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Cycles in nonrenewable resource prices with pollution and learning-by-doing

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ABSTRACT

We study how environmental regulation in the form of a cap on aggregate emissions from a fossil fuel (e.g., coal) interacts with the arrival of a clean substitute (e.g., solar energy). The cost of the substitute is assumed to decrease with cumulative use because of learning-by-doing. We show that optimal energy prices may initially increase because of pollution regulation, but fall due to learning, and rise again because of scarcity of the resource, finally falling after transition to the clean substitute. Thus nonrenewable resource prices may exhibit cyclical behavior even in a purely deterministic setting.

1. Introduction

More than 85% of commercial energy today is supplied by the three major fossil fuels, namely coal, oil and natural gas. Each of these resources, in varying degrees, is a major contributor to environmental problems such as global warming. These resources are also nonrenewable. However, there are many clean substitutes such as solar and wind energy which are currently more expensive in the cost of producing a unit of electricity or usable heat. Empirical evidence suggests that the cost of these clean substitutes fall as they begin to acquire more market share (McDonald and Schattenholzer, 2001).

In this paper, we examine the substitution of a clean energy source for a polluting one in energy production. For example, solar or wind energy are clean but expensive substitutes for coal in electricity generation.[1] We posit a scenario in which an extension to the Kyoto Protocol or another international agreement imposes a binding target for atmospheric carbon.[2] A forward-looking social planner internalizes the intertemporal knowledge spillovers from using the clean

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[1] This is true even when plausible externality costs are accounted for, as pointed out by Borenstein (2012) in a detailed study of the cost of electricity from solar photovoltaics in California. Further, while some sources (i.e. wind) have low variable costs, they may be intermittent or unreliable, and thereby need to be backstopped by another source in order to provide equivalent energy services to those provided by a fossil-fuel-fired source, thus raising their cost.

[2] Since fossil fuels account for 75% of global emissions (rest is deforestation) the effect of an international environmental agreement (e.g., the Kyoto Protocol) can be assumed to be a direct restriction on carbon emissions from the production of fuels such as coal. Many empirical studies on the effect of environmental regulation on energy use have concluded that the energy sector that is likely to be most impacted by climate regulation is electricity because it mainly uses coal, the dirtiest of all fuels. Clean substitutes for oil in the transportation sector or natural gas in residential heating (the cleanest

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technology. We ask: if there is significant learning in the clean substitute, how will that affect optimal energy prices and the process of substitution?

Many studies have looked at the problem of nonrenewable resource extraction as well as learning-by-doing in new technologies. However, the focus of our paper is on the role played by environmental regulation in this substitution process. Specifically, we ask how a cap on the stock of pollution or, equivalently, a carbon concentration target may affect the switch to the clean substitute when the latter exhibits learning effects.

We characterize this problem by assuming a fairly general cost specification for the nonrenewable resource and the learning technology. Unit extraction costs for coal increase with cumulative depletion. The average cost of solar energy is assumed to decrease with cumulative use but increase with the quantity supplied each period. For example, the unit cost of a solar panel may decline over time, the higher the number of panels built in the past.[3] But at any given time, the unit cost is increasing and convex with respect to the number of units supplied. This is quite realistic because as more and more solar units are brought into the market at any moment, they may have to be deployed in regions that are less favorable to solar energy such as those with lower incidence of solar radiation or in dense urban areas with higher installation costs.

There are several optimal solutions to this model, which we describe in the paper. But the key result arises when the clean technology is used before regulation becomes binding.[4] We show that in the initial period, energy prices rise because of scarcity and impending regulation. As soon as regulation becomes binding and the stock of pollution is at its maximum level, energy prices start falling. Clean energy use increases during this period but emissions cannot increase because of regulatory constraints. However there comes a time when resources are scarce enough that regulation no longer binds, and prices rise again, driven by the scarcity of the fossil fuel until it is no longer economical to mine higher cost deposits. This rise in prices also leads to an increased adoption of clean energy. Finally the polluting fossil fuel becomes too expensive to mine and the clean alternative takes over as the sole supplier of energy and once again, energy prices fall because of learning.

In standard models of Hotelling, the price of a nonrenewable resource rises until a clean substitute is used. If the substitute is available in infinite supply and fixed cost, energy prices rise until this transition and then stay constant. When learning in the backstop is included, energy prices rise until the resource is economically exhausted then fall once substitution to the backstop has taken place (e.g., see Oren and Powell, 1985). We show that with both learning and regulation, optimal energy prices may rise and fall *successively*.

This long-run non-monotonic behavior of energy prices is counter-intuitive and occurs because of the interplay of regulation, scarcity of the fossil fuel and learning in the clean technology.[5] It occurs when it is optimal to deploy the clean technology before regulation binds or during it, although in the latter case, the rise and fall of energy prices is not as pronounced, as shown later in the paper.

A recent review of the empirical significance of the Hotelling (1931) model suggests that "its most important empirical implication is that market price must rise over time in real terms, provided that costs are time-invariant" (Livernois, 2008). Livernois also points out that empirical tests of the model have been generally unsuccessful. Our results suggest that in the long run, resource prices may exhibit significant structural variations driven by regulatory policy and market forces, which may result in alternating phases with secular upward or downward price movements.

Although for convenience, the paper is motivated in terms of coal and a clean substitute such as solar energy, it is equally applicable to other settings, such as the monopoly production of oil by a cartel such as OPEC with a competitive clean technology (e.g., a hydrogen car). The solution predicts that oil prices may rise, followed by a *decline* when emissions constraints become binding. They rise again when regulation ceases to bind, followed by an eventual decline when there is a complete transition to the clean substitute. What is surprising is that energy prices may start decreasing upon attaining the regulated level of emissions.

(*footnote continued*)
of all fossil fuels) are much more expensive than the substitutes available in electricity generation such as hydro and nuclear power. That is, relative to coal, oil and natural gas have strong comparative advantage in their respective uses.

[3] This is consistent with historical evidence which suggests that cheaper production units will be brought online over time, gradually replacing more expensive units. For instance, McDonald and Schattenholzer (2001) report average cost reductions of 5–35% from a doubling of cumulative production in solar and wind energy generation. Duke and Kammen (1999) also find significant reductions in average cost from a rise in the cumulative production of solar panels.

[4] Empirically, this may be the most plausible case. Carbon regulation is not yet binding in most energy markets and stylized facts suggest that clean substitutes such as solar and wind energy already occupy a small but fast-growing share of the energy market. For example the global market for solar photovoltaics was worth more than 17 billion US dollars in 2007, exhibiting a 62% growth from the previous year (EETimes, 2008). The wind turbine market is even bigger, with revenues of $36 billion in 2007. It accounted for a significant 30% of new power generation in the United States in 2007, which along with Germany and Spain has the highest installed capacity (EWEA, 2008). However the global share of energy mix for these two energy sources is still less than 1%. This is consistent with most empirical modeling of climate stabilization scenarios considered by the IPCC and the IEA to meet long run goals such as limiting climate change to 2 °C. In calculating the optimal energy supply portfolio to respect a 450 ppm atmospheric CO_2 constraint, the IEA found that use of emissions-free sources would need to ramp up immediately, despite the fact that atmospheric CO_2 concentrations do not peak in their scenario until 2035. Importantly, the plausibility of this scenario does not depend on the costs of renewables today absent subsidies—this scenario is the most plausible so long as it will be optimal to use renewables before the emissions ceiling binds rather than choosing to meet the emissions constraint without deploying any alternative energy sources.

[5] See Chakravorty et al. (2006) for a model of a scarce nonrenewable resource with regulation but no learning.