Executive Summary

Energy Sector Innovation and Growth: An Optimal Energy Crisis

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While there is considerable controversy concerning the notion of "peak oil" or more generally "peak fossil fuel production", most energy economists would agree that at some time the world will transition from fossil fuels to alternative sources of energy. It is not so much that we will run out of available fossil resources in a physical sense. Rather, the cost of exploiting the dwindling stock of such resources ultimately will increase enough to make competing energy sources economically viable on a mass scale and without subsidies. Technological change, such as the recent development of techniques to extract oil and natural gas from shale or oil from Canadian oil sands, can extend the available fossil fuel resource and keep costs from rising for some time, but the effects of depletion must eventually overwhelm such developments.

This scenario raises the specter of rising real costs of energy supply with attendant negative implications for economic growth and welfare. Indeed, it could be argued that the threat of high real energy prices is critical in arousing passions about the notion of "peak fossil fuel."

The idea that the real cost of fossil fuels must eventually rise has been cited as another reason (apart from environmental or energy security externalities) for subsidizing the deployment of alternative renewable energy sources. The notion is that the adverse economic consequences of high energy prices are inefficient and policies should be implemented to avoid them if possible.

We study the optimal transition path from fossil fuel energy sources to renewable alternatives in a model of the world economy that allows for population and economic growth and requires energy as an input to production. In contrast to the existing literature, we allow for technological progress in *both* fossil and renewable energy production technologies. In the case of fossil fuels, while mining costs increase with cumulative resource development, new technologies can keep the cost of supplying fossil fuel energy services under control for some time. In the case of renewables, we assume that accumulated knowledge lowers unit production cost until a technological limit is attained. We assume a two-factor learning model, whereby direct R&D expenditure can accelerate the accumulation of knowledge. An important implication of our model is that the "parity cost target" for renewables is a moving one.

While we assume that energy services are essential for producing output, the real cost of energy is calibrated to be small share of overall GDP, as one observes in the real world. Nevertheless, we show that there is considerable economic "turmoil" associated with the transition in energy sources. Per capita economic growth rates rise substantially as the transition time approaches, but plummet to negative values right after the transition occurs. Furthermore, despite the rising growth in per capita output prior to the transition, per capita consumption growth, and the share of consumption in output, fall substantially.

The share of consumption in output also remains below current levels for a very long time after the transition to alternative energy sources.

The declining growth in per capita consumption in the face of increasing growth in per capita output as the transition point approaches occurs not only because the real cost of energy increases. A second reason is that the economy invests more in technology to counter the rising cost of producing energy services as physical resource depletion occurs.

The continuing low share of consumption in output after the transition in energy sources occurs also follows from two sources. First, the real cost of energy remains high and takes resources away from both consumption and the capital needed to produce final output. Second, immediately after the transition there is also a strong incentive to invest in renewable energy R&D in order to reduce the real cost of energy services.

Consistent with these explanations, the period before the transition to renewables is characterized by a growing gap between output and consumption growth as the real cost of energy is rising. Conversely, the period after the transition to alternative energy supplies is characterized by a shrinking gap between output and consumption growth rates as the real cost of energy services declines over time.

While these results are derived for a particular numerical calibration of our theoretical model, we believe that they are likely very general features of a growing economy incorporating energy production and investment in technological change in fossil fuels and their alternatives. To test this conjecture, we examined the behavior of the model for a range of alternative parameter values and specifications in addition to the one that is the main focus of the paper. We verified that the "energy crisis" aspect of the results remained valid in all the alternatives we examined.

The model has two other interesting implications that are worth mentioning. First, we show that the transition between energy sources occurs before the real cost of fossil energy services rises to equal the (initially) higher cost of the renewable alternative. The explanation is that, due to the learning by doing element of renewable energy production, there is an implicit additional benefit of starting on renewable energy use before it is competitive because the extra learning lowers future energy costs. Second, we find that, apart from the initial burst of investment in R&D following the transition, the optimal investment in R&D for reducing the cost of renewable energy sources is approximately proportional to the contribution of learning by doing. Hence, even though we assume that direct R&D is roughly twice as productive as learning by doing at reducing the cost of renewable energy, empirical studies may find that energy production learning by doing *alone* appears to explain the exponential relationship between accumulated output and cost.