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Equilibrium transitions from non-renewable energy to renewable energy under capacity constraints ☆

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ABSTRACT

We study the transition between non-renewable and renewable energy sources with adjustment costs over the production capacity of renewable energy. Assuming constant variable marginal costs for both energy sources, convex adjustment costs and a more expensive renewable energy, we show the following. With sufficiently abundant non-renewable energy endowments, the dynamic equilibrium path is composed of a first time phase of only non-renewable energy use followed by a transition phase substituting progressively renewable energy to non-renewable energy before a last time phase of only renewable energy use. The investment into renewable energy may either begin before actual production of renewable energy or be delayed until the energy price achieves a sufficient gap with respect to the renewable energy cost. With an initially abundant non-renewable resource, the features of the transition between non-renewable and renewable energy do not depend upon the initial resource stock.

1. Introduction

The transition between different natural resources exploitation regimes typically takes time. While significantly in use since the sixteenth century in Great Britain, coal mining replaced only very slowly charcoal in iron processing or wood in energy provision until the nineteenth century (Wrigley, 2010; Fouquet, 2008). The same may be said for the use of oil and natural gas which developed over a 60 year range period since the end of the nineteenth century. More recently, the development of new energy sources like solar or biofuel is expected to extend well over the current century (Nakicenovic et al., 1998, chap. 5). Most policy proposals to develop such alternatives in order to mitigate climate change are explicitly time dependent, the European Union 20–20–20 plan being one prominent example. Current and prospected energy policies thus strongly acknowledge the time lags implied by long run adaptations of the present energy mix. In some sense the climate challenge may be seen as a time to act problem, balancing the speed of possible adaptations to climate change with the speed of such a change.

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This time to build issue covers many different problems ranging from the need of a sufficiently rapid technical progress to develop economically relevant energy alternatives to a sufficiently fast investment pace in natural resources services provision. Adaptation, or more generally development of the exploitation of natural resources is a costly process falling under the heading of 'adjustment costs' in investment economics. This issue of adjustment costs is not only of concern for the development of new resources but also for the development of existing ones, a well-known feature of resource industries, either for the exploration and exploitation of new oil fields or for mineral resources.

The objectives of the paper are two-fold. First we want to stress the importance of investment constraints over the development of renewable energy alternatives. In order to focus upon the investment issue we shall dispense from considering explicitly the pollution problems raised by burning fossil fuels. Hence the main motivation for developing energy alternatives will be the increasing scarcity of non-renewable fossil fuels like oil. For the same reason we shall not deal with the important issue of technical progress or learning-by-doing in the use of new energy sources. This issue has raised significant attention in the macroeconomic endogenous growth literature recently (Acemoglu et al., 2012) but the precise micro-foundations of this analysis, both at the firm level and at the energy sector level remain to be carefully settled. Technical progress should result into the generation of higher quality capital goods, an issue which would require to plug the analysis inside some vintage capital model, a study worth a dedicated research.

Second we want to explicitly consider the price implications of the development of renewable energy. One should expect that the gradual increase of renewable energy inside the energy mix will affect both the energy price trajectory and the depletion path of the already in use non-renewable resource. Conversely, the time path of investment into renewable alternatives should depend upon the relative scarcity of the non-renewable resource. Such possible linkages have attracted a lot of attention in the climate change regulation literature recently, under the heading of the so-called 'Green Paradox' dilemma.

To deal with this issue we depart both from the usual investment analysis at the individual firm level and from the aggregate studies at a macro-level. We consider a partial equilibrium setting where the energy sector is composed of a population of identical competitive firms either producing energy from a non-renewable resource or from a renewable one. Furthermore we assume that the renewable energy industry has to purchase specific equipments, linking at the equilibrium the dynamics of the energy price to the dynamics of the renewable energy capital input price. We assume an upward slopping supply curve of specific equipment of the renewable energy industry or equivalently an increasing marginal cost curve of equipment provision to the renewable industry. Thus the renewable industry faces external adjustment costs in the Lucas (1967a) sense rather than internal adjustment costs in the Gould (1968) sense. For simplicity we assume constant average and marginal variable operating costs in the non-renewable and renewable energy industries and a lower operating cost of non-renewable energy.

Adjustment costs have received a lot of attention in investment theory, seminal contributions to this literature being Lucas (1967a,b), Gould (1968) and Treadway (1969). However, while fully acknowledged as an important issue in natural resource development problems at least since Hotelling (1931),[1] it has attracted a relatively modest attention from resource economists. The textbook treatments of substitution between natural resources (for example Herfindahl and Kneese, 1974) do not consider explicitly adjustment costs. This results into a description of the history of natural resources use development as a sequence of time phases of exploitation of a dominant resource (the wood age, the coal age, the oil age) separated by quick transitions from a dominant resource to another one, according to their relative cost order.

It is a commonplace observation (IEA, 2013) that in energy production, natural resources rather coexist than override each other. The possibility of various types of capacity constraints in natural resources provision lies at the heart of the rare attempts of the literature to provide a more realistic account of the dynamics of energy transitions (Kemp and Long, 1980; Amigues et al., 1998; Holland, 2003).

In the resource literature, reference to adjustment costs has served two main purposes. The first one concerns the validity of the Hotelling rule. The rule predicts an increasing trend of the non-renewable resources prices together with a decline of the production rate of these resources. However, the currently available data reveals that despite a formidable increase of the exploitation rate of the main mineral resources over the two last centuries, their prices have remained more or less constant in real terms, showing no definite upward trend that could be explained by the Hotelling rule (Gaudet, 2007). Various explanations have been proposed to reconcile the theory with the data (Livernois, 2009). On the theoretical side, it has been stressed that capacity constraints, technical progress, dynamic costs structures, uncertainties or market imperfections may account for the observed resource price trends. On the empirical side, the difficulty to gather relevant data over long time periods and various econometric estimation issues can also explain the apparent lack of evidence concerning the Hotelling rule.

In the context of the theory of the mine, the fact that investment costs may result in constant resource prices has been shown by Campbell (1980), extending the previous work of Puu (1977). The strength of the Campbell model is to take explicitly into account the consequences of extraction capacity constraints over the resource price, but its main weakness, as emphasized by Gaudet (1983), is to transform the gradual capacity development process into a static investment problem,

[1] "The cases considered in the earlier part of this paper all led to solutions in which the rate of production of a mine always decreases. By considering the influence of fixed investments and the cost of accelerating production at the beginning, we may be led to production curves which rise continuously from zero to a maximum, and then fall more slowly as exhaustion approaches. Certain production curves of this type have been found statistically to exist for whole industries of the extractive type, such as petroleum production." (Hotelling, 1931, p. 164).