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Supply elasticity matters for the rebound effect and its impact on policy comparisons

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ABSTRACT

We develop a model of the rebound effect which explicitly accounts for both the demand and supply sides of the energy sources. We consider a transportation sector originally using a "dirty" (fossil) fuel and examine the relative effectiveness of alternative policies: efficiency improvements in the dirty fuel technology sector (e.g., CAFE standards) and technology shifts by partial adoption of a new clean technology (e.g., low-carbon fuel standards). The model generates endogenous equilibrium quantities and prices for the dirty and clean fuels. We characterize the magnitude of the rebound effect as a function of demand and supply elasticities and use the equilibrium values to compare policy options. When the supply of the dirty fuel is inelastic, we find that introducing a new technology with non-zero emissions may actually increase the total level of emissions, similar to the leakage effect. A technology shift policy can perform better than an efficiency improvement policy in the dirty fuel sector only when the dirty fuel supply is sufficiently elastic, the emission intensity of the new technology very low, and the technology shift is greater than a threshold value. Using data for gasoline (as a proxy for the dirty technology) and several other cleaner technologies, we show that these conditions are satisfied by a hypothetical zero-emission technology, but not by electric vehicles using the average US generation mix or the current US corn based E85. Our results demonstrate the importance of accounting for the supply side in estimating the magnitude of the rebound effect and its impact on fuel consumption in a large-scale policy implementation.

1. Introduction

The rebound or take-back effect has been discussed extensively in connection with the impact of an improvement in energy conversion efficiency on energy use. An improvement in energy efficiency is expected to lead to a decrease in energy demand, based on engineering relationships between efficiency, energy and energy service demand. But increasing efficiency also reduces the price of an energy service which can lead to an increase in demand for the energy service which offsets the reduction in energy demand. This conventional rebound effect, however, does not consider the impact of the energy supply side.

Our objective in this paper is to model the impact of the supply side in characterizing the rebound effect and use it to compare the fuel consumption and emissions reduction potential of emissions reduction policies. We use our theoretical model to study two types of transportation sector policies: a fuel conversion efficiency improvement (e. g., CAFE standards[2]) and a technology shift policy, where a partial shift to a low-emission technology is mandated (e.g., low-carbon fuel standards, or zero-emission vehicle adoption). Low-emission technology mandates necessitate introducing biofuels or electricity as new sources of energy for vehicles. Following the literature we refer to the old technology as "dirty" and the new technology as "clean".

The common objective of both demand and supply side policies is to reduce the overall consumption of the dirty fuel, thereby reducing emissions. The impact of each policy on emissions will therefore depend on its effect on the final consumption of the dirty and clean fuels. To understand these effects we will examine the impact of policy changes where fuel consumers and producers react to a new

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2 Corporate Average Fuel Economy Standards set by the U.S. Environmental Protection Agency.

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policy[3] and as a result of these responses the endogenous values of equilibrium fuel price and fuel consumption change. In our model, the endogenous change in the price of the dirty fuel (e.g. gasoline) plays a role in offsetting the demand-based policy effects (or the conventional rebound effect).[4] We refer to this additional offset as the "supply-based" rebound effect.

Earlier models of the rebound effect in an end-use sector has mainly focused on the demand side.[5] Two key exceptions are Wei (2010), which also considers the supply side effect but in a macroeconomic context, and Borenstein et al. (2015), which briefly discusses the impact of supply elasticity on the conventional rebound effect. Our work offers a more micro-economic view focusing on a specific sector and analyses of the interaction between supply elasticity, rebound effect, and the relevant policy instrument. In particular, we model both energy demand and supply functions for an end-use sector to identify conditions under which one or the other policy instrument dominates in terms of fuel use and emissions reduction. Comparisons of the equilibrium fuel consumption and their resulting emissions between the two policies will enable us to compare the relative effectiveness of the two policies in emissions reduction.

In this respect, our paper is closer to general equilibrium models of the rebound effect in response to efficiency improvements. The commonest approach to a general equilibrium view of the rebound effect is to run a computational general equilibrium (CGE) model and observe the steady-state response of different fuel sources to interactions of efficiency improvements and prices. Although CGE models are useful for practical purposes, they tend to rely on numerical results of model simulation. A second approach uses theoretical models of economic interactions between the energy demand and production sides of the economy to study the impact of efficiency improvements on energy consumption.[6] Here, we use the latter approach in the context of a specific energy end-use sector and offer clear-cut theoretical results based on closed-form solutions to the model.

As stated earlier, we distinguish between demand-based and supply-based rebound effects on fuel consumption. The conventional demand-based rebound effect is the result of reduced cost of travel due to improved fuel conversion efficiency. Whereas, the supply-based rebound effect is due to a change in consumption because of a change in the equilibrium price of fuel. The less elastic the *supply* side of the dirty fuel is, the stronger its effect will be. We provide theoretical results characterizing the behavior of the fuel market and numerically illustrate them for a range of demand and supply elasticity parameters.

Our results show that when demand is inelastic (with absolute value between zero and unity) and the supply of dirty fuel is completely inelastic (i.e. a vertical supply function or supply wall), a partial shift to a cleaner technology will have no effect on emissions and will only reduce the equilibrium price of the dirty fuel! This is because the remaining segment of dirty fuel users will increase their consumption as fuel price decreases such that in the aggregate equilibrium they consume exactly the same quantity of dirty fuel as before. In this case, the strong dirty fuel price effect will completely offset the savings from the partial migration to a clean fuel resulting in a complete offset of the reduction in fuel consumption. This result has implications similar to the leakage effect, extensively discussed in the *green* paradox and climate change literature. On the other hand, if the fuel supply curve is horizontal (i.e the fuel is constant) the migration to clean fuel will have no effect on the price of dirty fuel and no supply-based rebound effect will occur.

In general, we find that a zero-emission technology-shift policy will result in greater emission reduction than an efficiency improvement policy of similar stringency, defined by an equal percentage change in technology and energy efficiency. For each efficiency improvement policy we characterize a corresponding threshold technology shift such that the given efficiency improvement dominates over the technology shifts below the threshold, in terms of emissions reduction. When the alternative technology is not emission free, policy comparisons will depend on the relative emission intensity and other features of the supply of that technology. We illustrate policy comparisons using data for two currently available clean technologies, 85% ethanol vehicles and electric vehicles.

This paper is organized as follows. A review of existing literature is offered in Section 2. Section 3 introduces the model and its components. Section 4 offers the solution of the model and theoretical results for fuel consumption effects of policies. In Section 5, we analyze the outcome of policies as well as the rebound effect on emissions. Section 6 quantifies our emissions related results, calibrated with real-world parameter values. Finally, in Section 7 we discuss the effect of key assumptions and the policy implications of our results, and Section 8 concludes the paper.

2. Literature review

Our paper is built on a mature strand of literature on energy rebound effect. However, to the best of our knowledge two issues have not received adequate attention in the rebound literature. First, we consider the effect of supply elasticity in an otherwise standard rebound model. Adding a supply function, introduces new and interesting effects. We discuss how the range of supply elasticity (from being fully elastic to a complete inelastic one) possibly offsets the effect of technology shift. Second, we apply the theoretical rebound model to policies related to technological change, increasing fuel efficiency, and using a portfolio of dirty and clean transportation technologies created by a partial shift to a low emission technology. In order to clearly justify the position of our work among a larger number of existing papers we provide a review of current rebound literature in this section.

The rebound or take-back effect originally referred to as the Jevons' paradox (Jevons, 1866; Khazzoom, 1980; Brookes, 1990) and later as the Khazzoom-Brookes postulate (Saunders, 1992), deals with the impact of an improvement in energy conversion efficiency on energy use. If based on engineering relationships alone, energy use is expected to decline in inverse proportion to an increase in energy efficiency improvement.[7]

However, an increase in energy efficiency can reduce the price of the energy service which can lead to an increase in its demand (Greening et al., 2000; Sorrell et al., 2009). This can result in lower energy savings than expected from the efficiency improvement, or a "direct rebound effect" whose magnitude depends on the price elasticity of demand for the energy service (Berkhout et al., 2000; Greening and Greene, 1998; Howarth et al., 2000; Laitner, 2000; Saunders, 2000b; Sorrell and Dimitropoulos, 2008; Thomas and Azavedo, 2013).

Linn (2013) shows that previous studies have implicitly ignores critical assumption about the correlation of vehicle features and fuel

[3] Vehicle producers may also respond to new policies by changing the characteristics of their products and their R&D spending on engine efficiency, etc. We abstract from these effects.

[4] See Jevons (1866), Khazzoom (1980), and Brookes (1990).

[5] See Berkhout et al. (2000), Greening and Greene (1998), Howarth et al. (2000), Laitner (2000), Saunders (2000b), Sorrell and Dimitropoulos (2008), and Thomas and Azavedo (2013).

[6] See Wei (2010), for example.

[7] Since energy intensity is the reciprocal of energy efficiency, energy consumption is expected to decrease proportionately with decreasing energy intensity, based on engineering identities alone.