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Ujjayant CHAKRAVORTY, Andrew LEACH and Michel MOREAUX

Institut d'Economie Industrielle (IDEI) – Manufacture des Tabacs
Aile Jean-Jacques Laffont – 21, allée de Brienne – 31000 TOULOUSE – FRANCE
Tél. + 33(0)5 61 12 85 89 – Fax + 33(0)5 61 12 86 37 – **www.idei.fr** – contact@cict.fr

INSTITUT D'ECONOMIE INDUSTRIELLE

Would Hotelling Kill the Electric Car? ⋆

Ujjayant Chakravorty,[a] Andrew Leach,[b,∗] and Michel Moreaux[c]

[a]Department of Economics and School of Business, University of Alberta
Business Building, University of Alberta, Edmonton, Alberta, T6G 2R6, Canada

[b]School of Business, University of Alberta (CIRANO, CABREE)
3-40K Business Building, University of Alberta, Edmonton, Alberta, T6G 2R6, Canada

[c]Toulouse School of Economics (IDEI and LERNA)
21 allée de Brienne, 31000 Toulouse, France

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Abstract

In this paper, we show that the potential for endogenous technological change in alternative energy sources may 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 necessarily the case that scarcity-driven higher traditional energy prices over time 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 resource extraction and greenhouse gas emissions. We show that the effectiveness and the incidence of emissions reduction policies may be altered by increased potential for technological change. Our results suggest that treating finite resource rents as endogenous consequences of both technological progress and policy changes will be important for the accurate assessment of climate change policy.

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

JEL classification: TBD

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∗ Corresponding author. Email address: andrew.leach@ualberta.ca.

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In this paper, we show that the potential for endogenous technological change in alternative energy sources may 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 necessarily the case that scarcity-driven higher traditional energy prices over time 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 greenhouse gas emissions. We show that the effectiveness and the incidence of emissions reduction policies may be altered by increased potential for technological change. Our results suggest that treating finite resource rents as endogenous consequences of both technological progress and policy changes will be important for the accurate assessment of optimal responses to climate change.

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1 Introduction

The contention of the 2006 film 'Who killed the electric car' is that, among other factors, strategic action on the part of the oil companies to maintain low fuel prices led to the devaluing of the electric car and led to its demise.[1] The scenario does not seem so far fetched as, in the midst of increasing oil prices in the Summer of 2008, Saudi Arabia called an emergency summit to address issues including the possibility that continued high oil prices would lead to increased uptake of alternative energy sources and lead to a permanent residual demand shift, or so-called *demand-destruction*. While oil prices have declined significantly since mid-2008, the view that alternative energy source may threaten the rents of finite resource owners remains. In late 2009, OPEC stated that, "energy policies and behavioural changes are bound to have some impact on consumption and this will gradually feed into overall demand patterns."

Our paper models a situation where resource oligopolists consider the future production from an alternative energy sector when determining the optimal supply from their finite resource. While it is often assumed that increasing resource prices driven by scarcity will lead to increased uptake of alternative energy sources which in turn will drive cost reductions in those sources, we show the opposite possibility. Our results suggest that where substitute energy sources have a high potential for learning-by-doing, this may induce higher rates of resource extraction and thus lower energy prices and less alternative

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

energy supply in spite of resource scarcity. Further, we show that both the effectiveness and price-incidence of environmental policies will be affected by increasing potential for learning-by-doing in alternative energy sources.

Strategic responses to competition have been extensively explored in the context of renewable and non-renewable resource management. Crabbé and Long [1993] examine a situation where fishery owners react to the potential entry of poachers by catching more fish even though poachers are less efficient. Mason and Polasky [2002, 1994] find that the actions of a common-property monopolist facing the threat of entry may lead to extinction of the resource, while competition from the outset would not. Harris and Vickers [1995] examine a case where a finite resource owner takes into account the endogenous probability of their consumers developing an alternative source of energy. They find that uncertainty over the time before a backstop technology displaces the resource-owning monopolist from the market is analogous to an increase in the resource owner's discount rate, reducing the shadow value of resource stocks. Similarly, in Cairns and Long [1991], excessive rent-seeking by resource owners leads to diminished future rents as a result of regulation. Long and Sinn [1985] find that extraction paths are altered by the surprise imposition of tariffs which increase extraction cost, and that these effects are ambiguous in sign depending on the magnitude and growth rate of tariffs. Sinn [2008] finds that when policies are applied slowly on the demand-side, supply-side responses lead to lower energy prices today as owners extract rents before it's too late.

Each of the papers listed above describes changes in future values of resource stocks as a result of competition or policy changes. In our paper, we explore resource extraction responses in a model economy where resource owners face 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, and the implied conservation of the resource stock, may be discouraged since higher energy prices encourage production by the emerging substitute. In fact, optimal inter-temporal pricing of the resource may lead to increased near-term exploitation of the resource and less quantity response to impending scarcity. Depending on market conditions, relative costs, and learning potentials, an equilibrium with learning may result in resources being extracted earlier such that greater potential for endogenous technological change may actually exacerbate the climate change problem. And so, while deployment of new technologies will be driven by energy prices, those energy prices are likely to be negatively related to the potential for technological change. The end result is intuitive: the better is the alternative energy source, the less likely are resource owners to encourage its deployment.

Our results have important implications for the development of optimal climate policy. The premise that technological change in substitutes will be induced by higher traditional energy prices resulting from resource scarcity as well as by climate policy is common in the economics literature in papers such as Nordhaus [2002] and Popp [2004, 2006a]. In this paper, we argue that induced technological change may not be a magic bullet for climate change mitigation and that strategic responses should be included when adapting models to include potential technological progress. For example, Nordhaus [2002] and Popp [2004] each assume that finite resource prices are invariant to endogenous changes in the cost of the emerging alternative energy technology. We provide strong evidence that equilibrium resource pricing functions are likely to be negatively related to the potential for future cost reduction as well as to the stringency of climate change policy. Ignoring this effect may lead to an over-estimate of policy-induced emissions reductions and/or an under-estimate of the optimal carbon tax.

The paper proceeds as follows. In Section 2, we develop the theoretical model of the economy, and in Section 3 we characterize the dynamic, competitive equilibrium implied by this model. In Section 4, we use numerical simulations to characterize the dynamic equilibrium with and without policy intervention to illustrate the role of dynamic market incentives. We also test the sensitivity of our results to market structure assumptions. 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 most Integrated Assessment Models (IAM's). In particular, we do not allow for climate change damages arising from emissions. These simplifications are not crucial 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 meaning-

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 dynamic oligopoly with n price-setting, resource extraction firms who each own an equal share of remaining fossil fuel resources and a price-taking alternative energy sector acting as a competitive fringe with m firms. Each of the firms in the economy act to maximize the net present value of revenues with perfect foresight.

2.1 Energy Demand

The economy uses energy as an input to production. Energy, 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 $p(q) = \frac{\partial P(q)}{\partial q} > 0$. Further, $P(q)$ satisfies $\frac{\partial^2 P(q)}{\partial q^2} < 0$.[3]

2.2 Resource Extraction

An initial, known stock of a composite fossil fuel, X_0, measured in gigatons of carbon equivalent (GtC) units is owned and extracted by $n \geq 1$ symmetric firms.[4] Denote by X_i the resource stock owned by an individual firm and denote that firm's extraction in each

ful comparative dynamics regarding energy supply and resource rents. As long as the private incentives to reduce pollution for the sake of preventing future climate change (notwithstanding incentives provided by policies) 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 where the marginal product of energy is the first derivative of a Cobb-Douglas production function.

[4] Here and elsewhere, we omit time subscripts and adopt the following notation. We denote, for example, X_t by X and X_{t+1} by X'.

time period by f, so that:

$$X_i' = X_i - f, \tag{1}$$

and by symmetry, aggregate resource stock, X, evolves as a function of aggregate extraction, F, as follows:

$$X' = X - nf = X - F. \tag{2}$$

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

2.3 Alternative Energy Supply

An emissions-free substitute for fossil fuels is produced by an alternative energy sector comprised of m symmetric, price-taking, dynamically optimal firms acting as a competitive fringe. Alternative energy is an experience good, such that future costs decrease with cumulative production. Denote each firm's alternative energy supply by a, measured in MTOE, and let the marginal cost of production, given the level of cumulative production experience, A, be given by:

$$C(A, a) = C_{\mathrm{f}} + C_0 A^{-\eta} + C_{\mathrm{s}} m a. \tag{3}$$

In (3), $C_{\mathrm{f}}+C_0$ is the value of the price-intercept before any learning-by-doing has occurred, while $C_{\mathrm{f}} \geq 0$ represents the lower bound for the cost-intercept. The slope $C_{\mathrm{s}} \geq 0$ represents the rate at which marginal costs increase with current production levels, admitting the possibility of a merit-order of alternative energy supply.[5] Let the law of motion for experience be $A' = A + ma$. We make the simplifying assumption that experience is perfectly transferable across firms in the alternative energy sector and is a public good, and so 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 if $m > 1$.[6] The aggregate marginal cost and that for each individual firm will be weakly increasing in production in any period (ma), and weakly decreasing in the level of accumulated experience (A).[7]

We will not be able to solve the model as written since accumulated experience will be non-stationary. In order to solve the model, we re-write the alternative energy firms' problem in terms of the intercept of the marginal cost function:

$$\Lambda = C_{\mathrm{f}} + C_0 A^{-\eta}. \tag{4}$$

Conditional on initial value C_0, Λ' can be expressed as a function of current Λ and current total production (a) as:

$$\Lambda'(\Lambda, a) = C_{\mathrm{f}} + C_0 * ((\Lambda/C_0)^{(-1/\eta)} + ma)^{-\eta}. \tag{5}$$

[5] The inclusion of the multiplier m in the slope term ensures that the marginal cost of a particular aggregate quantity will be invariant to the number of symmetric firms.

[6] We explore, in our results section, cases where all gains from learning-by-doing are internalized by firms in the sector as well as a case where m is sufficiently large that returns to experience are a pure externality.

[7] We do not allow for experience depreciation, so that all experience accumulated remains relevant for all future time periods. Depreciation would be analogous to slower learning rates or a higher discount factor and would imply a lower future value of current alternative energy supply.

The alternative energy firm's problem is stationary since Λ is bounded from above by $C_0 + C_{\mathrm{f}}$ and bounded from below by C_{f}. We re-define an individual firm's marginal cost of alternative energy production as:

$$c(\Lambda, a) = \Lambda + C_{\mathrm{s}} m a. \tag{6}$$

3 Equilibrium and numerical implementation

We define optimal behaviour in each sector and solve for the stationary Markov-perfect equilibrium (SMPE) of this economy. The economic state $S = \{X, \Lambda\}$ consists of the individual resource stocks owned by each of the n firms (X) and the cost of alternative energy production (Λ). Markov strategies $f(X, \Lambda)$ and $a(X, \Lambda)$ depend only on payoff-relevant information, and do not depend on time explicitly.[8] An SMPE is defined where $f(X, \Lambda)$ is the best response of each of the n resource owners to the strategy $a(X, \Lambda)$ of each of the m alternative energy firms and vice versa.

3.1 Optimal behaviour: Alternative energy sector

Alternative energy firms are identical and act as price takers. Let $f(X, \Lambda)$ represent the strategy of each fossil fuel firm and $\bar{a}(X, \Lambda)$ represent the total supply from the $(m-1)$ other alternative energy firms at each point in the state space, each taken as given. Each

[8] We do not consider punishment strategies or other equilibria which treat non-payoff-relevant histories as part of the information set. Since there is no autonomous technological change or other time trends, calendar time is payoff-irrelevant.

alternative energy firm solves the following dynamic program:

$$V(X,\Lambda) = \max_{a} \ p\Big(n\phi f(X,\Lambda) + \bar{a}(X,\Lambda) + a\Big)a - \int_0^a c\,(\Lambda,\tilde{a})\,d\tilde{+}\beta V(X',\Lambda') \qquad (7)$$

subject to laws of motion for X in (2) and for Λ in (5) and a constraint of $a \geq 0$. Omitting the non-negativity constraint and imposing symmetry which implies that $\bar{a}(X,\Lambda) = m\,a(X,\Lambda)$, the SMPE strategy for each alternative energy firm, $a(X,\Lambda)$, is the solution to:

$$p\Big(\cdot\Big) - c\,(\Lambda, a(X,\Lambda)) + \beta\frac{\partial V(X',\Lambda')}{\partial \Lambda'}\frac{\partial \Lambda'}{\partial a} = 0. \qquad (8)$$

The first-order condition in (8) equates the energy price to the marginal cost of alternative energy production net of the present value of the private future benefits of acquired experience, $\frac{\partial V(X',\Lambda')}{\partial \Lambda'}\frac{\partial \Lambda'}{\partial a}$. In this term, the first multiplier captures the change in net present value of the firm for a change in the cost of supplying alternative energy, and will always be positive. The second multiplier is the change in Λ which occurs due to an increase in alternative energy supply today. If learning is not possible, $\frac{\partial V(X',\Lambda')}{\partial a} = 0$. In this case, the problem of the alternative energy firm is static, and is analogous to a backstop energy source. Where learning is possible, the second multiplier will be negative, as future costs decline in a and so $\frac{\partial V(X',\Lambda')}{\partial a} < 0$. In this case, the alternative energy firm will be willing to produce at a price below marginal production cost in order to acquire experience to reduce future costs. Equation 3 implies decreasing returns to experience and so this shadow value will be decreasing in A, therefore increasing in Λ.

3.2 Optimal behaviour: Resource extraction

Each resource firm takes the extraction decisions of the other $(n-1)$ resource firms as given. Let f represent the individual firm's decision variable and let $\bar{f}(X,\Lambda)$ represent the total supply of the other $(n-1)$ resource owners (where $n>1$), and let $ma(X,\Lambda)$ represent the supply of alternative energy at a given point in the state space (the solution to (8)). Each resource-extraction firm solves the following dynamic program:

$$W(X,\Lambda) = \max_{f} p\Big(\phi f + \phi \bar{f}(X,\Lambda) + m\, a(X,\Lambda)\Big) f - c_X f + \beta W(X',\Lambda') \tag{9}$$

subject to laws of motion for X in (2) and for Λ in (5), and with choice constraint $X \geq f \geq 0$. Since fossil fuel firms are symmetric and take the actions of their competitors as given, $\bar{f}(X,\Lambda) = n\, f(X,\Lambda)$. The SMPE strategy $f(X,\Lambda)$ solves the first-order condition for the dynamic program in (9) given by:

$$\frac{\partial p\big(\cdot\big)}{\partial f} \phi f(X,\Lambda) + p\big(\cdot\big) - c_X = \beta \frac{\partial W(X',\Lambda')}{\partial X'}. \tag{10}$$

The first terms defining optimal resource extraction in (10) are standard for an oligopolist.[9] The firm equates the marginal revenue from further extraction with the sum of the extraction cost and the marginal future value of resources, $\frac{\partial W(X',\Lambda')}{\partial X'}$. The marginal future value of resources will be decreasing in the level of stock remaining and increasing in the cost of the alternative energy source, i.e. $\frac{\partial^2 W(X',\Lambda')}{\partial X^2} < 0$ and $\frac{\partial^2 W(X',\Lambda')}{\partial X' \partial \Lambda'} > 0$. While the resource extraction firms do not act as leaders, and so do not internalize the effect of

[9] Shadow values for the stock and non-negativity constraints are omitted from (10) for clarity.

extraction on alternative energy supply, $\frac{\partial a(X,\Lambda)}{\partial x}$, the response of the alternative energy sector affects resource extraction strategies. In equilibrium higher learning rates imply greater value of alternative energy supply, and any increase in supply lowers future alternative energy production costs and reduces the future value of resources. Similarly, a low-extraction decision by the firm would imply higher alternative energy production, more gain in experience, and less future resource value.

3.3 Characterizing the equilibrium

The SMPE is characterized by stationary Markov strategies $f^*(X,\Lambda)$ and $a^*(X,\Lambda)$, which satisfy (7), (8), (9), and (10). This simultaneous solution to four differential equations does not admit an analytical solution and so it is not possible to rigourously prove existence or uniqueness. However, we can draw on both results in the literature and numerical approximations to characterize the equilibrium.

Our model is analogous to the resource oligopoly in common property characterized by Salo and Tahvonen [2001], but the solution is complicated by the potential for learning-by-doing.[10] Like Salo and Tahvonen, we test for the necessary properties of the dynamic programming problem numerically. Rather than approximating the policy functions as adopted by Salo and Tahvonen, we employ a modification of the value function iteration algorithm of Kelly and Kolstad [1999] and Leach [2007], which characterizes the simul-

[10] When learning is not possible, (7), (8) become static conditions, since there is no impact of the choice variable, a, on the future cost of alternative energy.

taneous solution to each firm's dynamic program as the fixed point of a neural network approximation of the firm's value function over a discrete grid representing the state space.[11] The approximate value functions we derive conditional on the parameters defined in Section 3.4, are continuously differentiable over the state space (X, Λ) and the reaction functions intersect at a single locus. This yields a unique pair of $f^*(X, \Lambda)$ and $a^*(X, \Lambda)$ for each point (X, Λ) in the state space which constitutes the unique SMPE for our problem.

3.4 Parameterization

The intent of the present study is to provide qualitatively-informative comparative dynamics, not to draw specific quantitative conclusions which would be sensitive to particular parameter values and functional forms. As a result, we have kept the model sufficiently simple so as to clarify the intuition behind the results. To illustrate the economic relevance of our conclusions, we use parameters and functional forms which are comparable to those used in Integrated Assessment Models (IAMs) of climate change in the economics literature. The complete set of parameters used in the model solution and simulation is provided in Table 1 in the Appendix. We discuss key assumptions made to parameterize the model below.

Energy demand is assumed to be constant, and is described by a total revenue product

[11] A complete characterization of the algorithm used is available in Leach [2007]. The only change to the algorithm is that approximations for the value function of each firm type are calculated at each iteration.

function given by Ωq^{θ}, with Ω calibrated to match the total factor productivity, and labour and capital contributions in the first period of Nordhaus [2008]. The energy share of production is separated out by defining $\theta = .05$. We make a strong assumption that the two energy sources are perfectly substitutable, so $q = ma + n\,\phi f$, where ϕ is the energy content (MTOE/GtC) of fossil fuels, set to 1.45 to match the approximate value of this ratio in International Energy Agency [2007].

There is extensive evidence in the literature suggesting that market power plays a role in fossil fuel pricing. Nordhaus [2008], from which our model is derived, includes a composite fossil fuel which is supplied at marginal extraction cost plus a *markup*, which captures "transportation, distribution costs, and national energy taxes and is assumed to be constant over time." We assume that a portion of the difference between extraction costs and market prices is a result of the collection of oligopoly rents. Evidence, for example from Smith [2009] or Johansson et al. [2009], suggests that market power exercised by OPEC remains an important element in the global pricing of oil. Evidence also exists for market power in other energy commodities including electricity (see Joskow and Tirole [2000]), natural gas (see Hubbard and Weiner [1991]), coal (see Kolstad and Wolak [1983]), and gasoline (see Chakravorty et al. [2008] or Borenstein and Shepard [1996]). Nordhaus [2008] assumes an average markup of $350/ton of carbon (tC) for high income countries. In our benchmark model, we assume that finite resources as described by Nordhaus are owned by a symmetric oligopoly (n=3) which implies that one third of the Nordhaus *markup* is collected by resource owners in the form of oligopoly rents, with the remainder fixed within extraction cost. These rents are endogenous, and so will be modified by the resource owners in response to competition or future market share loss. [12], [13]

We model the alternative energy sector by assuming that a composite commodity is produced by price-taking firms. The production cost structure is intended to capture key stylized facts of alternative energy supply. First, the technology exists today to supply small quantities of energy at prices competitive with fossil-fuel-based energy. Second, the marginal cost of emissions-free energy would rise if we attempted to supply a greater portion of total consumption today; i.e. the merit order of supply is upward sloping. Third, as learning-by-doing occurs, costs will decrease and the market share held by emissions-free energy sources will increase, *ceteris paribus*. Finally, while learning-by-doing will be important to reducing future costs within the sector, only part of these gains will be realized by the firms currently engaged in alternative energy production. Each of these are discussed in turn below.

Our model posits an upward sloping marginal cost curve for emissions-free energy which is consistent with International Energy Agency [2005] and Energy Information Administration [2009] studies of production costs. An upward sloping supply curve at any point in time reflects a number of factors including different emissions-free energy sources, vin-

[12] The total value of market power rents varies with the choice of n; for example (n=1) yields oligopoly rents of \$230/tC, (n=2) yields rents of \$175/tC, and (n=10) yields oligopoly rents of \$30/tC. We address sensitivity to the choice of n in Section 4.3.

[13] This assumption, combined with the other parameters of the model described above, implies a fixed extraction cost of \$34/bbl (\$193/toe), with a market price equivalent to \$50/bbl in the first period of our benchmark simulation.

tage capital, and high-grading of generation sites.[14] The supply curve shifts downward as learning-by-doing occurs. We consider three learning scenarios. For our base case, we adopt a progress rate of 15%. Given historic progress data and estimates of future progress reported by McDonald and Schrattenholzer [2001] and Energy Information Administration [2009], we test 0% and 30% rates of progress for comparison.

We base our production cost assumptions on Popp [2006b], Energy Information Administration [2009], and International Energy Agency [2005]. We set the initial value for Λ, the marginal cost of the first unit of alternative energy supply, such that our base case predictions are consistent with International Energy Agency [2007] data showing 55 Mtoe of energy supplied globally using wind, solar and geothermal out of a global total supply of 11,000 Mtoe. Popp assumes that a backstop technology exists which supplies energy inelastically, and tests costs assumptions for this technology of 1.5-5 times the cost of fossil fuels, or \$432 to \$2100/toe. Energy Information Administration [2009] examines current technology and finds that the most expensive technology being employed for new electricity generation is solar photovoltaic at a levelized cost of \$4845/toe - almost twice the cost considered by Popp. We assume that the slope of the supply curve of alternative energy is such that, if we were to supply all current energy consumption of more than 11 Gtoe with renewable sources, the marginal cost of that energy would be the mid-range of

[14] For example, consider wind turbines where multiple technology vintages may be in use at any point in time, leading to an upward sloping merit-order of supply. Further, even if technology were to be the same in all turbines, better sites would generate at a lower average cost due to higher capacity factors, again implying an upward sloping supply curve.

the estimates considered by Popp at \$1200/toe.

The lower bound for emissions-free energy supply is important for our results since its magnitude relative to the extraction cost of fossil fuels will determine whether economic exhaustion of the fossil fuel resource may occur before physical exhaustion. Obviously, the limits to future learning-by-doing are speculative. We assume that as cumulative experience with emissions-free energy production tends to infinity, the price-intercept of marginal cost tends to zero, so $C_f = 0$ in (6). However, the chosen value of $C_s = \$36.4/\text{toe}^2$ implies that once learning potential has been exhausted, the marginal cost of providing the amount of energy we use today would be \$400/toe, or roughly the cost of the cheapest emissions-free energy available today. These assumptions imply that fossil fuel supply would not be completely displaced as our assumed extraction and delivery cost is \$193/toe (\$282/tC). As such, resource scarcity will always bind in the long run, although the time to exhaustion may be much longer. This implies that alternative energy substitution will not change cumulative emissions of GHG's but may extend the time period over which they occur. Since climate change damages are generally assumed to be emissions-path-dependent, the results remain relevant to the design of effective climate policies.

Emissions-free energy firms take prices as given, but internalize the future benefit of cost reductions. We assume that the sector is made up of $m = 10$ small firms, each with an identical individual marginal cost curve such that the horizontal summation of the individual marginal cost curves yields the market merit order described above. For large

m, the individual marginal cost curves are essentially vertical, and thus learning has limited effect on individual firm values. For small m, the individual marginal cost curves are more horizontal, and thus learning will have a greater effect on the present value of the producers' surplus earned by the individual firm. We test sensitivity to an assumption of $m \to \infty$, where learning gains are treated as a pure public good by the fringe firms, and an assumption of $m = 1$, equivalent to a first-best alternative energy subsidy, in Section 4.3.

The values used in the numerical analysis are important for the quantitative but not the qualitative results presented below. The results will be most sensitive to four assumptions in addition to the market structure assumptions discussed above. First, the combination of the intercept and slope of the alternative energy supply are such that there cannot exist an equilibrium in which fossil fuels remain *in situ*, and so any emissions impacts of policies are merely questions of timing not cumulative quantities. Second, the assumption that the slope of the marginal cost of production alternative energy does not decrease over time may under-estimate the possible impacts of learning. Third, our model of the fossil fuel sector is simplified in that we don't account for either technological progress or increasing extraction costs. These are potentially offsetting since high-grading will lead to more challenging deposits being extracted later, and so by assuming constant extraction costs we have implicitly built in some technological change. Finally, our results are unlikely to be consistent under increasing or decreasing energy demand.

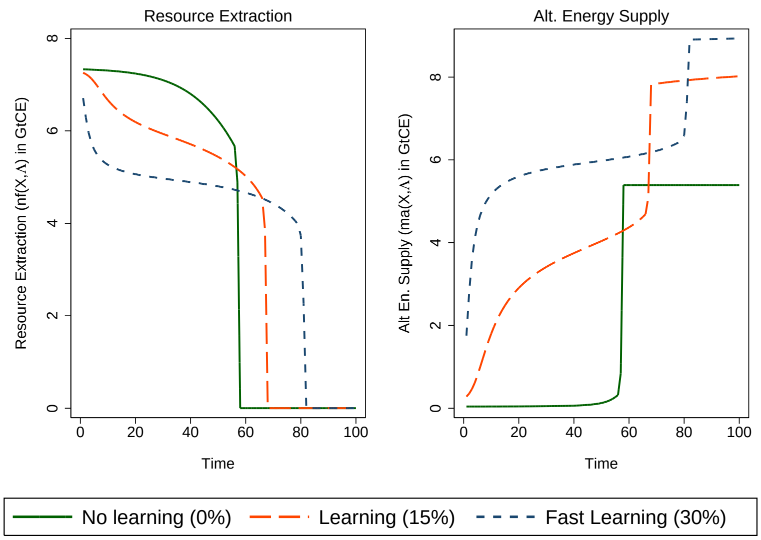

Fig. 1. Resource extraction and alternative energy supply over time for each of the considered learning rates.

4 Results

We characterize the equilibrium under three learning rates (0, 15, and 30%) using both simulations across time and projections of stationary Markov strategies and marginal values onto the state space.

4.1 Effects of learning-by-doing on energy supply

The potential for learning-by doing alters both alternative energy supply and resource extraction decisions. Figure 1 shows these choices over time for the same initial conditions for each of the 3 learning scenarios. Where no learning is possible, the time path of resource extraction and alternative energy adoption is analogous to that developed in Nordhaus et al. [1973] which assumed a perfectly elastic backstop alternative energy source. Adding

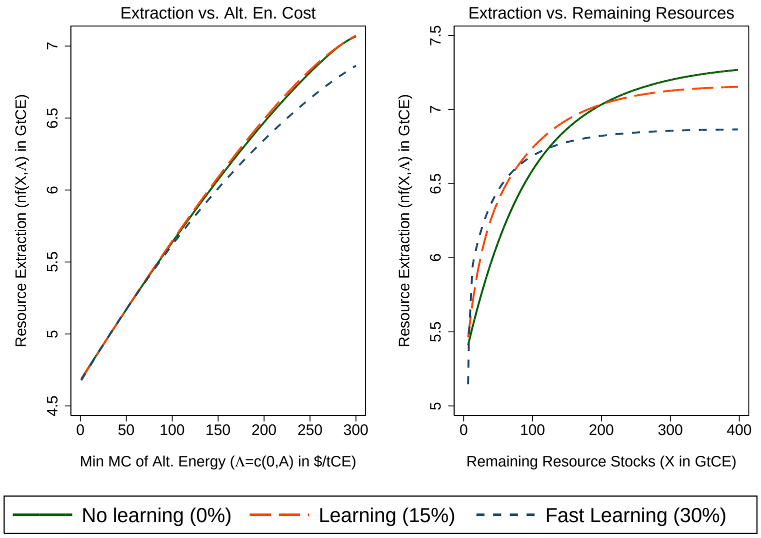

Fig. 2. Optimal extraction decisions of the resource-owning firm as a function of state values for each of three learning scenarios. The projection onto Λ-space in the left-hand panel treats aggregate remaining resource stocks as fixed at 400 GtC and the projection onto remaining-resource-space in the right-hand panel assumes Λ=$300/ton CE.

the potential for future cost reductions resulting from learning-by-doing leads to slower resource extraction with faster adoption of the alternative and slower resource exhaustion.

It is difficult to make meaningful generalizations based on a time path since the results will not necessarily generalize to all initial conditions. To characterize behaviour in more general terms, we examine the Markov strategies derived from the solution to the firms' problems, $nf(X, \Lambda)$ and $ma(X, \Lambda)$. Figure 2 shows projections of $nf(X, \Lambda)$ onto the state space. The left hand panel shows changes in equilibrium extraction which occur with changes in the alternative energy cost while the right hand panel shows how extraction decisions change with changes in remaining resource stocks. In each case the value of the other state variable is held constant.

The effect of learning-by-doing potential on extraction is more pronounced when alternative energy is more expensive, as shown in the left-hand panel. When the alternative energy source is of higher cost, extraction is more strongly decreasing in the learning potential. The potential for learning has an ambiguous effect on resource extraction depending on the level of remaining resources, as shown in the right-hand panel. When resources are plentiful resource extraction is decreasing in learning potential. This is due primarily to the willingness of the alternative energy firm to over-produce in order to take advantage of learning to decrease future costs. As resources become more scarce, the resource owner does not have the same incentive to conserve when learning is possible because the market will not bear higher prices given the availability of a substitute. As such, resource rents do not push down extraction rates as resources become scarce. This drives the reverse result that extraction is increasing in learning potential when resource are scarce. This is analogous to the *green paradox* of Sinn (2009), and similar to the reaction predicted by Crabbé and Long [1993] and Mason and Polasky [2002, 1994]; that extraction rates will increase, all else equal, in response to the increased threat presented by an alternative energy source with higher potential for learning. In Section 4.3, we show that this result is sensitive to assumptions about market structure, and that the choice of n and m will determine whether the effect of learning potential on resource extraction is ambiguous, positive, or negative.

Figure 3 shows the equilibrium supply decisions of the alternative energy firm. The results here are largely intuitive; equilibrium supply of alternative energy, $a(X, \Lambda)$ is decreasing

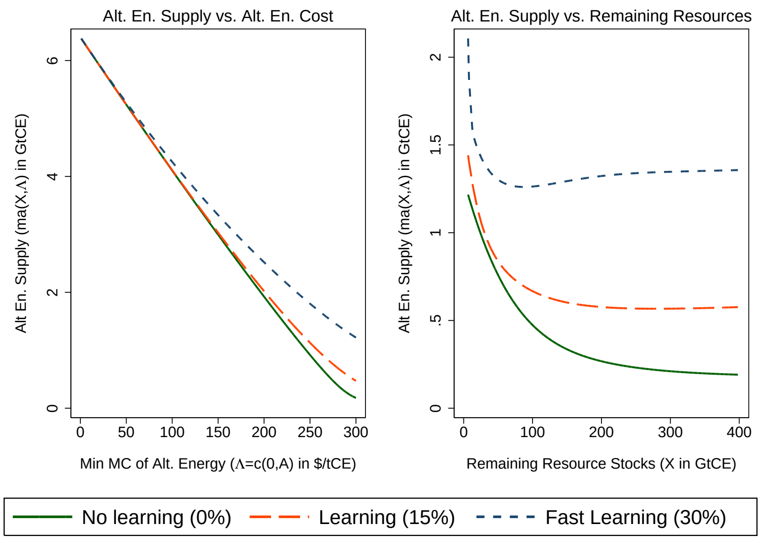

Fig. 3. Optimal supply decisions of the alternative energy firm projected onto the state space for each of three learning scenarios. Assumptions are the same as in Figure 2.

in the cost of supply (Λ) and in remaining resource stocks (X) and increasing in the assumed rate of cost reductions due to learning-by-doing. In the right-hand panel, we see that the increase in alternative energy supply due to resource scarcity occurs much closer to exhaustion with faster learning, as resource owners keep prices down through increased resource extraction. We show in Section 4.3 that the relationship between alternative energy supply and learning-by-doing potential is affected by market structure. In fact, under certain assumptions we show that greater learning potential may lead to less alternative energy supply as resources become scarce, *ceteris paribus*.

The future values of resource stocks, $\frac{\partial W(X',\Lambda')}{\partial X'}$, and the future value of cost reductions resulting from current alternative energy production, $\frac{\partial V(X',\Lambda')}{\partial \Lambda'}\frac{\partial \Lambda'}{\partial a}$, are key factors in determining the outcomes discussed above. While we do not model a Stackelberg game and

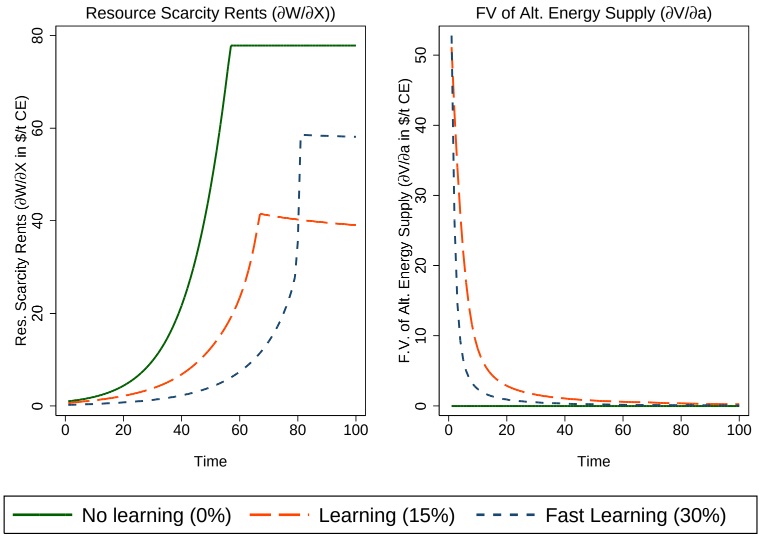

Fig. 4. Resource opportunity costs ($\frac{\partial W(X',\Lambda')}{\partial X'}$) and marginal future value of current alternative energy production ($\frac{\partial V(X',\Lambda')}{\partial a}$) over time for each of the tested learning rates.

so alternative energy supply is taken as given by the resource owners, the potential for cost reductions in the alternative energy source erodes future resource values as discussed in Section 3.2. 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 the marginal future value of current alternative energy production over time. In the left panel, the well-known results of Nordhaus et al. [1973] are replicated in the no-learning case where resource rents rise at the rate of discount until resources are exhausted. Since there is no learning, the opportunity cost of resources after this point is constant. In the learning cases, resource opportunity costs (or the value to a resource firm of an additional unit of resources at any point in time) peak at the point of exhaustion 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. The opportunity cost of resources will always be positive, and will asymptotically approach the equilibrium marginal revenue of resources at the lower bound of alternative energy costs.

In the right 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 15% cases, we see the expected results; 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. The non-monotonicity of the alternative energy shadow values over time is a consequence of the fact that the 30% learning scenario allows the alternative source to quickly decrease costs which quickly erodes the value of over-production in any one period.

The starting values of the simulations will determine the relative magnitude of resource and alternative energy shadow values. In Figure 5, we project $\frac{\partial V(X',A')}{\partial a}$ and $\frac{\partial W(X',\Lambda')}{\partial X'}$ 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

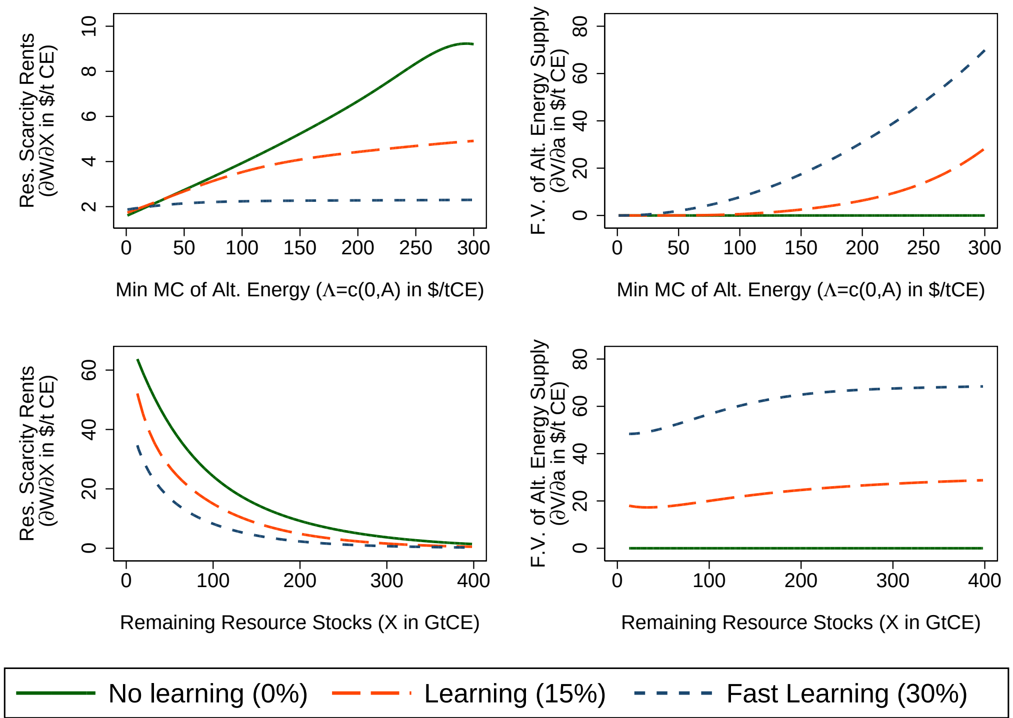

Fig. 5. Resource opportunity costs $\left(\frac{\partial W(X',\Lambda')}{\partial X'}\right)$ and marginal future value of current alternative energy production $\left(\frac{\partial V(X',\Lambda')}{\partial a}\right)$ projected onto the state, for the same assumptions are the same as in Figure 2.

resource-owner places on conservation. [15]

The left-hand panels of Figure 5 clearly show that the future value of resources is monotonically decreasing in the learning rate and increasing in the current cost of the alternative technology. This is analogous to the *green paradox* in Sinn [2008]. 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

[15] For readers more accustomed to an optimal control treatment of resources, the values for $\frac{\partial W(X',\Lambda')}{\partial X'}$ 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.

fuel prices.

Future values of alternative energy production today, shown in the right-hand panels of Figure 5, are largely intuitive. The gains from producing at a price below marginal cost are higher where more potential for cost reduction through learning remains, or the higher is the learning rate. What is perhaps counter-intuitive is that the willingness of alternative energy firms to over-produce today is lower as resource stocks move closer to exhaustion. This occurs because there is a greater incentive to conserve resources and to collect rents if the alternative energy source is more expensive as long as resources are scarce; $\frac{\partial^2 W(X',\Lambda')}{\partial X' \partial \Lambda'} > 0$. This remains true when learning may occur as the low stocks of remaining resource implies less gain to keeping the alternative source out of the market. Since the resource firm is willing to conserve, and thus bid-up energy prices, there is less need for the alternative energy firms to drive a wedge between price and marginal cost to increase production.

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 such as those in Nordhaus [2002] and Popp [2004, 2006b] which are derived under an assumption that resource prices will follow a fixed pricing function even in an environment with endogenous technological change. If the resource opportunity costs are not re-evaluated as a function of the introduction of technological change, our results suggest that these models would over-estimate resource prices, and

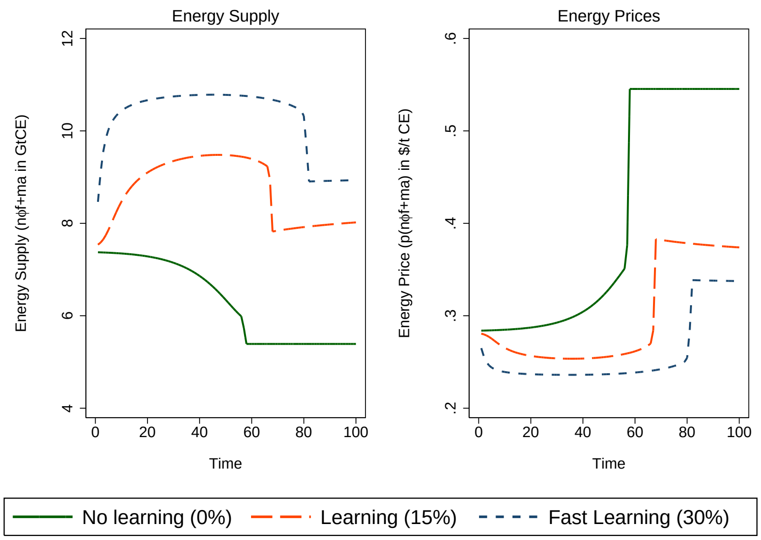

Fig. 6. Total energy supply and energy prices over time across learning rates

thus underestimate emissions, climate change damages, and the optimal carbon tax.

Figure 6 shows both total energy supply and energy prices over time for the 3 considered learning rates. The first important result shown 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. Figure 6 suggests that, in cases where learning-by-doing is possible, we may experience lower and possibly declining energy prices. This contrasts with 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.

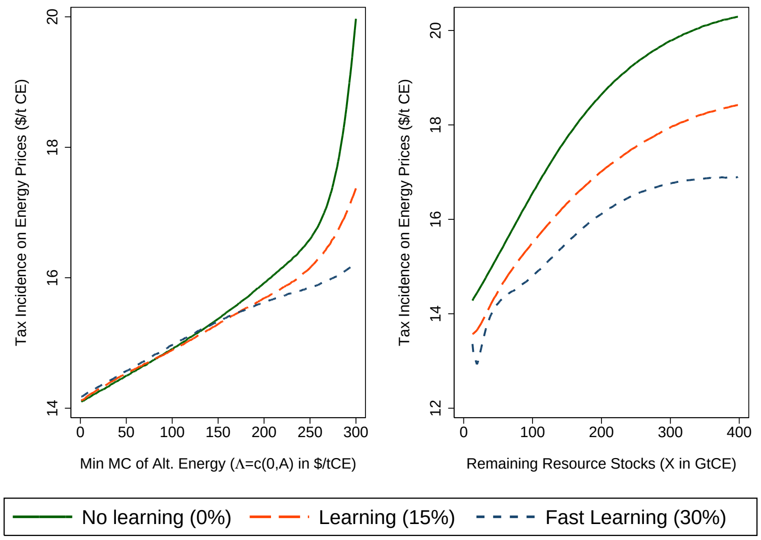

Fig. 7. Incidence of $25 per ton CE carbon taxes on equilibrium energy prices across states. Values of the state variable held fixed for projections are the same as in Figure 2.

4.2 Policies to reduce carbon emissions

The results reported thus far demonstrate that firm behaviour in both resource and alternative energy sectors will be altered significantly by learning rates in the absence of policies. While it is generally known that taxation of resources affects rent extraction, we are interested in how these effects may vary with the potential for learning-by-doing in an alternative energy source. When we set carbon taxes, we generally expect that energy prices will rise, fossil fuel supply will decrease, and alternative energy supplies will increase. We find that each of these expected effects occurs, but that their magnitudes vary with the assumed rate of technological progress. Below, we show how the dynamic incentives of resource owners may alter the incidence and effectiveness of fiscal policies. [16]

[16] We show the results of a carbon charge. Similar results derived for alternative energy subsidies do not add appreciably to the interpretation and so are not presented.

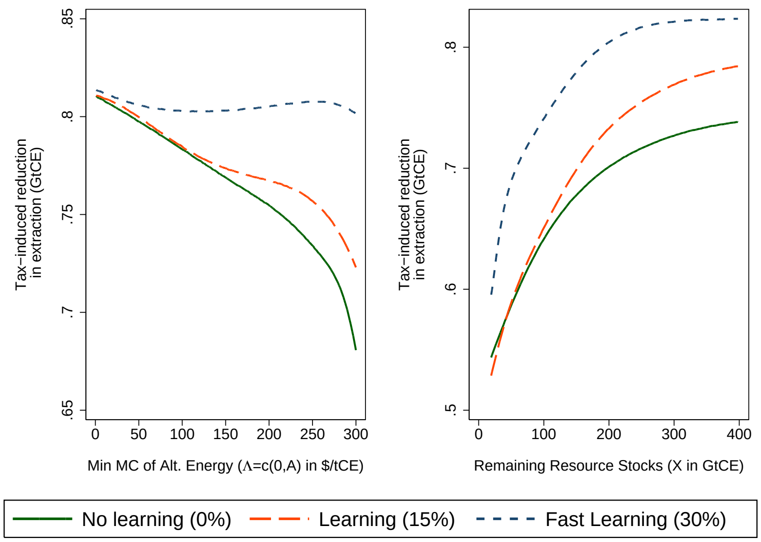

Fig. 8. Changes in Markov strategies $nf(X, \Lambda)$ after the imposition of a $25/ton carbon charge. Values of the state variable held fixed for projections are the same as in Figure 2.

Figure 7 shows that, while energy prices will rise in response to a carbon charge, the incidence of taxes on energy prices is negatively influenced by learning rates; the greater is the potential for learning, the lower is the incidence of the tax on energy prices. This effect is most pronounced at the points where we would normally look for the most effect of a carbon charge: where the alternative energy technology is most expensive, and/or where resource scarcity is not going to immediately speed the transition to alternative energy sources. The combined effect of decreased resource rents and increase alternative energy supply where learning potential is highest lead to the decreased tax incidence.

There are both direct and indirect effects of carbon charges on the decision-making environment. The direct effect of carbon charges is an increase in the effective marginal cost of resource extraction. While the effect is always captured in models of climate policy, the indirect effects may not be. The carbon charge erodes the future value of resource stocks $\left(\frac{\partial W(X',\Lambda')}{\partial X'} \text{ in } (10)\right)$, reducing the incentive to conserve. On the alternative energy side, the effect of the carbon charge on shadow values is ambiguous. The carbon tax makes fossil fuels more expensive and so there is less incentive for the alternative energy firm to over-supply to build experience $\left(\text{a decrease in } \frac{\partial V(X',\Lambda')}{\partial a} \text{ in } (8)\right)$. A countervailing effect occurs as the carbon charge makes the alternative energy sufficiently more cost-competitive to warrant an increase in the willingness to over-supply $\left(\text{an increase in } \frac{\partial V(X',\Lambda')}{\partial a} \text{ in } (8)\right)$. As shown in Figure 8, the sum of these direct and indirect effects amounts to a reduction in resource extraction. The effectiveness of a carbon charge is increasing in the potential for learning, the stock of remaining fossil fuel resources, and/or the cost of alternative energy technology.

4.3 Sensitivity to market structure assumptions

The results presented thus far suggest that resource extraction may be increased and resource scarcity rents will be decreased when there is potential for learning-by-doing in an alternative energy source. Below, we test the degree to which these results are robust to changes in market structure. Our assumption that oligopoly structure exists in the finite resource sector implies less (more) incentive to conserve resources and lower (higher) energy prices than would be predicted by a monopoly (perfectly competitive) structure. Further, our assumption that a finite number of firms operate in the alternative energy sector and internalize the private benefits of learning-by-doing on their own future production costs implies greater (less) dynamic behaviour than if learning-by-doing were taken as given (fully internalized) by firms operating in the competitive fringe. We show that our results are generally robust to these limiting cases for market structure, and that there are valuable lessons to learn where this is not the case.

We show results derived from 3 limiting cases. We first consider a model where we maintain the oligopoly structure for fossil fuels, but allow alternative energy production to maximize sector net-present-value; effectively a first-best subsidy which corrects the market failure in learning-by-doing. [17] We also consider the alternative case where each firm is infinitesimal ($m \to \infty$), and thus learning-by-doing is a public good. Finally, since our initial assumptions also limited the strategy space of the fossil fuel resource owners by assuming an oligopoly structure, we alter this assumption by looking at the case where $n = 1$, and so the net present value of resource stocks to the owner is maximized conditional on the existence of the competitive fringe (set at the base case value of $m = 10$).

Figure 9 shows the Markov strategies $f(X, \bar{\Lambda})$, for each of the variants of market structure. This figure shows significant sensitivity to the degree of market power and the degree to which learning-by-doing gains are internalized. The top-left panel shows the base case of $m = 10$ and $n = 3$, previously shown in Figure 2. To the right, we see the impact of assuming monopoly ownership. The first-order effect is that eliminating competition

[17] 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.

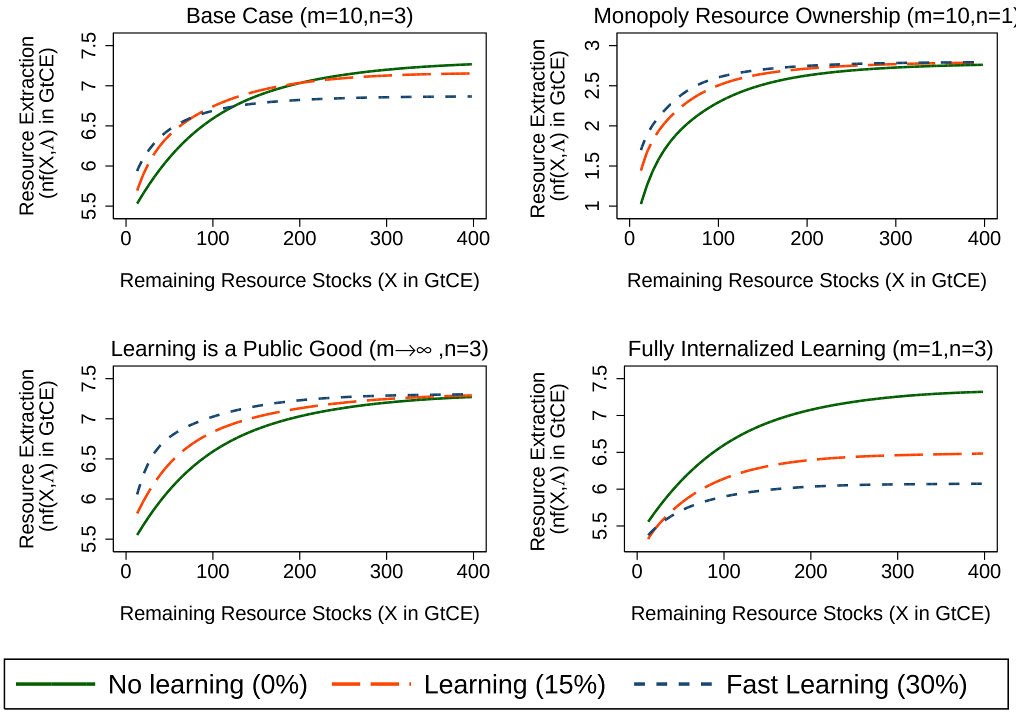

Fig. 9. The sum of equilibrium Markov strategies for the resource extraction firms projected onto remaining resource space for varying assumptions on the number of firms in the resource sector (n) and the number of firms in the alternative energy sector (m). Values of the state variable held fixed for projections are the same as in Figure 2.

leads to a stark decrease in extraction. The second-order effects are more interesting; under monopoly, rents are maximized through increasing extraction as learning potential is increased. This is a result analogous to those in the resource economics literature such as Crabbé and Long [1993] or Mason and Polasky [1994], since increased extraction leads to lower production of alternative energy and less future rent dissipation. As such, while monopoly is still better for the environment than oligopoly, it may be relatively worse for alternative energy technology since the greater market power allows for greater response to the threat to market share.

When learning-by-doing occurs as an externality, an incentive to over-extract where learning potential is highest also exists. Shown in the bottom-left panel of Figure 9, extraction by the oligopolists is highest where learning is possible at the fastest rate, and lowest where learning is not possible at all. This result is reversed in the bottom-right panel, where gains to learning-by-doing are fully internalized (equivalently by complete patent protection or by first-best subsidies to production). The former result is driven by smaller resource rents, while the latter is driven by the combination of much larger shadow values of current alternative energy production and lower resource rents caused by the substitute technology with higher learning potential. This equilibrium is closer in spirit to that examined in Harris and Vickers [1995], where the potential gains from an innovation which develops a substitute for fossil fuels are internalized by the energy buyer, and this leads to an erosion of resource rents collected by the seller.

While the discussion above shows that the effect of learning potential on resource extraction is ambiguous, the negative effect of learning potential on scarcity rents reported in Figure 5 is very robust, as shown in Figure 10. Intuitively, the highest rents are charged where the most market power exists ($m = 10$ and $n = 1$), and the lowest rents are charged where the greatest threat exists ($m = 1$ and $n = 3$). This figure emphasizes that regardless of market structure, resource pricing functions are sensitive to the potential for technological progress. The key implication of our results is that holding resource pricing functions fixed while modeling technological change in climate policy models may lead to biased results. This figure shows that this result will hold under a variety of assumptions.

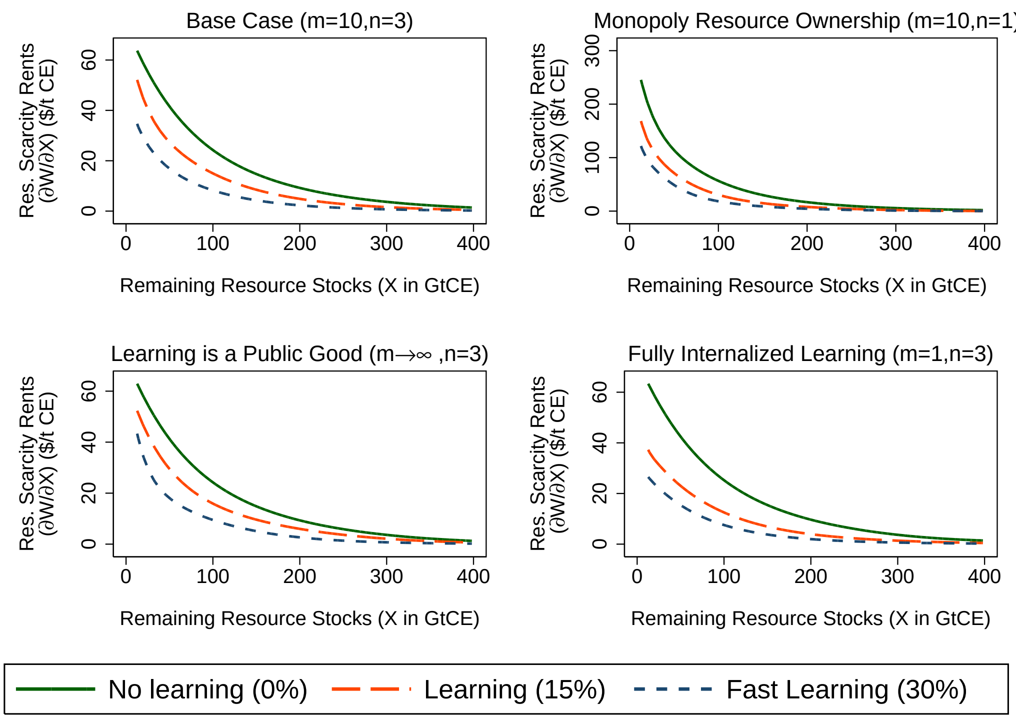

Fig. 10. Equilibrium resource scarcity rents projected onto remaining resource space for varying assumptions on the number of firms in the resource sector (n) and the number of firms in the alternative energy sector (m). Values of the state variable held fixed for projections are the same as in Figure 2.

Figure 11 shows significant differences in the Markov strategies of alternative energy firms relative to the base case of ($m = 10$ and $n = 3$), originally shown in Figure 3 and replicated in the top left panel. In our base case, alternative energy supply is monotonically increasing in learning potential. This result is reversed in the bottom left panel when the gains to learning-by-doing are effectively a public good. In this case, the reduced resource rents bid down energy prices such that equilibrium supply in the high learning case is the lowest among the considered scenarios; the resource oligopolists are not *killing the electric car*, but are certainly slowing its progress. Conversely, in the top right corner, when resources

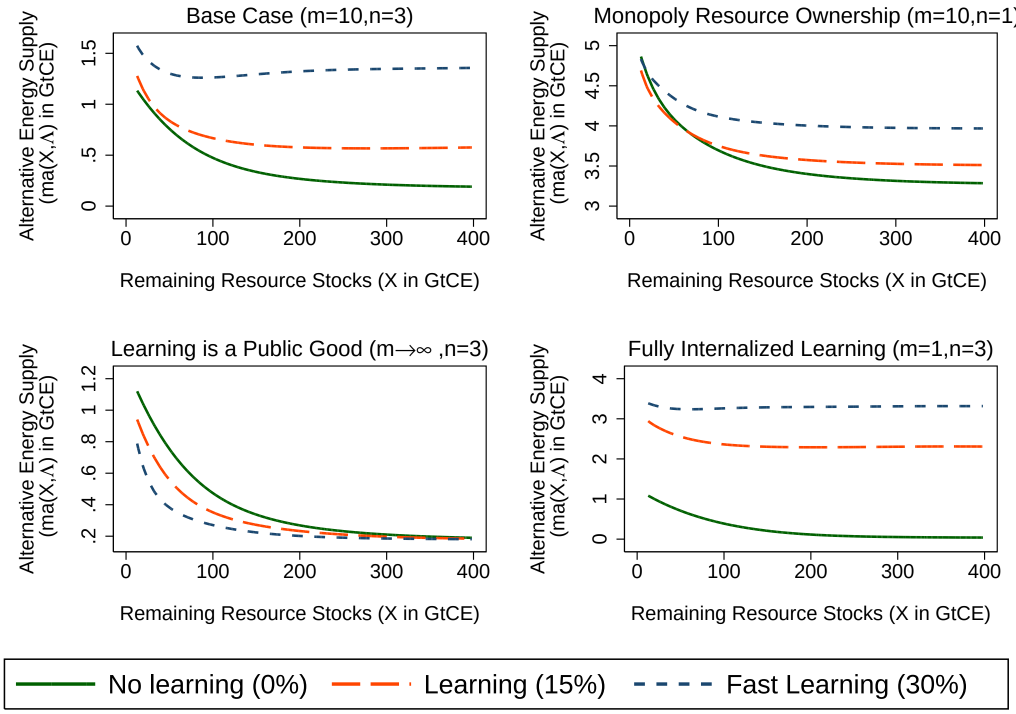

Fig. 11. The sum of equilibrium Markov strategies for alternative energy supply firms projected onto remaining resource space for varying assumptions on the number of firms in the resource sector (n) and the number of firms in the alternative energy sector (m). Values of the state variable held fixed for projections are the same as in Figure 2.

are owned by a monopoly, rents are maximized under what could be seen as a *make hay while the sun shines* approach under which high energy prices will encourage more production and learning-by-doing in the alternative. Prices under monopoly are lower when learning-by-doing is possible than they would be without, but still much higher than in the oligopoly cases. Under monopoly, we thus see production from both energy sources increasing in learning rates although alternative energy production does not increase by as much as it would if resource rents were invariant to learning.

The most important results from a policy perspective are seen in the bottom panels of

Figure 11. Depending on the degree to which future gains from learning-by-doing are internalized by those producing today, greater learning potential may or may not lead to greater supply of alternative energy. If gains to learning-by-doing are not internalized, the fossil energy firms have greater incentive to crowd-out alternative suppliers through over-extraction. Because alternative energy firms are effectively solving a static problem, the over-extraction is more effective as it is not compensated for by any willingness to supply at prices below marginal cost. As such, not only is resource extraction increasing in learning potential, but alternative energy supply is decreasing in learning potential when gains to learning are not internalized. The opposite result is reflected in the right-hand panel where the internalized gains to learning-by-doing imply higher supply and faster cost reduction.

5 Conclusion

This paper examines the impact of allowing for learning-by-doing in alternative energy sources on the decisions of a strategic nonrenewable resource owner. While it may be intuitive to suppose that resource scarcity will lead to increasing energy prices thus inducing technological change as alternative energy sources are adopted, we show an important reverse role. In our model, substitute energy sources with higher potential rates of learning-by-doing may induce higher rates of resource extraction and thus lower energy prices. In some cases, these equilibrium responses lead to lower adoption of alternative energy than would be the case if learning potential were lower.

With regard to emissions policies, we show that both the incidence of carbon charges on energy policy and the effectiveness of carbon charges at reducing emissions will be affected by the potential for learning-by-doing. In all the cases examined, carbon charges have a smaller effect on energy prices where learning potential is highest, although they will be more effective at reducing emissions where learning is possible.

While we present a simplified characterization of energy supply, our results consistently show that resource scarcity rents are negatively affected by the potential for learning-by-doing, and that resource extraction may increase in response to the threat presented by alternative sources. These results are consistent with an extensive literature in resource economics. The results suggest that climate policy models which include the potential for endogenous technological change should also include endogenous resource pricing responses. Failure include these effects may under-estimate resource extraction and emissions and thus under-estimate the optimal carbon charge.

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

Parameter	Description	Calibrated Value
Energy Demand		
Ω_0	Total factor productivity	59.46
θ	Energy share of production	.05
Carbon Sector Cost Function		
c^x	Constant extraction costs ($/ton carbon)	282
Alternative Sector Cost Function		
ζ_1	Fixed component of marginal cost	0
ζ_2	Determines learning rates (reported) [a]	0, 0.15, 0.3
ζ_3	Slope of aggregate marginal alternative energy cost($/toe^2)	36.4
State Variable Fixed Conditions for Projections		
and Starting Values for Simulations		
X_0	Initial aggregate resource stock (simulations)	400
$\bar{X}$	Fixed resource stock (projections)	400
$c(\Lambda(0), 0)$	Alternative sector cost (simulations)	.35
$c(\Lambda(0), 0)$	Alternative sector cost (projections)	.30

[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.