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On the dynamics of competing energy sources☆

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ABSTRACT

We characterize the dynamics of energy markets in which energy is derived from polluting (fossil) and clean (solar) resources. The analysis is based on geometric optimal control considerations. An important feature of solar energy technologies is that their cost of supply is predominantly due to upfront investment in capital infrastructure (rather than to actual supply rate) and this feature has important implications for the market allocation outcome. In particular, it gives rise to a threshold behavior in that solar energy is adopted only when the price of fossil energy exceeds a certain threshold. Under this condition solar technologies will (eventually) dominate energy supply by driving fossil energy altogether out of the energy sector. A tax on fossil energy can have a substantial impact since it changes the threshold price. A quantity restriction (e.g., a cap on fossil energy) allows for the coexistence of clean and polluting energy technologies also in the long run, and its effect on the use of fossil energy is more moderate.

1. Introduction

Fossil fuels are often mentioned as the main culprit for an impressive list of undesirable consequences, including acid rain, smog, increased atmospheric concentration of greenhouse gases and financing of failed states and terror organizations. Yet, they continue to be the primary source of energy generation worldwide, fueling over 80% of total energy production and this share is not expected to decline anytime soon (International Energy Agency, 2008). The obvious reason is that the market price of fossil energy is in most places cheaper than any of the alternative energy sources available. Market prices, however, ignore externalities and the adverse consequences listed above are all external effects par excellence. Regulating these external effects requires understanding the underlying market forces that determine the allocation of energy generation between fossil and alternative sources. We characterize the dynamics of the market allocation processes and use this framework to study market-based regulation in the form of taxes or production caps on fossil energy, or subsidies on solar energy.

The economic processes underlying the energy sector are of interest because of the social relevance associated with environmental consequences and because their study reveals a rich structure of dynamic behavior, calling for novel techniques of characterization and interpretation (Bencheckroun, Katayama, & Long, 2005; Haurie, 2005; Haurie & Moresino, 2006). The recent Special Issue of Automatica (Haurie & Malhamé, 2008) attests to the increasing attention they receive from the Dynamic Optimization community (see, in particular, Bahn, Haurie, & Malhamé, 2008; Leizarowitz, 2008). The present work contributes to this line of research by presenting a complete analytic characterization of the multi-dimensional energy allocation processes via geometric optimal control considerations.

We study an economy in which energy is a primary input of production along with the traditional labor and capital inputs. Energy can be derived from fossil fuels or from alternative sources, e.g. solar, wind or hydro, referred to generically as solar energy. Solar energy entails none of the external effects listed above and also differs in another important respect: while fossil energy generation depends on supply of fuels that give rise to a substantial variable cost component, solar energy generation is based on capital designated especially for that purpose. Once the solar infrastructure (wind turbines, solar thermal collectors, photovoltaic panels) has been installed, the generation of solar energy entails very little additional cost. This distinctive feature is important for understanding the market forces underlying the energy sector and the ensuing market allocation of fossil and solar energy. In particular it gives rise to a threshold fossil energy

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price below which solar energy will never be used. In contrast, if the price of fossil energy exceeds this threshold, investment in solar energy capital will begin at some finite time and gradually increase until eventually driving fossil energy out of the energy sector altogether. The threshold effect, in turn, renders the market allocation sensitive to the details of the regulation policy designed to restrict the use of fossil energy.

The economy, described in Section 2, consists of a final good sector, an energy sector, and households owning labor and capital. The energy sector consists of fossil energy firms and solar energy firms. This structure extends that of Tsur and Zemel (2008) by treating solar energy as an endogenous sector of the economy.[1] In Section 3 the dynamic market allocation processes (the long-run equilibrium as well as the transition path leading towards it) are characterized. This task is carried out by analyzing the geometric relations between three characteristic curves (see Tsur & Zemel, 2005, 2007, for similar analysis) that give rise to the turnpike of this problem. Here, however, an essential input (energy) consists of a combination of state and control variables, hence the usual characteristic curves (the singular arc and the locus of feasible equilibria) must be complemented by a third curve, measuring the demand for energy when the latter is supplied at the fossil price.

The intersection of the curves determines the above-mentioned threshold fossil price which is shown to provide a necessary and sufficient condition for the adoption of solar technologies. Economies that satisfy this condition, referred to as solar-based economies, begin to invest in solar capital at some finite time, gradually increasing the share of solar technologies in total energy generation until eventually driving fossil energy out of the energy sector altogether. In economies that fail to satisfy this condition (referred to as fossil-based economies), investment in solar capital never takes place unless induced by some form of regulation. In order to focus our attention on the difference in cost structure between the two energy sources and the associated threshold, the analysis in this section abstracts from other important features of the energy market such as the technological constraints associated with solar energy as well as trends and fluctuations in the price of fossil energy and regulation measures to address the externalities entailed by its use.

Several common forms of energy regulation, namely fossil emission taxes and caps, as well as solar energy subsidies, are studied in Section 4. As expected, all policies reduce the use of fossil energy in the long run. However, the threshold feature of the market allocation outcome implies that an emission tax can have a drastic effect if set at a rate that gives rise to an effective fossil energy price above the threshold energy price, in which case the economy's type switches from fossil-based to solar-based. The effect of subsidizing solar energy is similar. Under the fossil energy cap policy, however, the use of fossil energy will not diminish below the imposed cap, hence the effect of this regulatory tool is more moderate than that of the emission tax.

The literature on energy economics and the competition among various technologies is vast and no attempt is made to review it here. Early concerns revolved around scarcity of fossil resources and the limit it imposes on economic growth (Barnett & Morse, 1963). Technological progress and discoveries of new coal, oil and gas reserves on the one hand, together with rapidly deteriorating environmental quality on the other, have swung the pendulum towards environmental concerns. R&D efforts to develop a backstop substitute for fossil fuels have been suggested as an answer to both the scarcity and environmental concerns (Dasgupta & Heal, 1974, 1979; Dasgupta & Stiglitz, 1981; Nordhaus, 1973; Tsur & Zemel, 2003, and the references therein). The recent Stern (Stern, 2007) and IPCC (IPCC4, 2007) reports added urgency to the environmental concerns and renewed interest in threats associated with advancing occurrence of catastrophes of global scale (Alley et al., 2003; Clarke & Reed, 1994; Nævdal, 2006; Roe & Baker, 2007; Tsur & Zemel, 1996; Weitzman, 2009). The regulation literature deals primarily with tradeoffs between prices (carbon tax) and quantity (cap-and-trade) measures (see Bushnell, Peterman, & Wolfram, 2008; Dietz & Maddison, 2009; Stern, 2007, and the references cited therein). The present effort studies the market forces underlying the penetration of solar energy technologies and provides the analytic framework to compare these regulation measures within a dynamic context.

[1] In Tsur and Zemel (2008) solar energy is purchased at a given (exogenous) price.

2. The economy

A realistic description of the energy market is highly complex. In order to allow a sharp focus on the difference in cost structure between fossil and the alternative energy sources and on the associated threshold, we simplify in several ways. First, we use a rather aggregate model of the economy, consisting of a final good sector and households, in addition to the energy sector where the important action takes place. Apart from the distinction between fossil and solar, the energy sector is also aggregated and we ignore the multiple costs of different fossil energy resources as well as the specifics of the various renewable energy technologies. Moreover, we ignore all exogenous time dependence of the model parameters such as the price of fossil energy, the production technologies and energy conversion efficiency. Thus, important issues associated with trends and random fluctuations of fossil energy prices, advances in solar technologies and growth of the labor force and its productivity are not considered here. The payoff is an analytically tractable model that allows focusing on the important distinction between fossil and solar energy generation (namely that the former entails a substantial variable cost component while the latter consists mainly of a fixed upfront cost) and studying its implications on regulation. With these qualifications in mind, we set to describe the model.

2.1. Final good

Firm i uses capital K_i, energy $X_i = X_i^f + X_i^a$ and labor L_i to produce output Y_i according to the constant-returns-to-scale technology $Y(K_i, X_i, L_i)$, where X_i^f is fossil energy and X_i^a is energy derived from alternative sources, such as solar and wind, which serve as perfect substitutes. We refer to these alternative sources generically as 'solar energy'. Thus,

$$Y_i = L_i y(k, x) \tag{2.1}$$

where $y(k, x) \equiv Y(k, x, 1)$, $k \equiv K_i/L_i$ and $x \equiv X_i/L_i$ are the same across firms that use the same technology, hence the firm subscript i can be dropped. The production function $y(\cdot, \cdot)$ satisfies, for $k > 0$ and $x > 0$, the standard properties

$$\begin{aligned} &y(0, x) = 0; \quad y(k, 0) = 0; \quad y_k(k, x) > 0; \\ &y_x(k, x) > 0; \\ &y_k(0, x) = \infty; \quad y_{kk}(k, x) < 0; \quad y_{xx}(k, x) < 0; \\ &y_{kx}(k, x) > 0; \quad y_{kk}(k, x)y_{xx}(k, x) - y_{kx}^2(k, x) > 0, \end{aligned} \tag{2.2}$$

where k and x subscripts signify partial derivatives with respect to k and x.

Firms take as given the capital rental rate r, the prices of fossil and solar energy, p^f and p^a, and the wage rate w and plan production in order to maximize instantaneous profit

$$L_i[y(k, x) - (r + \delta)k - p^f x^f - p^a x^a - w] \tag{2.3}$$

where x^f and x^a are, respectively, the per worker fossil and solar energy inputs and δ is the capital depreciation rate. Necessary