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Monopoly extraction of a nonrenewable resource facing capacity constrained renewable competition

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HIGHLIGHTS

- We study the monopoly extraction of a nonrenewable resource.
- The monopolist faces competition from a capacity constrained renewable resource.
- The price and extraction paths of the nonrenewable resource are discontinuous.
- The result is robust to the cost structures of the nonrenewable and renewable resources.

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ABSTRACT

This paper studies monopoly extraction of a nonrenewable resource with the presence of a competitively supplied capacity constrained renewable substitute. The monopolist staves off the renewable supply when the latter becomes competitive and then lets the resource price jump up.

1. Introduction

When studying the interactions between renewable and nonrenewable resources (e.g., renewable energies and fossil fuels), resource economists commonly treat the renewable resource as a pure backstop without capacity constraints: once the resource price reaches its marginal cost, the backstop floods the market and drives out the nonrenewable resource (see, e.g., Dasgupta and Stiglitz (1981), Dasgupta et al. (1982, 1983) and Chakravorty et al. (2006, 2008)).[2] However, most renewable resources are not pure backstops, since they have capacity constraints, so by themselves they cannot supply the entire market. For example, the production capacity of biofuels is limited by land availability and increasing demand for food and feed. The prime wind sites and rivers that are available for generating wind power and hydro power are limited by natural landscapes and endowments. In all cases, the marginal production costs are expected to increase sharply after certain thresholds, e.g., if these energies replace fossil fuels as dominant energy sources.

In this paper, we study a monopolist owner of a nonrenewable resource facing competition from a renewable resource with a capacity constraint. We find that, given the capacity constraints, the

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2 Amigues et al. (1998) and Holland (2003) are the few studies that highlight the important roles of capacity constraints. They show that capacity constraints could change the order of extraction of heterogeneous resources, for the scarcity rent generated by the capacity constraints changes the cost order of different resources.

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monopolist has incentive to stave off the renewable resource even when the latter becomes competitive: when the resource price increases to the marginal cost of the renewable resource, the monopolist "floods" the market, so that the market share of the renewable is still zero.[3] Further, when the renewable resource does enter the market, the resource price jumps up. That is, when the monopolist finds it not desirable to continue staving off the renewable resource, it will allow the price to jump up so that the renewable substitute produces at full capacity, and act as a monopolist of the residual demand.

Our study is the first one examining the price and extraction paths of a nonrenewable resource when the production of the renewable substitute is capacity constrained. To our knowledge, it is also one of the few studies in the literature showing that the price path can be discontinuous in a deterministic setting.[4] The rest of the paper is organized as follows. Section 2 presents the model and Section 3 discusses the linearity assumptions of the model. We conclude in Section 4. Proof and technical details are included in the Appendix.

2. The model

Consider two substitutable resources: a nonrenewable resource (indexed by $i = 1$) with a starting reserve of $S_0 > 0$ and constant unit extraction cost of c_1, and a renewable resource (indexed by $i = 2$) with a constant marginal production cost of c_2. We assume that $0 < c_1 < c_2$. Let $S(t)$ be the remaining reserve of the nonrenewable resource in period t. We assume a stable resource inverse demand function $p = h(q_1 + q_2)$ with $h'(\cdot) \le 0$, where $q_i \ge 0$ is the output of resource i, $i = 1, 2$. Further, we assume that the renewable resource has a production capacity constraint of $\bar{q}_2$, and that, by itself, the renewable resource cannot supply the whole market at the moment that it becomes competitive: $\bar{q}_2 < h^{-1}(c_2)$. Finally, we assume that the sector of the renewable resource is competitive (i.e., when $p = c_2$), but that the nonrenewable resource is owned by a monopolist.

First, we derive the renewable resource supply function. Since the production of the renewable resource is perfectly competitive with a constant marginal cost, its supply follows

$$q_2(t) \begin{cases} = 0, & \text{if } p(t) < c_2 \\ \in [0, \bar{q}_2], & \text{if } p(t) = c_2 \\ = \bar{q}_2, & \text{if } p(t) > c_2. \end{cases} \tag{1}$$

Let T be the depletion time of the nonrenewable resource. The monopolist takes the supply function (1) as given and maximizes its own discounted profit:

$$\max_{q_1(t), q_2(t), T} \int_0^T e^{-rt} \left[h\left(q_1(t) + q_2\left(p(t)\right)\right) q_1(t) - c_1 q_1(t) \right] dt$$
$$\text{s.t. } \dot{S}(t) = -q_1(t), \qquad q_1(t) \ge 0, \qquad S(0) = S_0,$$
$$S(T) \ge 0, \quad \text{and} \quad (1),$$

where r is the market interest rate. We assume that the revenue function $h(q_1 + q_2) q_1$ is concave in q_1. Let λ be the present shadow value of the nonrenewable resource stock. Then the Hamiltonian at time t can be written as

$$H_t = h\left(q_1(t) + q_2\left(p(t)\right)\right) q_1(t) - c_1 q_1(t) - \lambda e^{rt} q_1(t). \tag{2}$$

The optimality condition on $q_1(t)$ involves comparing the marginal revenue $MR(q_1(t))$ with $c_1 + \lambda e^{rt}$, which, following Holland (2003), is called the "augmented marginal cost" and is denoted as $AMC(t)$. In calculating $MR(q_1(t))$, the monopolist takes into consideration the reaction function (1), and, since $q_2(t)$ is discontinuous in price $p(t)$, $MR(q_1(t))$ is also discontinuous. We will discuss the formula for $MR(q_1(t))$ later; for now, it suffices to note that the optimal $q_1(t)$ is determined by a Kuhn–Tucker condition comparing $MR(q_1(t))$ with $AMC(t)$.

Since $\lambda > 0$, the transversality condition means that $S(T) = 0$, i.e., the nonrenewable resource will be exhausted. The free choice of exhaustion time T implies that $H_T = 0$. Notice that, at the exhaustion time T, the renewable supplies the entire market, so $p(T) = h(\bar{q}_2)$. Hence $H_T = 0$ is equivalent to

$$h(\bar{q}_2) = c_1 + \lambda e^{rT}. \tag{3}$$

The market equilibrium is the sequence of $\{q_1(t), q_2(t), p(t)\}_{t=0}^{\infty}$ such that (a) given $\{p(t)\}_{t=0}^{\infty}$, $\{q_1(t), q_2(t)\}_{t=0}^{\infty}$ satisfy (1) and the Kuhn–Tucker condition on $q_1(t)$; (b) the resource market clears at every moment: $p(t) = h(q_1(t) + q_2(t))$; and (c) the transversality conditions $S(T) = 0$ and $H_T = 0$ are satisfied.

We now proceed to characterize the marginal revenue function $MR(q_1)$. Fig. 1 illustrates the residual demand for the monopolist, obtained by subtracting supply function (1) of the renewable from the demand curve, and Fig. 2 shows the corresponding marginal revenue function. When $q_1 > h^{-1}(c_2)$, $p < c_2$ and (1) implies that $q_2 = 0$, i.e., the renewable is not competitive. In this case, the monopolist's marginal revenue function is

$$MR^1(q_1) = h'(q_1) q_1 + h(q_1). \tag{4}$$

When $q_1 < h^{-1}(c_2) - \bar{q}_2$, $p > c_2$ and (1) implies that $q_2 = \bar{q}_2$, i.e., the renewable supplies at its full capacity. Then the marginal revenue is

$$MR^3(q_1) = h'(q_1 + \bar{q}_2) q_1 + h(q_1 + \bar{q}_2). \tag{5}$$

When $q_1 \in \left[h^{-1}(c_2) - \bar{q}_2, h^{-1}(c_2)\right]$, $p = c_2$, $q_2 \in [0, \bar{q}_2]$, and this is a range of q_1 within which the monopolist can increase its output without driving down the market price, since the renewable supply will decrease accordingly. This is represented by the flat segment of the residual demand curve in Fig. 1, with the range of q_1 being $[h^{-1}(c_2) - \bar{q}_2, h^{-1}(c_2)]$ since the total market demand is $h^{-1}(c_2)$ and $q_2 \in [0, \bar{q}_2]$. Since $\partial h / \partial q_1 = 0$ in this interval,

$$MR^2(q_1) = c_2, \tag{6}$$

and the marginal revenue jumps at the two end points of the range, i.e., at $q_1 = h^{-1}(c_2)$ and at $q_1 = h^{-1}(c_2) - \bar{q}_2$ (because $\partial h / \partial q_1 < 0$ when q_1 is outside the interval). We denote the two marginal revenue levels at the jump points as MR_1 and MR_2 in Fig. 2.[5]

Based on Fig. 2, we study the price and extraction paths of the resources by comparing $MR(q_1)$ given in (4)–(6) with $AMC(t)$, which is increasing in time. In Fig. 2, $AMC(t)$ is a horizontal line,

[3] This result is similar to that in Hoel (1978, 1983), which study the case where the monopolist faces competition from a renewable substitute that is a pure backstop (without capacity constraints). The author shows that, when the resource price increases to equal the marginal cost of the backstop, the monopolist would flood the market until its nonrenewable resource stock is exhausted. The resource price is still continuous over time.

[4] Groot et al. (1992) show that a resource price can jump when a cartel and a competitive fringe, both owners of nonrenewable resources, play an *open-loop* von Stackelberg game. However, these open-loop strategies involving price jumps are not dynamically consistent. (Groot et al. (2003) identifies which of the strategies in Groot et al. (1992) are dynamically consistent.) In contrast, the equilibrium in our model is subgame perfect, which, of course, is also dynamically consistent. Gaudet et al. (2002) and Holland (2013) show that in the case of extraction of an open access resource, the tragedy of the commons implies that all Hotelling rents would be dissipated so that the resource price equals the (average) extraction cost. In this case, once the reserve is depleted, the resource price would jump up to choke off the demand or to the marginal cost of a substitute good.

[5] Specifically, $MR_1 = h'\left(h^{-1}(c_2)\right) h^{-1}(c_2) + c_2$, and $MR_2 = h'\left(h^{-1}(c_2)\right) \left[h^{-1}(c_2) - \bar{q}_2\right] + c_2$.