour have been consistent with the optimal resource extraction model of Hotelling? In this paper, we show that the potential for endogenous technological change in alternative energy sources may greatly alter the behaviour of resource-owning firms. When technological progress in an alternative energy source can occur through learning-by-doing, resource owners face competing incentives to extract rents from the resource and to prevent expansion of the new technology. We show that in such a context, it is not the case that higher energy prices will induce alternative energy supply as resources are exhausted. Rather, we show that as we increase the learning potential in the substitute technology, lower equilibrium energy prices prevail and there may be increased emissions. We show that the effectiveness of emissions reduction policies may be altered by increased potential for technological change. Our results show that rather than harnessing the power of endogenous technological change to reduce emissions, carbon taxation may have less effect on emissions the greater is the potential for technological change. Hotelling may not have advocated killing the electric car specifically, but we show that optimal resource extraction does not imply behaviour which will quickly render a substitute cost-competitive and the existence of such a substitute can increase research extraction and decrease the effectiveness of carbon charges.

*Key words:* Resource Extraction; Climate Change; Induced Innovation; Learning-by-doing.

*JEL classification*: TBD

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# 1 Introduction

Increasing oil prices prompted Saudi Arabia to call an emergency summit in June of 2008. Among concerns cited was a feeling that continued high oil prices would lead to increased uptake of alternative energy sources and a permanent demand shift. (CNN, 2008) While oil prices have declined significantly since mid-2008, the recent push for investment in the *green economy* suggests that competition between scarce, fossil-fuel resources and alternative energy providers may return again to threaten the rents of finite resource owners. Our paper models a situation where a oil-owning oligopolist must consider the future production from an alternative energy sector when determining the optimal supply from their finite resource. In our model, production costs and the competitiveness of the alternative are influenced by both traditional resource scarcity and emissions-control policy changes.

The contention of the 2006 film 'Who killed the electric car' is that, among other actions, strategic action on the part of the oil companies to maintain artificially low fuel prices, led to the devaluing of the electric car and led to its demise.[1] We show cases where, under Nash equilibrium, resource owners can continue to extract rents in the presence of a credible alternative technology because they have a credible threat to reduce rents at any point. Further, we show cases were it is optimal to maintain low and constant energy prices almost until the point of exhaustion to maintain market share in the face of a competing alternative. It seems that Hotelling would, under the right circumstances, have found it optimal to price resources so as to keep the electric car at bay.

Exploring the effect of potential or actual competition on the decision to extract resource rents is not restricted to Hollywood. Similar strategic responses have been explored in the context of the optimal management of both renewable and non-renewable resources in economics. Crabbé and Long (1993) examine a situation where fishery owners react to the potential entry of poachers by catching more fish. Poachers are assumed to be less efficient, but still induce a quantity response from the resource owner. Mason and Polasky (1994,2002) examine the impact of future competition on the management of a common property resource. Here, the actions of a monopolist under the threat of entry may lead to

[1] see "Who killed the electric car?", Sony Pictures, 2006.

extinction of the harvested resource, while competition from the outset would not. Harris and Vickers (1995) examine a related problem for non-renewable resources. In their case, a resource owner must take into account that the likelihood of their consumers developing an alternative source of energy due to increases in the price of their product. Similarly, in Cairns and Long (1991), excessive rent-seeking by resource owners leads to diminished future rents as a result of regulation.

In our paper, we explore the importance of extraction responses in an environment where a resource owner faces a threat of competition from a substitute which is an experience good. The substitute may initially be significantly higher in cost, but potential learning-by-doing implies that this cost disadvantage is affected by the actions of the resource owner. The extraction of rents from the resource stock through conservation may be discouraged since higher energy prices encourage production by the emerging substitute. In equilibrium, dynamic incentives resulting from potential future competition may lead to either increased exploitation of the resource or over-use of the alternative technology for long-term gain. Depending on the relative costs and learning potentials, an equilibrium with learning may result in resources being extracted earlier and, in such a case, the potential for endogenous technological change may exacerbate the climate change problem at least in the short term.

Our paper also has important implications for the setting of optimal climate change policy. A common thread through many policies designed to combat global climate change is the premise that technological change in substitutes will be induced by higher traditional energy prices. The upshot of this is the implication that new technologies will play a key role in eventual emissions reductions and lower the total abatement costs and/or decrease the optimal quantity of emissions. In this paper, we argue that induced technological change may not be a magic bullet for climate change mitigation. In fact, we show that when previous results on resource extraction are revisited, strategic incentives to maintain market share may lead to higher extraction of the resource relative to a case with a less viable substitute, and that these effects may significantly detract from the effectiveness of climate change policy.

Our results and previous work discussed above suggests that the pricing of resources by their owners will not be independent of available substitute technologies, current and future climate policies, or potential future cost reductions in substitutes. However, literature on climate change policy has largely ignored these links. In papers such as Nordhaus (2002) and Popp (2004, 2006) which explore the potential for endogenous technological change to reduce abatement costs for climate change mitigation, resource prices are treated as a fixed function of cumulative extraction in both policy and no-policy scenarios, and are invariant to the state of the emerging alternative energy technology. We provide strong evidence that the resource pricing function which would be applied by a resource owner is strongly negatively related to the quality of any available substitute.

Our results show that the potential for significant endogenous technological change may detract from the effectiveness of fiscal climate change policy. A carbon charge or alternative energy subsidy makes the emerging technology relatively more competitive and increases the long-term value of the alternative technology, which leads to greater alternative energy production. However, the carbon policy also leads to lower long term values of resources, an effect which is exacerbated by learning-by-doing, which means that the resource-owner may see fewer gains to conservation. Depending on which effect dominates, equilibrium energy prices and emissions may increase or decrease after the imposition of fiscal climate change policy.

The paper proceeds as follows. In Section 2, we develop the general model of the economy. We characterize the dynamic, competitive equilibrium implied by this model and describe the algorithm used to solve it in Section 3. In Section 4, we use numerical simulations to characterize the dynamic equilibrium with and without policy intervention to illustrate the role of strategic incentives. Section 5 concludes.

## 2 The Model

The model characterizes an economy which uses energy at decreasing returns to scale. Energy may be derived from two sources: fossil fuels or alternative energy.[2] Alternative

[2] We opt for a model structure which is simplified relative to that proposed in most Integrated Assessment Models (IAM's). In particular, we do not allow for climate change damages arising from emissions. These simplifications are not crucial here since our purpose is not to provide predictions of the magnitude of climate change or to compute optimal climate change policy, but rather to provide meaningful comparative dynamics. As long as the private incentives to reduce

energy is an experience good, and so both its total and marginal production costs decline with cumulative production.

The industrial organization of the energy sector is a Cournot oligopoly with $n$ price-setting, resource extraction firms and a price-taking alternative energy sector acting as a competitive fringe. We assume that experience is a public good in the alternative energy sector, such that firms capture private gains from learning-by-doing but these are smaller than the total value of learning-by-doing to all firms in the sector. We explore, in our results section, an case where all gains from learning-by-doing are internalized by firms in the sector through the application of a first-best subsidy. Below, we define each sector of the model in detail before describing and solving for the competitive equilibrium.

## 2.1 Energy Demand

Energy supply, $q$, measured in million barrels of oil equivalent (MBOE) is paid its marginal revenue product in production. Denote the total revenue product of energy consumption by $P(q)$, and the marginal revenue product of energy by $p(q) = P_q(q) > 0$. Further, $P(q)$ satisfies $P_{qq}(q) < 0$. [3] Energy prices throughout the paper are measured in dollars per ton of carbon-equivalent energy ($/ton CE).

## 2.2 Resource Extraction

An initial, known stock of fossil fuels, $X_0$, measured in gigatons of carbon emissions (GtC) units is owned and extracted by $n \geq 1$ symmetric firms. Denote by $X_{i,t}$ the resource stock owned by an individual firm and denote that firm's extraction rate by $f_{i,t}$, so that:

$$X_{i,t+1} = X_{i,t} - f_{i,t}, \tag{1}$$

and

$$X_{t+1} = X_t - nf_{i,t} = X_t - f_t. \tag{2}$$

pollution for the sake of preventing future climate change are negligible, then this assumption will not have significant leverage on our results.

[3] This structure is analogous to that used in the integrated assessment literature. Generally, the marginal product of energy is the first derivative of a Cobb-Douglas production function, which we use in the numerical simulations for this paper.

The resource stock is subject to extraction and delivery costs which are constant in both in the intensity of extraction in each period and cumulative extraction, $c_X(f_t) = c_X$. Conversion parameter $\phi$ specifies the ratio of barrel of oil equivalent energy per ton of carbon emissions, such that $\phi f_t$ is the energy content of fossil fuel supply.

### 2.3 Alternative Energy Supply

An emissions-free substitute for fossil fuels exists for energy production. The alternative energy sector is comprised of $m$ price-taking, dynamically optimal firms. Alternative energy is an experience good, such that future costs of production are decreasing in current production levels. Denote aggregate alternative energy supply by $a$, measured in MTOE, where $a = \sum_{j=1}^{m} a_j$. Let the marginal cost of production of alternative energy for each firm be increasing in production in any period ($a_j$), and decreasing in the level of accumulated experience (A). In particular, let $c(A, a_j) = c_0 A^{-\eta} + c_s a_j$, $\eta > 0$. By construction, $c_A(A, a_j) < 0$, $c_{AA}(A, a_j) > 0$. Experience always reduces both the marginal and total costs of production, but at decreasing returns to scale; a doubling of experience reduces the price-intercept of marginal costs by a factor of $1 - 2^{-\eta}$.

Given initial experience level $A(0) = A_0 > 0$, experience evolves according to a learning-by-doing law of motion as:

$$A_{t+1} = A_t + a. \tag{3}$$

We do not allow for experience depreciation, so that all experience accumulated remains relevant for all future time periods. The addition of depreciation would be analogous to slower learning rates or a higher discount factor in that such an assumption would imply a lower future value of current alternative energy supply.

## 3 Equilibrium

A subgame perfect equilibrium of this economy is defined such that firms each choose supply to maximize the net present value of profits under perfect foresight. The state space is the same for firms in each sector; the choices of each firm will be affected by current resource stocks (X) and accumulated alternative energy production experience (A). In the characterization of the economy, we also introduce carbon taxes and alternative energy subsidies, denoted by $\tau_c$ and $\tau_a$ respectively. With minor modifications, the indirect profit functions of each firm represent contraction mappings over this state and policy space. [4] The simultaneous solution to the dynamic programs for the $m+n$ firms constitutes a subgame perfect equilibrium of (or closed-loop solution to) the economy.

## 3.1 Optimal behaviour: Alternative Energy Supply Sector

We assume that each alternative energy firm acts as a price taker and takes fossil fuel supply and the supply of other alternative energy firms at each state as given. Let $\bar{f}(X, A)$ be the total supply of fossil fuels and $\bar{a}(X, A)$ be the total supply from the $(m-1)$ other alternative energy firms at any point in the state space. Let $\tau_{a_t}$ represent a subsidy to alternative energy supply. Each alternative energy firm solves the following dynamic program:

$$\begin{aligned} V_1(X, A) = \max_{a_j} \;\; & p\Big(\phi \bar{f}(X, A) + \bar{a}(X, A) + a_j\Big) a_j - \int_0^{a_j} c\,(A, \tilde{a})\, d\tilde{a} + \tau_a a_j \\ & + \beta V_1(X', A') + \gamma_a a_j \end{aligned} \tag{4}$$

subject to:

$$X' = X - \bar{f}(X, A) \text{ and} \tag{5}$$

$$A' = A + \bar{a}(X, A) + a_j, \tag{6}$$

where $\gamma_a$ denotes the shadow value for the non-negativity constraint on $a_j$. The first order condition for the optimal choice of $a_j$ given state $(X, A)$ is:

$$p\Big(\phi \bar{f}(X, A), a_j + \bar{a}(X, A)\Big) - c\,(A, a_j) + \tau_a + \beta \frac{\partial V_1(X', A')}{\partial a_j} + \gamma_a = 0 \tag{7}$$

while the accompanying complimentary slackness condition is:

$$\gamma_a \geq 0 \text{ and } \gamma_a a_j = 0. \tag{8}$$

[4] The model as written is not stationary in accumulated experience, $A$. In solving the dynamic program, we redefine the the model in terms of the cost-intercept-shift term, $A^{-\eta}$, which will always be bounded from below by zero and from above by its initial value, $A_0^{-\eta}$.

The future value derived from experience, $\frac{\partial V_1(X',A')}{\partial a_j}$, will be critical in the results shown below. Intuitively, this term should be decreasing in resource stocks, decreasing in accumulated experience, and increasing under both carbon taxes and alternative energy subsidies.

The solution to this dynamic program yields a policy function, $a_j(X, A|f)$ which describes optimal behaviour at each point in the state space, given the actions of the resource extraction and other alternative energy firms. Alternative energy firms are symmetric, so in equilibrium $a_j = \bar{a}(X, A)$ and $ma_j = a$.

## 3.2 Optimal Behaviour: Resource Extraction Firms

Each resource firm takes the extraction decisions of the other $(n-1)$ resource firms as given. Let $f_i$ represent the individual firm's decision variable and let $(n-1)\bar{f}_j$ represent the supply of the other $(n-1)$ resource owners (where $n \leq 1$), and let $\bar{a}(X, A)$ represent the supply of alternative energy at a given point in the state space (the solution to the dynamic program described in Section 3.1). Let $\tau_f$ represent an emissions tax. Each resource-extraction firm solves the following dynamic program:

$$\begin{aligned} V_2(X, A) = \max_{f_i} \;\; & p\Big(\phi f_i + \phi(n-1)\bar{f}_j + \bar{a}(X, A) + (n-1)\bar{f}_j)\Big) f_i - c_X f_i \\ & -\tau_f f_i + \beta V_2(X', A') - v_f\Big(X - f_i\Big) + \gamma_f f_i \end{aligned} \tag{9}$$

subject to:

$$X' = X - f_i - (n-1)\bar{f}_j \tag{10}$$

$$A' = A + \bar{a}(X, A). \tag{11}$$

In the equations above, $v_f$ and $\gamma_f$ denote the shadow values for the individual extraction constraint, $\Big(X/n - f_i\Big) \geq 0$,and the non-negativity constraint on $f_i$ respectively. Resource firms are symmetric, so in equilibrium $f_i = \bar{f}_j$ and $nf_i = f$.

## 3.3 Numerical Solution and Simulation

The simultaneous solutions to the dynamic programs defined in (4) and (9) will allow us to define the subgame perfect equilibrium for the competitive economy. Due to the structure employed, there will be no closed-form solution, so we base our results on numerical approximations of the value functions. We specify a particular case, however the results should generalize to any where an equilibrium with alternative energy only cannot result in a price lower than the resource extraction cost. We solve the model using a value function iteration algorithm previously used in Leach (2007), which characterizes the solution to each value function as the fixed point of a neural network approximation of firm's value (indirect profit) function over a finite set of grid points.[5,6] The parameters used in the simulations are presented below and shown in Table A-1 in the Appendix.

## 3.4 Parameterization

The intent of the present study to provide informative comparative dynamics based on reasonable parameter values and functional forms. We use parameters and functional forms which are comparable to those used in Integrated Assessment Models (IAMs) of climate change in the economics literature.

We adopt a total output function of $\Omega q^{\theta}$, with $\Omega$ calibrated to match total factor productivity, and labour and capital contributions in the first period of the Nordhaus (2008) DICE-07, for the year 2005. The energy share of production is separated out as $\theta = .05$, an alteration of the DICE-07 environment. We make a strong assumption that the two energy sources are perfectly substitutable, so $q = a + \phi f$, where $a$ is measured in megatonnes of oil equivalent (MTOE), and $\phi$ is the energy content (MTOE/GtC) of fossil fuels, set to 1.45, the emissions to fossil energy supply ratio observed in 2005 IEA data.

The marginal cost of fossil fuel extraction is set so that global emissions match the observed 7.4 GtC for 2005 when oil extraction is undertaken by a 4 firm oligopoly. The parameter values imply an extraction cost equivalent to $32 per barrel of oil. Firms choose

[5] The algorithm used is based on previous work by Kelly and Kolstad (1999, 2001).
[6] For a detailed discussion of neural networks and their approximation properties, the interested reader is referred to Hassoun (1995).

price-setting and rents above this cost in each period to maximize their gain from resource extraction. Resource extraction costs are assumed not to increase with cumulative extraction for clarity of interpretation.

We assume that the lower bound of the cost of alternative energy is such that if we were able to instantly achieve the limit of possible learning, half of fossil fuel demand would be displaced by alternative energy use, and that total energy supply would by 60% supplied by wind, solar, geothermal and other emerging sources (i.e. total energy supply would increase). Based on IEA (2008) data, we parameterize the model such that 0.5% of energy supply is from emerging alternative energy sources (consistent with 55 Mtoe of energy supplied using wind, solar and geothermal out of a global total supply of 11200 Mtoe). To be consistent with these figures, we set the lower bound of alternative energy costs at $11/Mtoe, or $7/MWh. We then assume that these costs increase in intensity, such that for each additional Mtoe of supply, costs increase by $1.50/Mtoe, or $1/MWh. Based on historic cost data and estimates of future progress in alternative energy, we assume baseline progress ratio to 15%, and test 0% and 30% rates of progress for comparison.

The exact values used in the numerical example are, for the most part, important only for the quantitative but not the qualitative results presented below. There are two characteristics of the numerical example which we consider important to the qualitative results. First, the combination of the intercept and slope of the alternative energy supply are such that there cannot exist an equilibrium in which oil remains in the ground forever, and so any emissions impacts of policies are merely questions of timing not cumulative quantities. Second, the way in which we cast the model implies that an endowment of initial experience in the alternative energy technology has been given to the firms in that sector. Without this assumption, we would have to cast the model in terms of a state variable of cumulative experience and the model would not be stationary. We assume that the endowment accounts for a minimum of 25% of the total cost reductions possible for the technology.

The complete set of parameters used in the model simulation is provided in Appendix 3.4.

# 4 Results and Discussion

We characterize the equilibrium under three learning rates (0, 15, and 30%) using both simulations across time and projections of optimal reaction functions and marginal values onto the state space. For clarity of presentation, we assume monopoly extraction (n=1) with a 50-firm (m=50) competitive fringe. We relax the former condition in the sensitivity analysis section by considering an oligopoly among multiple resource owners ($n = 4$).

## 4.1 Learning and Emissions in the Strategic Equilibrium

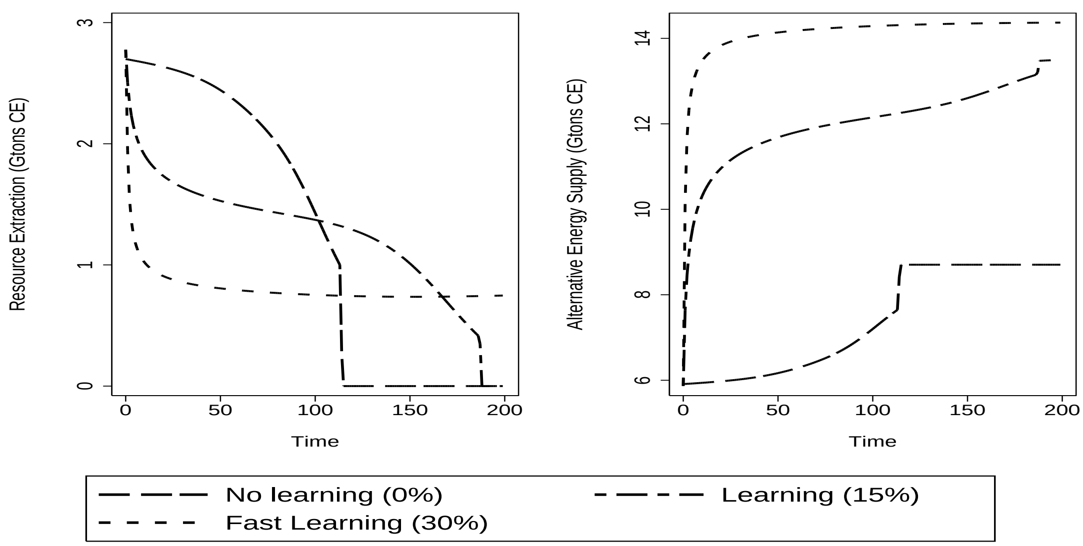


**Fig. 1**. Resource extraction and alternative energy supply over time across learning rates

Figure 1 shows the choices of resource extraction and alternative energy supply over time for the same initial conditions for each of the 3 learning scenarios. It is immediately obvious that learning plays an important role in determining the sequence of equilibrium choices over time. Where no learning is possible, the alternative is used steadily more over time as the resource becomes scarce, rent extraction increases, and extraction decreases. The time path of extraction here is analogous to that developed in Nordhaus et al. (1973), where the only differences arise as a result of the assumed imperfectly elastic supply function for the alternative energy source. Where learning is possible, the future costs reductions resulting from current production move the extraction paths away from those of the type developed in Nordhaus et al.

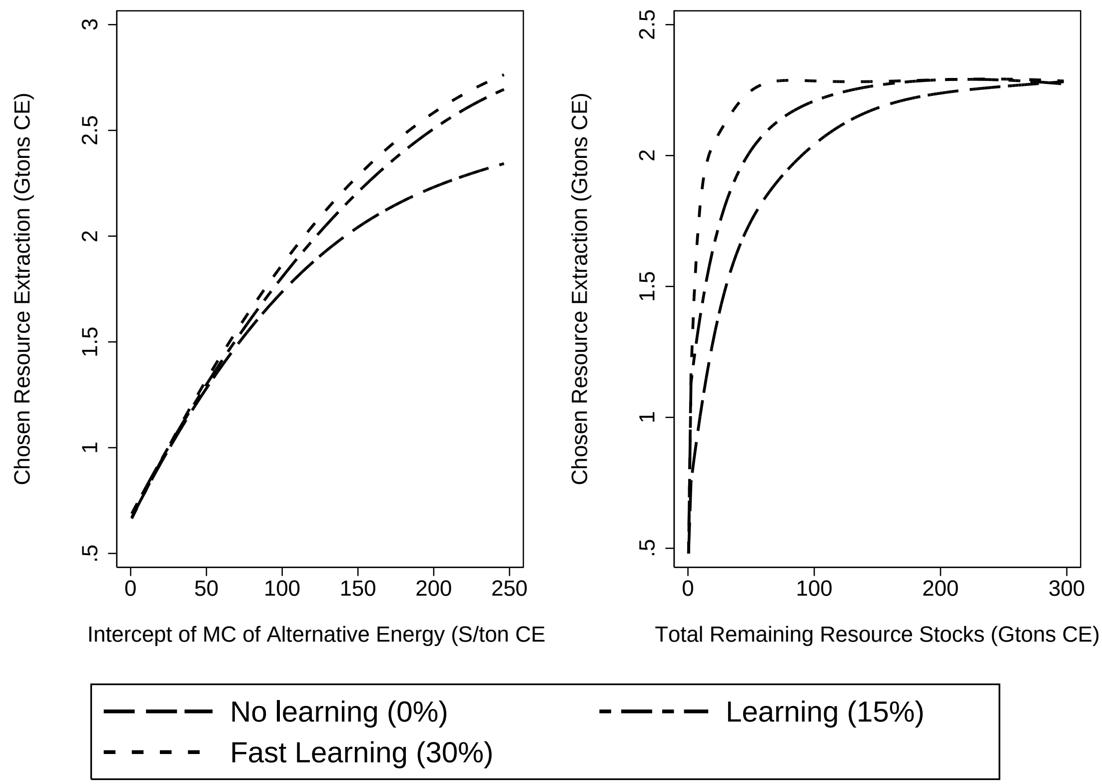


**Fig. 2**. Optimal extraction decisions of the resource-owning firm as a function of state values for each of three learning scenarios. In the left-hand panel, the alternative energy cost is fixed at \$200/ton CE, while the right-hand panel has remaining resource stocks is fixed at X=100.

It is difficult to make meaningful generalizations based on a time path since the initial values hold significant leverage over the results. To build the intuition for the solution, we now examine the state-contingent reaction functions derived from the solution to the firms' problems. Figure 2 shows two projections of equilibrium extraction onto the state space. The left hand panel shows the equilibrium extraction decisions as functions of the remaining resource stocks (with the intercept of alternative energy cost held fixed at \$200/ton CE, 60% of the resource extraction cost of \$300/ton CE), while the right hand panel shows equilibrium extraction as a function of the alternative energy cost, with resource stocks held constant at $X = 250$ Gtons CE. The left hand panel shows the role of what might be termed 'scarcity insurance'. The X-axis, read from left to right, denotes the state of alternative energy cost. The costlier the technology, the more the economy is dependant on resources. Intuitively, we might expect that greater learning rates offer greater abilities to conserve, *ceteris paribus*, but the competitive economy reveals another, more damaging equilibrium where the resources supplier has less incentive to conserve. We see the same effect echoed in the right hand panel. As resources become more scarce, the resource owner does not have the same incentive to conserve because the market will not bear higher prices given the availability of a substitute with the potential for cost reductions. As such, resource exhaustion occurs very suddenly rather than following a smooth increase in price and reduction in quantity as we have come to expect. Increasing extraction in response to increased potential for learning, and maintaining that increased extraction rate as long as possible matches very closely with the anecdotal evidence of the strategic responses of OPEC presented in the Introduction.

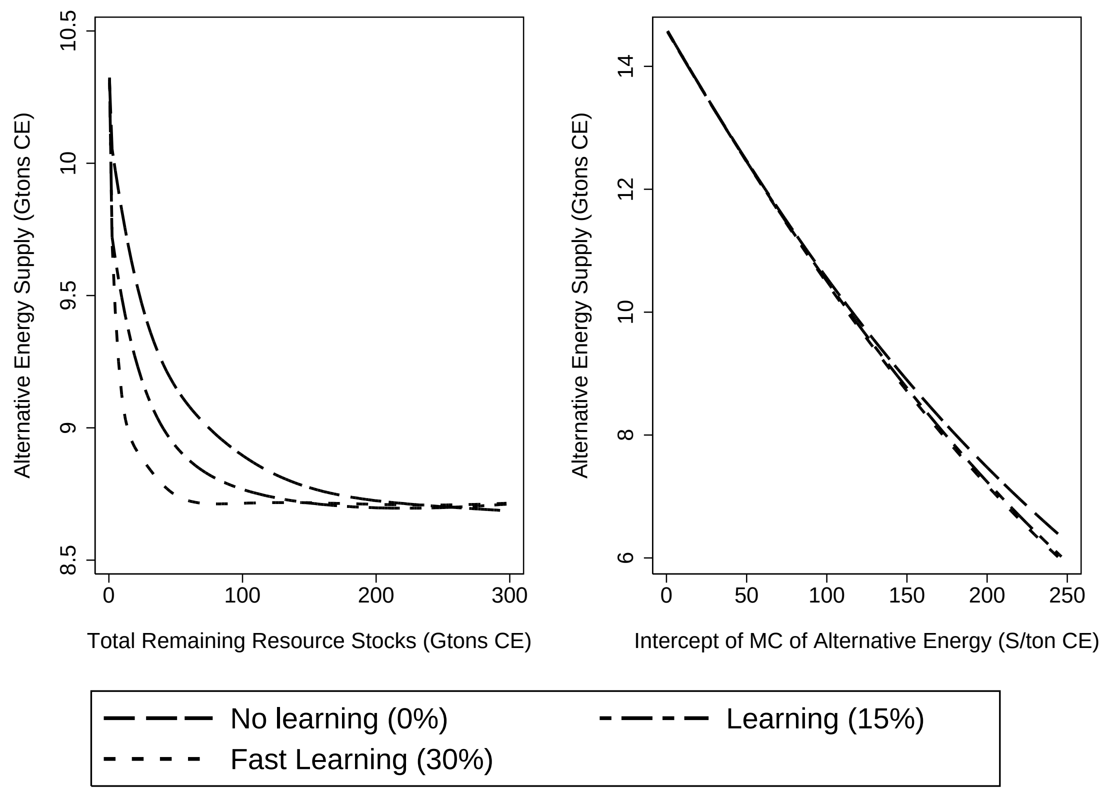


**Fig. 3**. Optimal extraction decisions of the alternative energy firm of state values for each of three learning scenarios. Assumptions are the same as in Figure 2.

Figure 3 shows the equilibrium supply decisions of the alternative energy firm under the same assumptions discussed above. The alternative energy supply function is again some-what counter-intuitive. The right-hand panel does not show significant supply differences, but the sign is surprising: *ceteris paribus*, the slower the learning rate at points where the cost of the technology is high, the higher the supply of alternative energy. One might expect that the potential to learn would lead to higher production of alternative energy, but this is offset by the response of the resource owner in Nash equilibrium. Also surprising and echoing these results is that, in the left hand panel, we see that holding all else constant, as resource stocks decline we see much earlier adoption of alternative energy sources in the slow or no-learning cases. The faster learning cases, in equilibrium, see the resource owners forgo most of the rents from extraction, so extraction occurs quickly but with less cumulative production of alternative energy. In our model, learning rates are known with certainty. If, in fact, learning potential were uncertain by expected values were high, such a strategic response could have disastrous implications. We could see the exhaustion of resource stocks because the threat of potential innovation led to a lack of conservation, even though, *ex post* we might discover that learning potentials were over-estimated.

The future values of resource stocks, $\frac{\partial V_2(X',A')}{\partial x}$, and the future value of cost reductions resulting from current alternative energy production, $\frac{\partial V_1(X',A')}{\partial a}$, are key factors in determining the outcomes discussed above. While we do not model a Stackelberg game, and so learning is taken as given by the resource owner, learning in the alternative will affect future resource values. Similarly, while resource extraction is taken as given by the alternative supplier, the level of remaining resources will affect the willingness of the alternative energy provider to produce at a price below marginal cost. Figure 4 shows the evolution of scarcity rents and marginal future value of current alternative energy production over time. This shows that the rent sequences do not obey the traditional Hotelling or Nordhaus et al. rules once learning is introduced.

In the left hand panel of Figure 4, we see the willingness of the alternative energy firm to produce at a price below marginal cost. In both the 30% and the 15% cases, we see the expected results that the willingness to produce at a price below marginal cost is decreasing over time because there are decreasing returns to new experience in terms of future cost reductions. The 30% learning rate is so fast that rents from greater experience are almost non-existent after the first 50 years. In the right hand panel, we see again the results of Nordhaus et al. being replicated in the no-learning case where resource rents rise at the rate of discount until the resources are exhausted. Since there is no

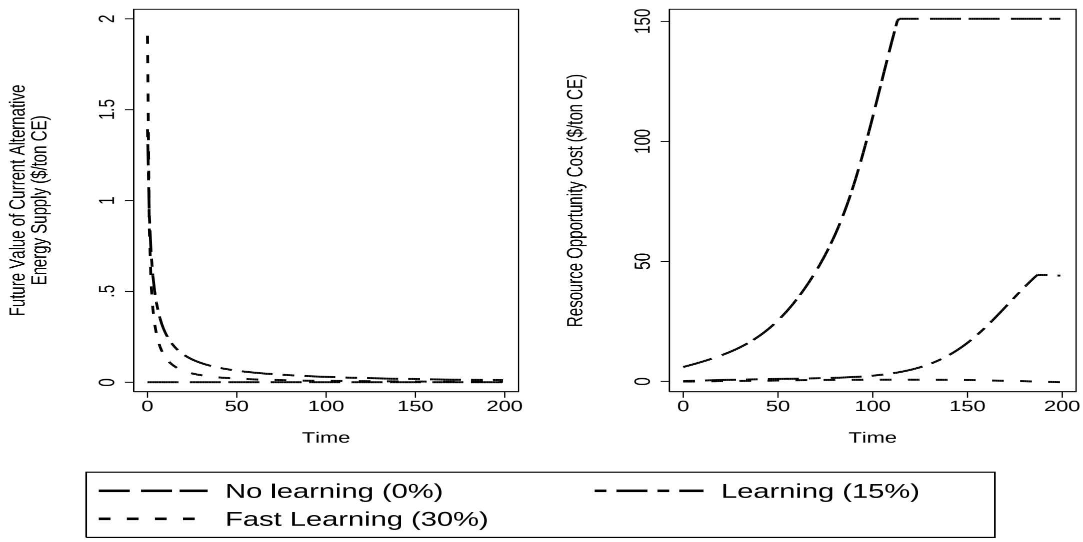


**Fig. 4**. Resource opportunity costs and marginal future value of current alternative energy production over time across learning rates.

learning, the opportunity cost of resources after this point is constant. In the learning cases, this is not true - resource opportunity costs (or the value to a resource firm of an additional unit of resources) peak at the point of exhaustion by design and then decline over time after exhaustion. With learning, the dynamic problem of the resource owner is analogous to a model of resource extraction with a backstop and with decreasing (residual) demand for resources.[7] The opportunity cost of resources will always be positive, and will asymptotically approach the equilibrium energy price at the lower bound of alternative energy costs, $C(\infty, a^*)$.

In Figure 5, we project $\frac{\partial V_1(X',A')}{\partial a}$ and $\frac{\partial V_2(X',A')}{\partial X}$ onto the state space to show the degree to which, for a given state of the world, the alternative energy firm is willing to produce at a price below marginal cost and the importance the resource-owner places on conservation. Future values of alternative energy production today are largely intuitive. The gains from producing at a price below marginal cost are higher the more scarce are resources, the more potential learning remains, or the higher is the learning rate. In the two left-side

[7] The rate of cost decrease has slowed considerably by the time resource exhaustion occurs, and so the decreasing rents are not easily perceptible on the graphic. In the 25% learning case, at the time of resource exhaustion resource rents are $56.56/ton CE, while at t=150, the value of an additional unit of resources to the owner would be $55.25.

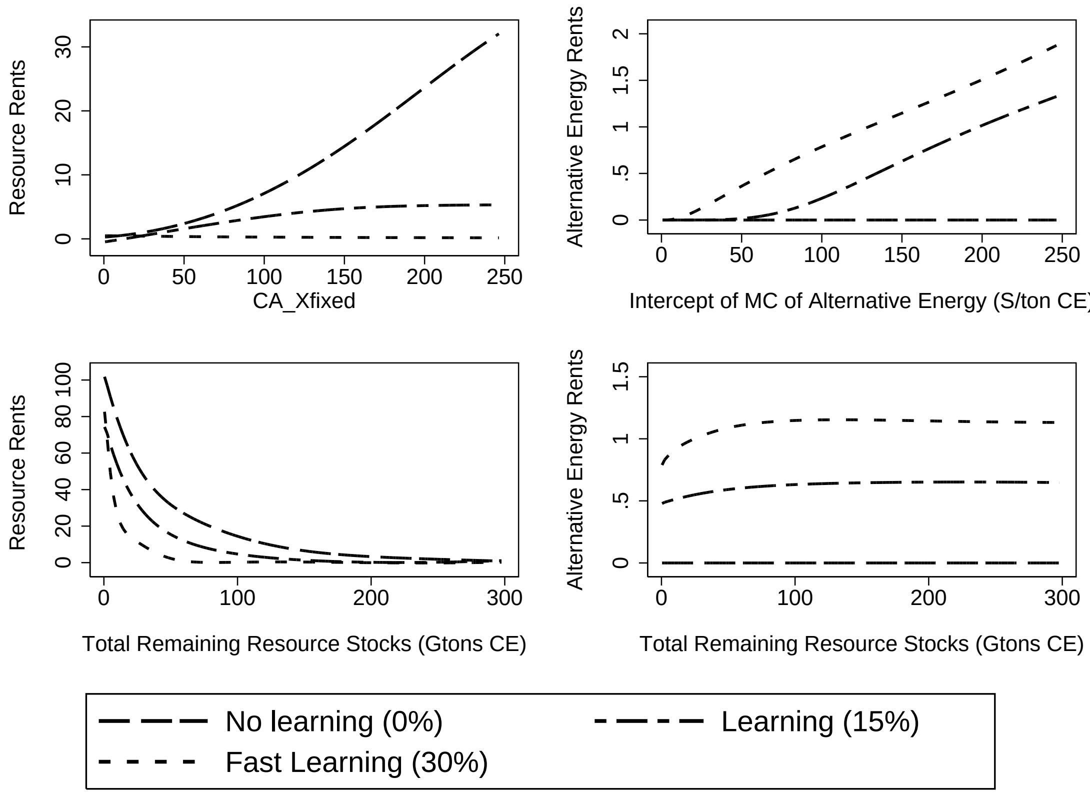


**Fig. 5**. Shadow values of resources and alternative energy production as a function of the state, for the same assumptions are the same as in Figure 2. All y-axis units are in \$/ton CE.

graphs, we see the important effect of learning rates on resource rents. Where learning can occur quickly, the future value of resources is negligible except when resource stocks will soon be exhausted. The future value of resources is monotonically decreasing in the learning rate and in the current cost of the alternative technology. Rather than suggesting that higher fossil fuel prices will drive learning-by-doing in the alternative sector, these results suggest that the greater is the potential for learning-by-doing, the lower are fossil fuel prices.

Figure 5 suggests the importance of evaluating resource pricing and alternative energy supply jointly as a function of the potential for endogenous technological change. This has important implications for results in work such as Nordhaus (2002) and Popp (2004, 2006) which are derived under an assumption that resource prices will follow a fixed rent/pricing function curve even in an environment with endogenous technological change. The resource opportunity costs for which owners must be compensated in our model are strongly negatively related to learning rates and to the cost of the alternative technology.[8] The resource opportunity cost function for the no-learning case is analogous to the resource pricing function used in DICE-99 and ENTICE, which defines the marginal opportunity cost of a unit of resource as the stock declines. Our results show how the potential for endogenous technological change should lower resource opportunity costs, which suggests that holding these values fixed would over-state the impact of allowing for such technological change in a climate model.

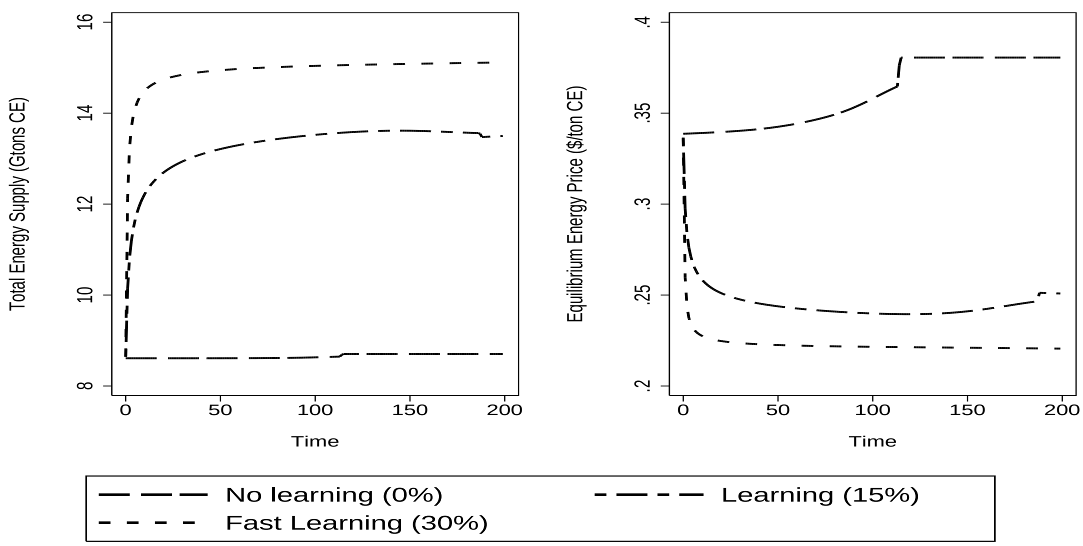


**Fig. 6**. Total energy supply and energy prices over time across learning rates

Figure 6 shows both total energy supply and energy prices over time for the learning rates. The equilibrium rents lead to interesting pricing profiles. The first important result of note here is that, the faster is learning, the lower is the energy price in all periods. Perhaps more importantly, we see energy prices declining or flat over much of the simulation path, as increasing alternative energy supply and relatively small resource rents combine. While we admittedly present a stylized model, Figure 6 is important since it shows that a subgame perfect resource extraction decision may lead to either increasing, decreasing, or constant energy prices over time. This is important for understanding results from empirical tests of the Hotelling model (summarized in Gaudet (2007)) as well as for understanding the

[8] For readers more accustomed to an optimal control treatment of resources, the values for $\frac{\partial V_2(X,\bar{A})}{\partial X'}$ can be interpreted as initial scarcity rents, which would then rise at the rate implied by the co-state conditions of the solution to the optimal control problem over time.

policy implications of induced innovation.[9] These initial results suggest that, in cases where learning-by-doing is possible, we should expect lower and possibly declining energy prices, rather than the traditional view in much of the climate change economics literature that increasing fossil energy prices, taken as given, will drive alternative energy production and endogenous technological change.

## 4.2 Policies to reduce carbon emissions

Above, we have shown that firm behaviour in both resource and alternative energy sectors will be altered significantly by learning rates in the absence of policies. In particular, we have emphasized the fact that, rather than modeling endogenous technological change as occurring as a result of resource prices which increase over time, it is imperative to internalize the reality that optimal resource prices will be lower the greater is the potential for endogenous technological change. This may invoke a stronger role for policies which can induce resource price increases earlier in the time horizon. Below, we show that these same dynamic incentives may significantly alter the results of such policies.

When carbon charges or alternative energy subsidies are introduced in our model, the present and future playing fields are altered for all firms in three key ways. First, emissions charges increase the marginal cost to the resource firm, and erode its ability to earn rent from the resource. This is magnified in the presence of the substitute energy source, which erodes rent extraction absent the increased cost of the fossil fuel. Second, the alternative technology is a relatively greater threat (i.e. it is more cost-competitive) under emissions charges or if production subsidy is offered, which also decreases expected future resource rents. Finally, from the alternative energy firm's point of view, since a carbon charge renders the technology it exploits more cost-competitive, future gains to learning-by-doing today may be increased since it can gain more market share in a shorter time.

Consider Figure **??** where we show the changes in emissions levels resulting from a \$25 per ton carbon charge an from an equivalent subsidy to alternative energy. Clearly a relationship exists between learning potential, economic state, and the effect of fiscal emissions control policies. Emissions reductions (in percentage terms) induced by a these

[9] In related work, we show that a social planner's decisions in a similar model can lead to "twin peaks" in energy prices. See Chakravorty, Leach, and Moreaux (2008).

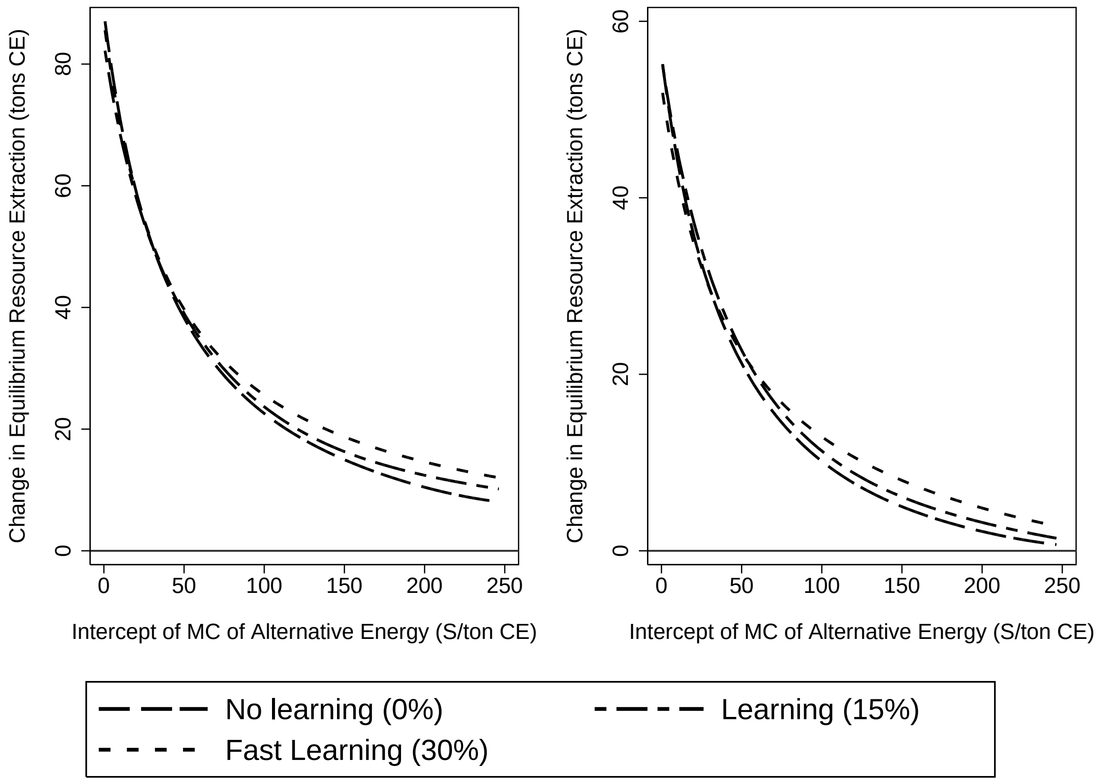


**Fig. 7**. Effect of $25 per ton CE carbon taxes (left panel) and alternative energy subsidies (right panel) respectively across learning rates.

policies are negatively related to the cost of the substitute technology and positively correlated with learning potentials.

When we set carbon taxes, we generally expect that three things will occur. First, we expect that energy prices will rise. Second, we expect that emissions will fall. Third, we expect that alternative energy supply will increase and, where possible, that this will drive increased experience accumulation and eventual cost reductions in the alternative sector. Similarly, we expect that an alternative energy subsidy will increase energy supply, and shift production toward alternative sources while decreasing the price of energy. While these expectations are realized in most cases in our model, learning rates and present states of alternative technologies have substantial influence on the magnitude of the effects of emissions taxes and alternative energy subsidies.

The incidence of taxes and subsidies on energy prices is strongly influenced by learning

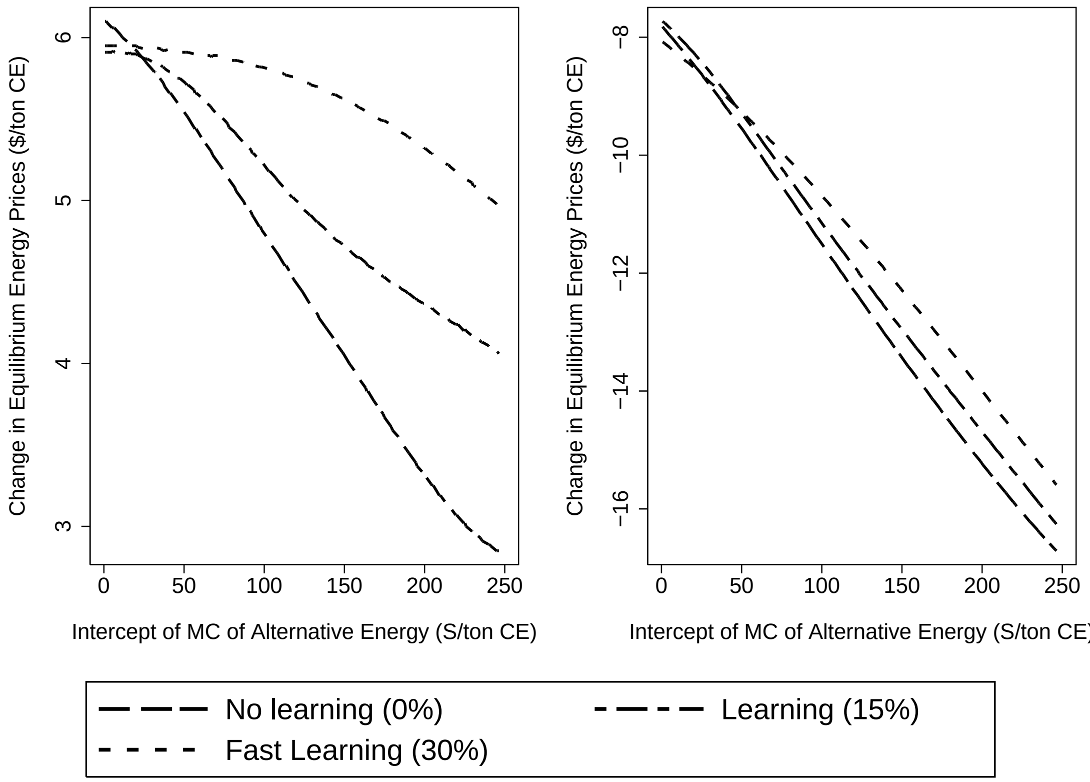


**Fig. 8**. Effect of $25 per ton CE carbon taxes (left panel) and alternative energy subsidies (right panel) respectively on the equilibrium energy prices in the economy.

rates. In Figure 8, we see the effect on energy prices of the two policies considered. For a carbon tax, the increase in energy prices is greatest where the most learning potential exists. This occurs because the carbon tax acts to erode the future value of resource stocks, and therefore the incentive to conserve. As such, there is less incentive for the alternative energy firm to over-supply to build experience. Prices increase because there is a decrease in resource extraction combined with a smaller increase in alternative energy supply. For slower learning rates, the resource firms have greater strategic motive to absorb some of the cost of the tax, and so the incidence of the tax on energy prices is lower. For an alternative energy subsidy, the overall effect on energy prices is always a reduction, however these reductions are highest for the lowest learning rates.

The causes of the effects on prices can be seen in the reaction of finite resource rents to policies changes shown in Figure 9. In the slower learning cases, the resource extraction firm can sacrifice some rents today to maintain market share. In the fast learning case, the strategy is not worthwhile as the subsidy renders the resources essentially irrelevant since any decrease in supply can be compensated for by only slightly more expensive alternative energy. Even if the alternative is more expensive now, in net present value terms, it would worthwhile for the firm to supply well below marginal cost, and so in Nash equilibrium, we see few resource rents collected and no strategic response to the subsidy or the tax. While we certainly acknowledge that the exact magnitude of responses, including the sign of the tax incidence, would depend on the supply and demand elasticities of the economy imposing the tax, the qualitative conclusions that resource rents, and the emissions reductions resulting from fiscal environmental policy, are highly variable as a function of the current cost of the alternative and the potential for endogenous technological change.

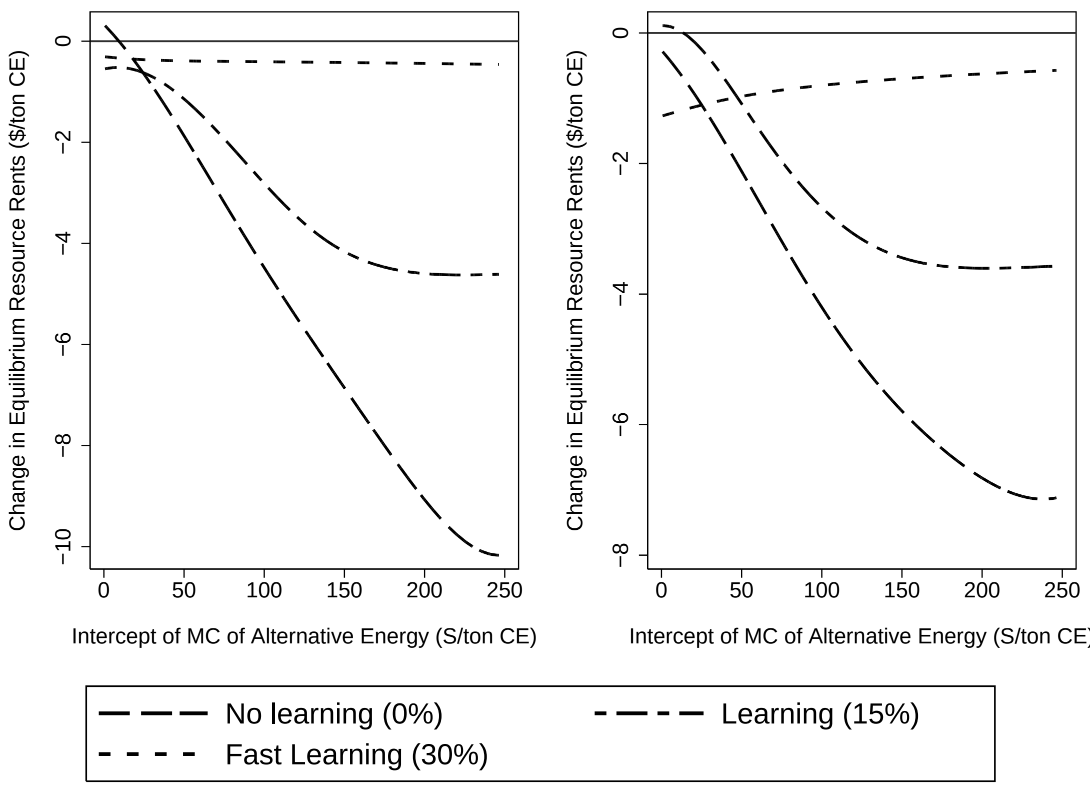


**Fig. 9**. Effect of $25 per ton CE carbon taxes (left panel) and alternative energy subsidies (right panel) respectively on the rents charged to finite resources.

Overall, we see that that it is important to consider the impact of emissions policy, learning, and competition on the resource firm's decision making with respect to extraction.

The traditional Hotelling rent curve is certainly not invariant to introduced emissions control policy or to the nature of the substitute advantaged by the policy. If we were to consider resource prices as fixed, we would certainly see a greater shift in the alternative energy supply being brought about by the subsidies, and more importantly we would not see the increase in propensity to extract brought about by strategic efforts to maintain market share. It would seem that, while much has been made of the expectation of increasing resource prices which Hotelling's model predicted and their interaction with carbon emissions control policy, it is important to remember that these policies will effect the degree to which optimal resource rent extraction will imply increasing prices over time.

## 4.3 First-best Alternative Energy Subsidies

Alternative energy subsidies are often intended to provide a "foot-in-the-door" for new energy sources. In our environment, we can also think of alternative subsidies as correcting for the market failure in learning-by doing. We tested the implications of a fixed subsidy for alternative energy development, presumably deployed as an emissions control policy, above. In this section, we examine what for the purposes of our model is a first-best subsidy which corrects the market failure in learning-by-doing. [10]

Alternative energy firms' capture only a small part of the aggregate future cost decrease generated by their production activities. We consider a policy which internalizes the benefits from each firm's production activities on all other firms. Specifically, we alter the optimal conditions of the alternative energy firms such that they continue to solve the following dynamic program:

$$\begin{aligned} V_1(X,A) = \max_{a_j} \;\; & p\Big(\phi \bar{f}(X,A) + \bar{a}(X,A) + a_j\Big) a_j - \int_0^{a_j} c\,(A,\tilde{a})\, d\tilde{a} + \tau_a a_j \\ & + \beta V_1(X',A') + \gamma_a a_j \end{aligned} \tag{12}$$

subject to:

$$X' = X - \bar{f}(X,A) \text{ and} \tag{13}$$

$$A' = A + \bar{a}(X,A) + a_j, \tag{14}$$

[10] As we do not specifically model climate damages, a first-best policy in this case must only internalize the market failure with respect to the public good aspect of alternative energy production.

but we define $\tau_a a_j$ such that in equilibrium firm $j$ is paid a subsidy for each unit of production which satisfies:

$$\tau_a = \sum_{k \neq j} \frac{\partial V_1(X', A')}{\partial a_j}, \tag{15}$$

and since all firms are symmetrical, this implies that

$$\tau_a = (m-1) \frac{\partial V_1(X', A')}{\partial a_j}. \tag{16}$$

The left-hand panel of Figure 10 shows the value of the subsidy for the base-case assumptions of $n = 1$ and $m = 50$ under the two learning scenarios (the subsidy is zero in the no-learning case since without learning, alternative energy production has no public or private future value). Not surprisingly, the subsidy is decreasing in accumulated experience and increasing in the magnitude of the learning rate. The right-hand panel of Figure 10 shows the effects of this subsidy on energy prices.

It is surprising that, for a doubling of the learning rate, only a small increase in the first-best subsidy is required. This is likely due to two factors. First, as the learning rate increases, holding resource stocks constant, there is less relative need to over-produce to capture market share, and smaller over-production needed to exhaust most of the learning opportunities. Second, as the model is calculated in Nash equilibrium, the higher learning rate generates a higher threat point which leads to lower resource rents, lower energy prices and requires lower actual subsidy payments under resources are extracted fully. We can also see that, when the alternative energy sector is rendered first-best through a subsidy, the incidence of that subsidy amount on energy prices is nearly 1:1.

## 4.4 Oligopoly in the Resource Sector

Assuming a single firm may overstate the role for strategic responses. We remove this assumption here by assuming a 4-firm oligopoly in the resource sector, with each firm owning an equal share of the resource. In the sections above, the resource firm would alter its rent extraction behaviour on the basis of the future value of the alternative energy cost function. As firms are added to the resource sector, there are fewer rents extracted in each period, and therefore we would expect the future value of resources to drop in absolute value. However, this change does not alter the key driver of the results presented above -

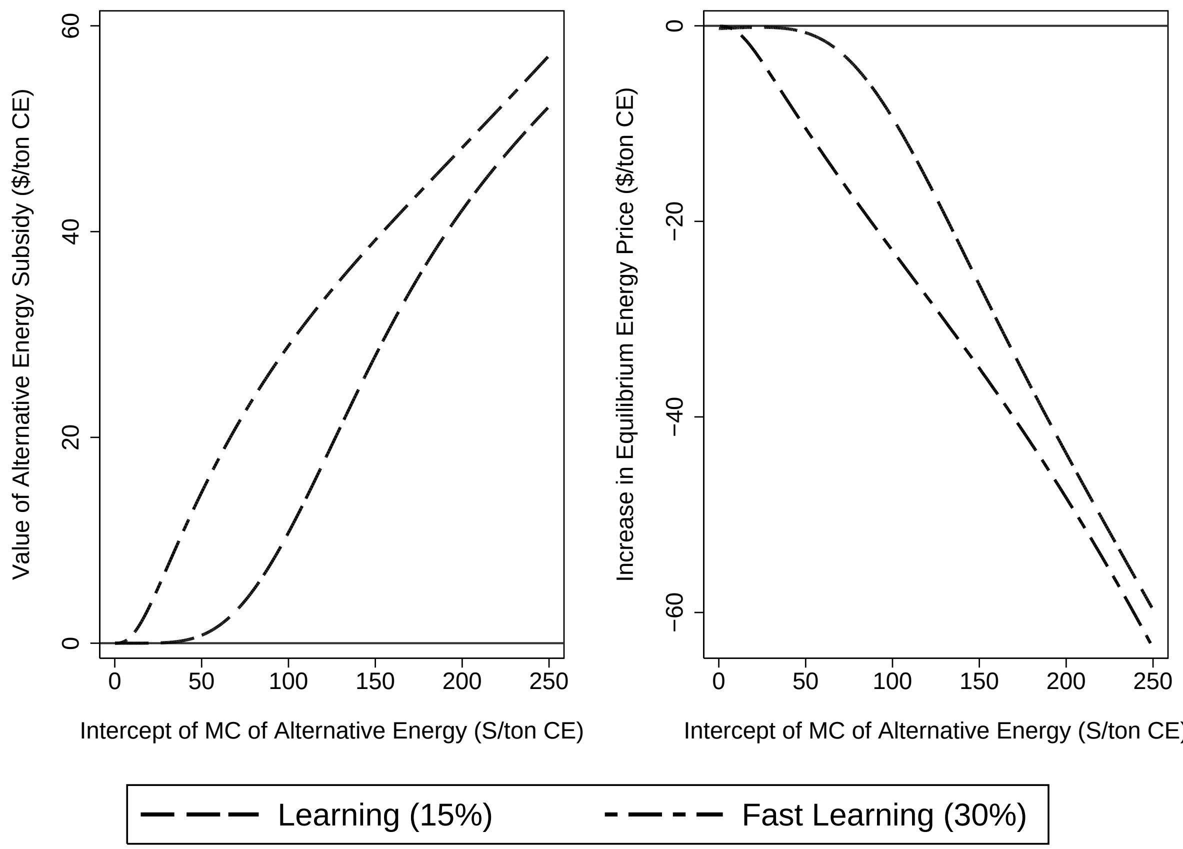


**Fig. 10**. Value of first-best alternative energy subsidy as a function of the cost of the initial unit of alternative energy, and the impact of the imposition of this subsidy on energy prices.

that resource rents will be highly sensitive to both the potential learning-by-doing in the alternative and the current cost state of the alternative energy source. The resource rents shown in Figure 11 replicate the rent curves developed in the right hand panel of Figure 4 and the bottom-left-hand panel of Figure 5, and show that resource rents are lower in absolute value, but follow similar paths in the 4-firm case as in the single firm case. Again, the peaks in the resource rents occur at the point of exhaustion, after which, even though there is no extraction, the marginal value of an additional ton CE of fossil fuel would be less as learning occurs.

The simulations in Figure 11 show two disturbing effects. Most importantly, in all cases the lower equilibrium resource rents lead to earlier extraction of the resource - this is not surprising. More importantly, this figure again highlights that in Nash equilibrium, it may

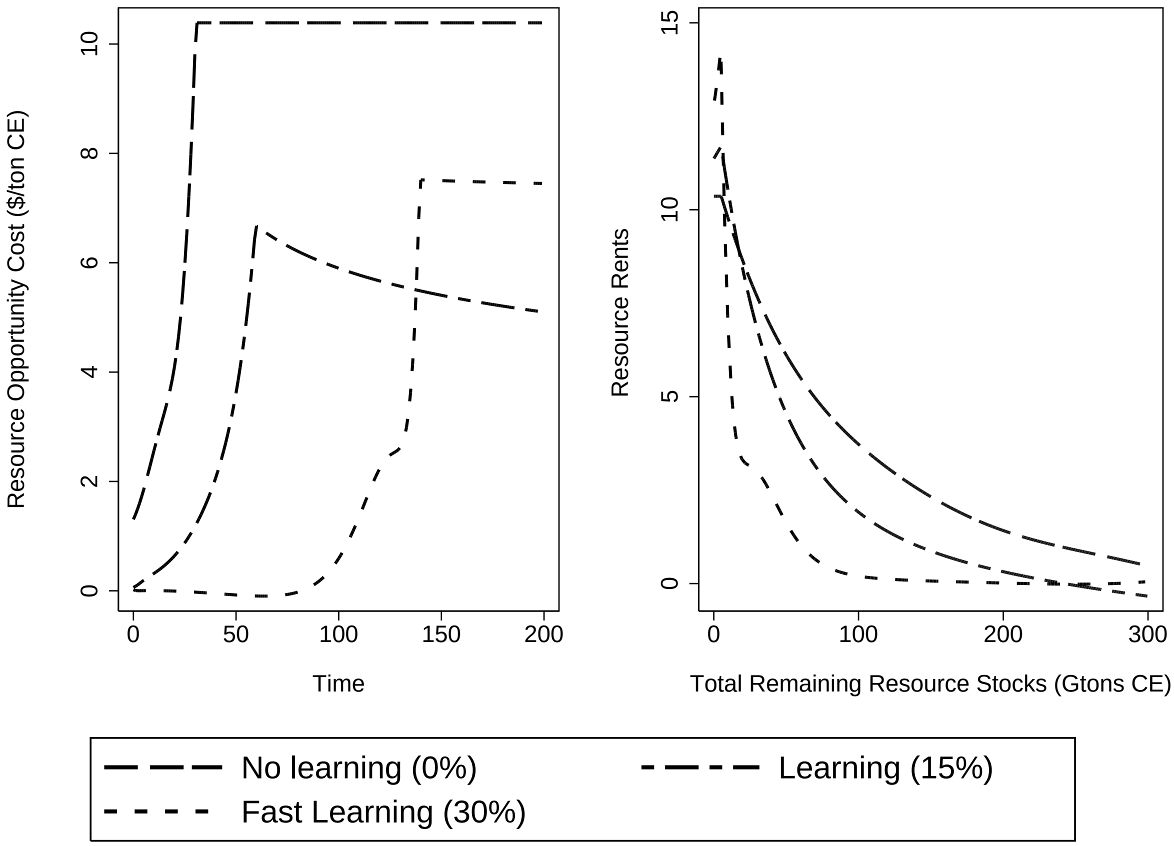


**Fig. 11**. Simulations over time and projections of resource rents onto remaining resource space when n=4.

not be optimal to charge significant rents on resources until they are very near exhaustion. This has disturbing implications for world energy markets which may be characterized as oligopolistic with a competitive fringe. If, as evidence suggests, energy producers are aware of the costs of alternative technologies and the implications for residual future demand for fossil fuels, we should not necessarily expect to see the long-term run up in energy prices as we head toward exhaustion. While this is certainly a stylized model, it produces a subgame perfect extraction equilibrium in which both extraction and prices are effectively constant until only 40-50 years before the stock is fully extracted.

# 5 Conclusion

This paper examines the role of learning-by-doing and environmental regulation on the extraction decisions of a strategic nonrenewable resource owner. In general, policy design has tended to focus on the roles of carbon taxes and scarcity in increasing energy prices and on the role of higher prices in inducing technological change, be it through research and development or learning-by-doing. We show an important reverse role. In our model, the higher the quality of the substitute, or the faster is learning, the higher may be the no-policy rate of resource extraction, which implies lower energy prices. In such a context, carbon taxes can have an important role in accelerating development of alternative technologies, however they may not always lead to large energy price increases. The latter has important consequences for climate policy evaluation, which has concentrated on the economy-wide effects induced by higher energy prices following from carbon taxes. Further, we show that while carbon taxes are immune to negative consequences in terms of emissions increases, the same cannot be said of an alternative energy subsidy. Our results suggest the potential for subsidies to increase emissions in states of the world where alternative energy sources do not currently represent a viable alternative to fossil fuels. We are able to show that, under a variety of conditions, extraction and price paths for finite resources do not match what has been traditionally viewed as a Hotelling path, and that with learning-by-doing in an alternative, optimal rent extraction may imply price paths which are increasing, decreasing, flat or all of the above.

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Table A-1
Parameter values and state variable initial conditions used for simulations

| Parameter | Description | Calibrated Value |
|---|---|---|
| **Energy Demand** | | |
| $\Omega_0$ | Total factor productivity | 59.46 |
| $\theta$ | Energy share of production | .05 |
| **Carbon Sector Cost Function** | | |
| $c^x$ | Constant extraction costs ($/ton carbon) | 300 |
| **Alternative Sector Cost Function** | | |
| $\zeta_1$ | Fixed component of marginal cost | 0 |
| $\zeta_2$ | Determines learning rates (reported) [a] | 0, 0.15, 0.3 |
| $\zeta_3$ | Slope of aggregate marginal alternative energy cost | .015 |
| **State Variable Fixed Conditions for Projections** | | |
| **and Starting Values for Simulations** | | |
| $X_0$ | Initial resource stock | 250 |
| $c(A_0, 0)$ | Alternative sector cost intercept | .25 |

[a] This parameter value is set such that the reduction in marginal cost for a doubling of accumulated experience corresponds to the learning rate specified.

# Approximate Numerical Solution

In order to solve the value functions, we use a technique described in Kelly and Kolstad (1999, 2001) and Leach (2007), which characterizes the fixed point of the value function using an iterative algorithm combined with a neural network approximation of the value function over a finite set of grid points.

The neural network approximation is defined as follows.[11] Define by $L = 16$ the number of nodes in the hidden layer, and let $n = 2$ represent the number of state variables in the model, such that the state space is $\mathbb{R}^n$. Denote by $\mathbf{x} \in \mathbb{R}^{n+1}$ a set of real-valued signals to the network, with the first element ($x_0 = 1$) being a bias signal (analogous to a constant), and the remaining elements being the state vector for a particular point in the state space. Let $\chi_1$ be a $(n+1) \times L$ matrix of inner weights, and let $\mathbf{z}(\mathbf{x}, \chi_\mathbf{1}$ be a $(L+1) \times 1$ vector, with the first element ($z_0 = 1$) being a bias signal. The additional elements ($z_1..z_L$) are the output values from the hidden layer of the network, $\mathbf{z_l} = \tanh(\chi'_{1l}x)\, \forall l = 1..L$, where $\chi_{1l}$ represents a column of $\chi_1$. The $L+1$ elements of $\mathbf{z}(\mathbf{x}, \chi_\mathbf{1})$ are then aggregated using outer weights $\chi_2$, a $(L+1) \times 1$ vector. We can thus express the approximation as:

$$\Phi(\mathbf{x}|\chi) = \chi_2' \left(z(x, \chi_1)\right). \tag{.1}$$

Using $\Phi_k(\mathbf{s_i}|\chi_\mathbf{k})$ to denote the approximation to the value (revenue) function of firm $k$ defined over $\mathbb{R}^3$, we use the following iterative algorithm to solve the simultaneous solution to the value functions in the competitive equilibrium.[12]

Denote the set of choices by $\{a^j(s_i)\}_{i=1}^N$ and $\{f^j(s_i)\}_{i=1}^N$ for alternative energy supply and resource extraction respectively, for iteration $j$. Given this notation, the solution algorithm is implemented as follows:

### Numerical Approximation Algorithm

*Algorithm Preliminaries*: Choose a convergence criterion $\epsilon$, number of neural network nodes $L$, and starting values for the weights $\chi_{1,k}$ and $\chi_{2,k}$ in $\Phi_k(\mathbf{x}|\chi_\mathbf{k})$ for $k = \{a, f\}$. Define ranges for each of the state variables to be covered by a grid, and a number of points $N$ to make up the grid. Draw $N$ points from a 2-dimensional low-discrepancy

[11] For a detailed discussion of neural networks, the interested reader is again referred to Hassoun (1995).

[12] The approximation at state space point $s_i$ is defined over $\mathbb{R}^3$ - the 2-dimensional state space, plus a constant. We use the notation $s_i$ without the addition of the constant for simplicity.

sequence and transform these points to meet the desired bounds of the state space.[13] We set $\epsilon = 10^{-4}$, L=12, and N=1000. We set state space bounds so that $0 \leq X < 500$ and $0 < A^{-\zeta 2} < .2$.

*Step 1*: Solve the maximization problems given in (4) and (9), taking other firm's choices as given. For iteration $j$, at each each state $s_i$, $a^j(s_i)$ solves:

$$p\Big(f^{j-1}(s_i), a^j(s_i), Z\Big) - c\left(A, a^j(s_i))\right) + \tau_a + \beta \frac{\partial \Phi_a((\mathbf{s_i}'|\mathbf{x_i},\ f^{j-1}(s_i),\ a^j(s_i))|\chi_{\mathbf{a}}))}{\partial a} + \gamma_a = 0, \tag{.2}$$

while $f^j(s_i)$ solves:

$$\begin{aligned} &p\Big(f^j(s_i) + a^{j-1}(s_i), Z\Big) + f^j(s_i)p'\Big(f^j(s_i) + a^{j-1}(s_i), Z\Big) - c_X - \tau_f \\ &-\beta \frac{\partial \Phi_f((\mathbf{s_i}'|\mathbf{s_i},\ f^j(s_i),\ a^{j-1}(s_i))|\chi_{\mathbf{f}}))}{\partial X'} + \beta\phi \frac{\partial \Phi_f((\mathbf{s_i}'|\mathbf{s_i},\ f^j(s_i),\ a^{j-1}(s_i))|\chi_{\mathbf{f}}))}{\partial Z'} \\ &-v_f + \gamma_f = 0. \end{aligned} \tag{.3}$$

*Step 2*: Denote by $\Pi_k(a^j(s_i), f^j(s_i), s_i)$ the profit of firm $k$ at state $s_i$ given choices. Update the value for each firm $k$ at each point on the grid as:

$$V_k^{j+1}(s_i) = \Pi_k(a^j(s_i), f^j(s_i), s_i) + \frac{1}{1-\beta}\Phi_k((\mathbf{s_i}'|\mathbf{s_i},\ f^j(s_i), a^j(s_i))|\chi_{\mathbf{k}})) \tag{.4}$$

*Step 3*: Use updated values $\{V_k^{j+1}(s_i)\}_{i=1}^N$ to solve for new weights $\chi_{1,k}$ and $\chi_{2,k}$ that minimize $\|V_k^{j+1}(s) - \Phi_k(\mathbf{s}|\chi_{\mathbf{k}}))\|$.

*Step 4*: Return to Step 1 unless $\sum_{i=1}^N \left(V_k^{j+1}(s_i) - V_k^j(s_i)\right)^2 < \epsilon$ for each firm.

As specified in the text, we make a change to the model so that it can be solved using the algorithm detailed above. Since the model is not stationary in accumulated experience, $A$, we redefine the the model in terms of the cost-intercept-shift term, $A^{-\eta}$, which will always be bounded from below by zero and from above by its initial value, $A_0^{-\eta}$. The other state variable, $X$ is implicitly bounded as it can never exceed its initial value and is bounded by zero from below.

[13] We use a Halton sequence to draw a set of grid points which are uniformly distributed within the state space. For details on low-discrepancy sequences, see Judd (1998).