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Fueling growth when oil peaks: Directed technological change and the limits to efficiency ☆

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ABSTRACT

While fossil energy dependency has declined and energy supply has grown in the postwar world economy, future resource scarcity could cast its shadow on world economic growth soon if energy markets are forward looking. We develop an endogenous growth model that reconciles the current aggregate trends in energy use and productivity growth with the intertemporal dynamics of forward looking resource markets. Combining scarcity-rent driven energy supply (in the spirit of Hotelling) with profit-driven Directed Technical Change (in the spirit of Romer/Acemoglu), we generate transitional dynamics that can be qualitatively calibrated to current trends. The long-run properties of the model are studied to examine whether current trends are sustainable. We highlight the role of extraction costs in mining.

1. Introduction

All developed countries have been heavily dependent on fossil fuels over the past decades, which helps explaining why terrorism and oil security are so high on national policy agendas, why "peak oil" stories (e.g. Deffeyes, 2001) engender emotional discussion, and why national governments postpone signing international climate change treaties. Since fossil fuels are nonrenewable resources, their use cannot grow forever and oil dependence might seem to only become a bigger threat. Energy suppliers can be expected to anticipate future scarcity and manage their extraction-production strategies accordingly. Therefore, one has naturally wondered when and to what degree this dependence puts limits to economic growth.

While in the short run oil shocks can have a big impact on the overall economy, there is little evidence that in the second half of the 20th century oil dependence has caused direct problems for economic growth. According to the trends observed during those years, the supply of energy (both in absolute and in per capita terms) has increased steadily and the share of

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energy in total cost has declined secularly. Although alternative fuels have become cheaper over time, the use of conventional energy has become more attractive at an even faster pace. Technological change has mainly benefited the productivity of conventional fuels, reducing the need to exploit alternative energy sources. An important indicator of these technological developments is the productivity of energy, as measured by value added per unit of energy, which has steadily increased.

Noticing that the path for the supply of conventional (non-renewable) energy has been increasing but knowing that it will inevitable decline in the future, we can naturally predict a peak in oil supply in the future. The marked slowdown in energy use in the first decade of the 21st century might be the beginning of a change in this direction, but the phenomenon is too recent to know if a structural trend change has occurred already.[1] As long as oil productivity improves fast enough to offset scarcity, the economic consequences can be small. A key question is therefore how technological developments respond to oil supply changes. Profit-seeking entrepreneurs will start looking for energy-saving technologies in the face of energy scarcity. Similarly, forward-looking energy suppliers will adjust their production plans to future events like growing demand because of aggregate economic growth or falling demand because of energy saving. Future resource scarcity could cast its shadow on world economic growth soon when energy and technology markets are forward looking.

Our aim is to understand how the trends observed during the second half of the 20th century and the first decade of the 21st century in aggregate energy use and productivity growth can be linked to future scarcity. We build a model that generates both phases: a *first* phase of growth fueled by expanding energy supply and a second phase of declining oil production, as part of the same fundamental dynamics that arise from profit-maximizing technology development and energy supply.

The Hotelling (1931) model has been the workhorse model to think about how profit-maximizing forward-looking suppliers of nonrenewable resources – like oil – would allocate production over time. It assumes a finite (cumulative) physical supply and predicts rising prices for extracted resources in the long run. Given that these results carry over to partial and general equilibrium models that assume finite resource supply and forward-looking profit maximizing agents, it seems hard to ignore Hotelling's insights when analyzing growth and resource markets. However, because the model is notoriously difficult to reconcile with stylized facts, the practical application of the insights has been questioned. First, as Gaudet (2007) documents, the empirical pattern of prices is difficult to reconcile with the predictions from the simple partial equilibrium models as long as these models ignore uncertainty and cannot endogenize technology responses to energy scarcity. Second, at the aggregate level, there is a difficulty to reconcile growing energy use with the Hotelling framework. For example, merging the standard neoclassical growth model with the Hotelling model, one typically finds that resource use declines monotonically over time (Dasgupta and Heal, 1974, p. 17; see also Benchekroun and Withagen, 2011, who examine the transitional dynamics of the model analytically). In the literature there seems to be a gap between, on the one hand, analytical approaches that start from first principles and apply the Hotelling model but generate extraction patterns that are at odds with facts (e.g. Chakravorty et al., 2008; Van der Ploeg and Withagen, 2011), and, on the other hand, applied and calibrated models that abstract from Hotelling rents for the sake of calibration. For example the DICE model (Nordhaus 1994), the model most often applied to evaluate the consequences of greenhouse emissions associated fossil fuel use, assumes away finiteness of energy supply despite its long time horizon.[2]

In this paper we try to fill this gap by developing an analytically tractable model that both can be calibrated to stylized facts and assumes finite resource supply with profit-maximizing intertemporal behavior. By analyzing the key mechanisms of the model, rather than calibrating the model as a black box, we show how the structure of the model allows stylized facts to be replicated. In this procedure, which we dub "qualitative calibration", we analytically derive bounds for parameters we have to pick in each calibration to a model outcome that satisfies a list of well documented stylized facts. This approach allows us to point out that changes in the cost of extraction of the resource play a major role in the calibration. In order to show that this result holds very generally, we deliberately choose to take developments in extraction costs over time as exogenous.

Another contribution of our analytical approach is that we derive the dynamics of our model in terms of a variable that directly captures oil dependence, namely the energy share in GDP. The model predicts a clear-cut relationship between the energy share in GDP, the direction of technological change, and total factor productivity growth. Moreover, given technological change in oil extraction, the dynamics of the energy share can be determined. As a result the model explains how oil dependence – as measured by the energy share in GDP – evolves over time and how it affects the dynamics of technological change and production growth.

When qualitatively calibrating our model, we start from the following stylized facts observed during the last decades of the 20th century: a growing per capita energy supply, declining cost share of energy in GDP, declining energy cost relative to

[1] Per capita energy consumption in USA grew on average at an annual rate 1% over the period 1949–1999, but over the period 2000–2010 it declined at a rate of 1% (EIA, 2012).

[2] There are two alternative ways to avoid introducing the Hotelling assumption and results. First, there might be a "backstop technology" that makes the scarce resource input superfluous. Second, the resource supply may be physically unlimited, but subject to increasing extraction costs (Heal, 1976). Both approaches basically assume away the economic relevance of physical scarcity and cannot therefore address its economic consequences. This is not to say that such approaches are not generating useful insights. Rather, we claim that our approach complements these approaches by showing that even with our more "conservative" assumption (i.e. physical finiteness), current trends can be explained. Moreover, physically abundant energy resources, coal in particular, cannot perfectly substitute for the physically scarce resources oil and gas (e.g. in transport), so that both types of models are needed. For this reason, when we write "energy", we restrict ourselves mainly to energy from oil and gas rather than from coal.

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