Energy 148 (2018) 1173–1180

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Innovation and site quality: Implications for the timing of investments in renewable energy☆

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ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form
28 January 2018
Accepted 29 January 2018

JEL codes:
C61
D21
D92
Q42

Keywords:
Sequential investment
Technological progress
Capital deployment
Investment in renewable energy
Wind power

ABSTRACT

We study the optimal sequence of investment in renewable energy when technology improves over time and the productivity of deployed capital differs with site quality. Our perspective is that of a price- and technology-taking individual or firm. We begin with a model where the price of output produced with the technology is a known constant and technology improves according to a known differential equation. We specify an optimization problem that allows for the solution of the optimal date of initial investment and the dates for optimal replacement. We then develop models where output price evolves according to geometric Brownian motion and technology evolves deterministically or stochastically, with up-jumps (breakthroughs). The possibility of breakthroughs will further delay initial investment compared to the model where technology evolves deterministically. Our analysis is relevant for the initial investment in renewable energy (wind or solar) and determining when and where to replace capital that is inefficient relative to current technology.

1. Introduction

The question of when to adopt a new technology, whose future efficiency is likely to improve, is a fundamental economic question. In addition to the optimal timing of initial investment, optimal replacement, when capital that is more efficient becomes available, is also of critical importance. These questions arise when considering investments in renewable energy,[1] which is the focus of this study, in information technology,[2] and other forms of durable capital that continue to improve over time.

Initial investment and replacement can be viewed as a series of real options [3,8,15]. Options to initially invest or upgrade to more efficient capital arise when a firm is faced with one or more sources of uncertainty [12]. identify three sources of uncertainty that can affect the value of options and thus the timing of adoption or replacement: (1) stochastic output price, (2) evolving technology with periodic breakthroughs, and (3) public policies which might be introduced or terminated. In addition to these three sources of uncertainty, several authors have shown that the evolving structure of an industry can influence strategic adoption. In non-competitive industries, there may be an incentive for preemptive investment, which might be followed by a war of attrition [5].

The current paper differs from the above contributions in two important respects. First, we allow technology to evolve according to a differential equation, but with the possibility of periodic up-jumps (breakthroughs) in efficiency. Second, we allow for heterogeneity in the productivity of deployed capital based on location or site quality, such as the wind energy potential of a site. If an individual or firm owns several sites of differing quality, which sites should be developed first, high or low quality sites? This second feature of our research is especially relevant for the timing of investments in renewable energy, such as solar panels or wind

☆ We are grateful to two anonymous referees for helpful comments. This research was supported in part by an Insight Development Grant from the Social Sciences and Humanities Research Council (SSHRC) of Canada.

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[1] See e.g. Refs. [1,2,12].
[2] See e.g. Refs. [6,9–11].

https://doi.org/10.1016/j.energy.2018.01.166
0360-5442/

turbines where site quality can vary widely. In our deterministic model, we identify a sufficient condition for high quality sites to be saved for more mature technology. To the best of our knowledge, this is the first paper to explore the timing of investment with technological improvement and heterogeneous site quality.

A plausible form for the evolution of technical efficiency has the gap between maximum efficiency and current efficiency proportionally closing over time. When this deterministic growth in efficiency is paired with output price evolving as geometric Brownian motion (GBM), we can derive a closed-form expression for a separating barrier in efficiency-price space. The optimal time to initially adopt or upgrade will be a random variable, determined by the time it takes for a stochastically evolving efficiency-price realization to reach the separating barrier. We then add the possibility of Poisson up-jumps to the evolution of efficiency and re-derive the separating barrier. A numerical example, loosely based on the evolving efficiency of wind turbines and the annual price of electricity in the US, is analyzed to quantitatively assess the shift in the separating barrier when Poisson up-jumps are added to the evolution of efficiency.

The remainder of this paper is organized as follows. In the next section we present a deterministic model where output price is constant and the efficiency gap proportionally closes over time. This deterministic model allows us to address the question of which quality sites to develop first. In Section 3, the deterministic model of efficiency is now paired with output price evolving as GBM. In Section 4 we then add the Poisson up-jump process to the evolution of efficiency and re-derive the separating barrier. In Section 5 we calibrate both stochastic models to the evolution of efficiency in wind turbines and average annual electricity prices in the US. We can then quantitatively identify the extent to which the Poisson up-jump process causes the separating barrier to shift in efficiency-price space. Section 6 concludes.

2. The deterministic model

Both wind and solar energy has an enormous energy potential, and the challenge is to harness as much of this available energy as possible, at the lowest possible cost. Over the past decades, there has been rapid growth in renewable energy production and capacity, and extensive technological progress in both solar and wind energy technologies. Production costs have fallen drastically, while production units have become more efficient, reliable, and durable, thereby increasing the amount of electricity they produce (see e.g. Refs. [4,14,16]).

For a given unit of land, there is nonetheless an upper limit to how much electricity it is possible to produce given the wind or solar energy potential. The available technology determines how much of this available energy one is able to harness; the more efficient the technology, the more of the available energy one is able to convert into electricity. Technological progress gradually reduces the gap between how much energy one is able to harness and this upper limit on what is possible.

Let $X = X(t)$ denote the efficiency of a capital item, such as a solar panel or wind turbine, at instant t, $\infty > t \geq 0$. We assume efficiency is increasing over time according to a first-order differential equation $dX/dt = X'(t) = f(X(t))$. We will consider special cases where this differential equation has an analytic solution given by $X(t) = F(t)$ and where $X(t)$, $X'(t)$, and $X''(t)$ are all continuous. We further assume that there is a maximum, practical efficiency for this capital item, denoted by $\overline{X}$, and that $X(t) \to \overline{X}$ as $t \to \infty$. Finally, we assume that current efficiency is less than the practical maximum, so that $X(0) < \overline{X}$. Henceforth, we will simply refer to this particular capital item as "capital."

While the efficiency of capital at instant t is available to all potential investors, the productivity of deployed capital may differ based on site quality. Suppose there is a continuum for site quality, Q, on the unit interval, so that $Q \in (0,1)$. If $Q_i > Q_j$, then site i has higher quality, and greater production potential, than site j for any efficiency $X(t)$.

For a particular site of quality Q, let τ_k denote the date that capital of efficiency $X(\tau_k)$ was installed at that site. Then, $X(\tau_1)$ is the efficiency of capital initially installed at site Q and $X(\tau_2)$ would be the efficiency of capital replacing $X(\tau_1)$, where $X(\tau_2) > X(\tau_1)$ when $\tau_2 > \tau_1$. We assume the production of electricity is the product of site quality Q and the efficiency of the capital installed at a site: $E = E(t) = QX(\tau_k)$. Hence, the better the quality of the site, the more productive the capital installed on that site, and the more efficient the capital, the less sun or wind is needed to produce the same amount of electricity.

Suppose that $P > 0$ is the constant per unit price for output produced using capital of efficiency $X(\tau_k)$ at a site of quality Q. Instantaneous revenue would be given by $PQX(\tau_k)$.[3] Let C_k denote the cost of purchase and installation of capital of efficiency $X(\tau_k)$. This cost would probably vary by site, but we will ignore this possibility in the present paper. Finally, let $\delta > 0$ denote the instantaneous discount rate. Then, the owner of site Q wants to maximize the net present value (discounted cash flow) by determining the optimal time to install and replace capital. Specifically, the owner of site Q wishes to

$$\underset{\tau_1,\tau_2,\tau_3,\ldots}{\text{Max}} N = -\sum_{k=1}^{\infty} C_k e^{-\delta\tau_k} + \int_{\tau_1}^{\tau_2} PQX(\tau_1)e^{-\delta t}dt + \int_{\tau_2}^{\tau_3} PQX(\tau_2)e^{-\delta t}dt + \ldots$$

$$= -\sum_{k=1}^{\infty} C_k e^{-\delta\tau_k} + \left[\frac{1}{\delta}PQX(\tau_1)\right]\left[e^{-\delta\tau_1} - e^{-\delta\tau_2}\right] + \left[\frac{1}{\delta}PQX(\tau_2)\right] \times \left[e^{-\delta\tau_2} - e^{-\delta\tau_3}\right] + \ldots$$

The optimality condition for deploying capital of efficiency $X(\tau_k)$ at site Q requires

$$\delta C_k - PQX(\tau_k) + \left[\frac{1}{\delta}PQX'(\tau_k)\right]\left[1 - e^{-\delta(\tau_{k+1}-\tau_k)}\right] = 0 \quad (1)$$

In general, optimality condition (1) requires that one know all the future optimal replacement times, $\tau^*_{k+1}, \tau^*_{k+2}, \ldots$ before one can determine τ^*_k.[4] If, however, $\tau^*_{k+1} \gg \tau^*_k$, so that $e^{-\delta(\tau^*_{k+1}-\tau^*_k)} \approx 0$, then the optimality condition for τ_k simply requires

$$\delta C_k - PQX(\tau_k) + \frac{1}{\delta}PQX'(\tau_k) = 0 \quad (2)$$

or equivalently

$$PQX(\tau_k) = \delta C_k + \frac{1}{\delta}PQX'(\tau_k) \quad (3)$$

Equation (3) says that at the optimal time to install technology

[3] We could define $p \equiv PQ$ as quality-adjusted price, where lower site quality implies a lower effective price. The comparative statics of adoption time, τ_k, as discussed below, with respect to Q or p will be the same and we prefer to retain Q explicitly.

[4] One might select a distant date, say τ_K and solve Equation (1) recursively backward in time to determine τ_1. Alternatively, one could numerically maximize N for initial investment and a finite number of replacements. We use this approach, solving for τ_1, τ_2, τ_3, τ_4, and τ_5 in Section 5.