

Costs of Energy Efficiency Mandates Can Reverse the Sign of Rebound

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Abstract

Improvements in energy efficiency reduce the cost of consuming services from household cars and appliances and can result in a positive rebound effect that offsets part of the direct energy savings. We use a general equilibrium model to derive analytical expressions that allow us to compare rebound effects from a costless technology shock to those from a costly energy efficiency mandate. We decompose each total effect on the use of energy into components that include a direct efficiency effect, direct rebound effect, and indirect rebound effect. We investigate which factors determine the sign and magnitude of each. We show that rebound from a costless technology shock is generally positive, as in prior literature, but we also show how a pre-existing energy efficiency standard can negate the direct energy savings from the costless technology shock – leaving only the positive rebound effect on energy use. Then we analyze increased stringency of energy efficiency standards, and we show exactly when the increased costs reverse the sign of rebound. Using plausible parameter values in this model, we find that indirect effects can easily outweigh the direct effects captured in partial equilibrium models, and that the total rebound from a costly efficiency mandate is negative.

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New energy efficiency technology can reduce electricity or fuel use needed to get the same services such as cooling from an air conditioner or refrigerator, heat from a furnace, or miles driven in a car. It reduces the marginal cost of those services, so it encourages consumers to make more use of those appliances – and thus causes a rebound effect that offsets at least part of the energy savings. Many papers demonstrate this positive rebound effect, both in empirical partial equilibrium models and in theoretical general equilibrium models. Here, we demonstrate potential problems interpreting those results and their implications for energy policy. In particular, these papers analyze effects of a costless technology shock (CTS) and correctly shows the important economic effects of technology, but policymakers cannot require a costless technology shock. They can require that firms use more resources to achieve more energy efficiency in the appliances they produce, but the economic effects of such requirements cannot be inferred from studies of a CTS. A few papers consider costs of energy efficiency in partial equilibrium or computable models. None provide analytical general equilibrium results for a costless technology shock and for increased stringency of an energy efficiency standard (EES) in a world with a pre-existing standard that is already binding and therefore costly.

In other words, we focus on the costs of policies that require energy efficiency in a model that incorporates economy-wide resource constraints and where these policies face increasing marginal cost of achieving greater energy efficiency. Our general equilibrium model is solved analytically to decompose rebound into direct effects and indirect effects, each of which is explained by income and substitution effects. The closed-form solutions show exactly how each effect depends on parameters. Then we also calibrate the model to show numerical illustrations. We show that this view of the policy experiment can indeed improve energy efficiency and has the same kind of direct efficiency effect of reducing energy use, but the sign of rebound likely switches from positive to negative. What do we mean by “likely”? The sign is still formally ambiguous, but our theoretical results show exactly the conditions under which rebound is negative. And the most plausible cases we consider in our numerical illustrations have negative rebound.

The intuition is clear: the CTS is an exogenous improvement in technology that makes more possible with less, expanding the production possibility frontier (PPF). It raises real income, which induces consumers to purchase more heating or cooling services. In contrast, the EES requires a move along the PPF. With no pre-existing mandate, introducing a small EES has small costs. But, most developed economies have substantial energy efficiency

requirements. If technology is given, and consumers are constrained to buy more-expensive appliances with more energy efficiency than they would if unconstrained, then an increase in stringency can have rising marginal costs that reduce real income. Those extra costs could well be justified by benefits of reduced negative externalities from energy use, but costs of complying with the mandate still reduce household incomes and thus have negative income effects on the purchases of all goods including appliance services. We show how the negative income effect offsets part of the positive direct effect on energy used for those services, and it creates a large negative indirect rebound effect on energy used in production of other goods.

Over a hundred economics papers have provided theoretical and empirical analyses of rebound effects from energy efficiency improvements, but the size of rebound is still under debate.¹ These papers include both partial equilibrium (PE) and general equilibrium (GE) models, but most focus on a costless technology improvement in energy efficiency and find positive rebound.² Some research considers the costs of energy efficiency improvements in PE models, and they find smaller rebound effects than in the case of a costless technology change.³ But, PE studies do not usually incorporate economy-wide resource constraints. A few papers include costs of energy efficiency in numerical results using quantitative, multi-sectoral, dynamic, GE growth models.⁴ While these PE or GE papers may consider the costs of greater energy efficiency, however, they are not clear about whether these costs are incurred voluntarily by firms and consumers or are mandated by government. Yet, voluntary costs can be presumed to *raise* consumer welfare, with positive income effects. We calculate rebound effects from a mandated increase in costly energy efficiency, and compare them to effects of a costless technological improvement.⁵ We also show how the effect of either such shock is altered by pre-existing costly efficiency standards.

Our simple general equilibrium model has many identical consumers who get utility

¹ For examples of reviews, see Greening *et al.* (2000), Sorrell and Dimitropoulos (2008), Sorrell *et al.* (2009), and Gillingham *et al.* (2016).

² For PE examples, see Thomas and Azevedo (2013) and Chan and Gillingham (2015). The GE models include Grepperud and Rasmussen (2004), Wei (2007, 2010), Abdesslem and Labidi (2016), and Lemoine (2017).

³ See Mizobuchi (2008) and Nässén and Holmberg (2009). Borenstein (2015) considers the consumer's choice to spend more for additional energy efficiency; this cost reduces income and can reduce purchases of energy (negative rebound). But it is a choice by consumers, not the imposition of extra costs by a mandate.

⁴ See Allan *et al.* (2007), Barker *et al.* (2007, 2009), Turner (2009), and Chang *et al.* (2018).

⁵ The review by Gillingham *et al.* (2016) points out the distinction between rebound from a costless technology shock and a costly policy shock, and they describe how empirical estimates mix the two sources. Interestingly, however, none of the papers in this large rebound literature has analyzed an energy efficiency improvement – either costless or costly – as we do here in a world with a pre-existing policy that is both costly and binding.

from vehicle or appliance services and from another composite good. They own a single factor of production that they can sell to firms for income to buy appliances, energy to run them, and the other composite good. We model all budget constraints and zero profit conditions of competitive firms, and then we differentiate all equations to linearize the model. We then analyze three kinds of exogenous shocks. First, we consider a costless technology shock with no change in spending on appliances. We show how that shock raises welfare and reduces direct energy use – with positive rebound as in prior literature. Second, we consider a CTS in a world with a pre-existing efficiency mandate that is binding and costly. When consumers can change all their other choices, we show how the CTS allows them to reduce their expenditures that were formerly necessary to satisfy the mandate. The result is no gain in energy efficiency, which still barely satisfies the unchanged mandate, but the CTS does have a positive income effect and so still yields positive rebound. Third, and finally, we consider the basic policy question: what are the effects of increasing the energy efficiency requirement of a pre-existing mandate? The answer depends on the curvature of the cost function for acquiring additional energy efficiency (given existing technology). If that extra efficiency is cheap, then overall welfare costs are low, but we consider the likely case that the marginal cost of achieving additional energy efficiency is not only significantly positive but rising – as policymakers attempt to achieve greater energy efficiency.

Following sections describe the model (section 1), our linearization (2), theoretical results for the three types of shocks just described (sections 3, 4, and 5), our calibration (6), numerical results (7), sensitivity analysis (8), separate appliances (9), and conclusions (10). All appendices are included below, but later will be online only.

1. The Analytical General Equilibrium Model

For simplicity, we assume a static, one-period, closed economy with competitive markets and a large number n of identical consumers (or households). These consumers each own and supply a single primary factor K , which can be labor, capital, or a composite of both. As specified below, K is used in production of energy E , appliances A , and a composite of all other goods X (such as clothing, food, and shelter). With this aggregation for tractability, we define A to include air conditioners, furnaces, and all other consumer durables that use energy – including vehicles. Then a costless technological discovery might increase a refrigerator's cooling per kilowatt hour of electricity, or it might increase a car's miles per gallon. In fact, one of our major examples of a mandate is the federal corporate average fuel economy

(CAFE) requirement that manufactures meet a minimum fleet-average miles per gallon. Several nations have such requirements and might increase their stringency.

In a form of home production, each household produces services S from purchases of appliances A and energy E_S (that is, energy, E , used for services, S). These services include refrigeration, cooling in summer, heat in winter, and miles driven. Consumers get utility from these services, and from the composite good, and they get disutility from the economy-wide aggregate use of energy. Thus, each consumer's utility function takes the following form:

$$U = U(S, X; nE) \tag{1.1}$$

where U is twice continuously differentiable, quasi-concave, and homothetic. It is increasing in the first two arguments and decreasing in nE , aggregate energy use.⁶ This public good or bad is separable in utility, so changes in nE do not affect consumer choices of S or X .

Our simple model cannot consider the discrete choice of whether to buy an appliance or vehicle. Instead, the household can choose any amount of the aggregate “ A ” commodity. Moreover, conceptually, features of a car not related to energy efficiency such as leather seats are best considered to be part of the other good, X . Similarly, a home's double-pane insulated glass window is part of A , but the stained-wood window frame is part of X . Thus, we use A not to represent total cars and appliances, but only the portion devoted to energy efficiency.⁷

With those clarifications, the home-production function is:

$$S = \epsilon A E_S \tag{1.2}$$

where ϵ is a technology parameter, and ϵA is energy efficiency. If ϵA is in miles per gallon, for example, then multiplication by E_S in gallons of gasoline yields S in miles. Or, if ϵA is in cooling per kwh, and E_S is kwh of electricity, then S is measured in degrees of cooling. With only one type of A , consumers who want more energy efficiency must buy more A . Then, with this model, we can study a small exogenous increase in the technology scalar, ϵ , in order to solve for rebound effects from a costless technology shock (CTS), and we can study a small increase in required spending on A to analyze an energy efficiency standard (EES).

Extra energy efficiency in A can be purchased, and it is produced by firms using extra resources, so the total cost of making appliances or cars more energy efficient is expressed in

⁶ If n is large enough, then an individual household can disregard its own contribution to aggregate energy use and take as fixed the third argument in utility (nE). In any case, we do not make use of this third argument in our analysis. We include it in utility only as a reminder of the reason to have an energy efficiency policy.

⁷ With no data to identify the portion spent on fuel efficiency, our calibration below uses alternative assumptions.

units of the composite input, K_A (that is, composite input, K , used in production of A):

$$K_A = B(A - A_0)^\beta, \text{ with } 0 \leq A_0 \leq A, B > 0, \text{ and } \beta \geq 1 \quad (1.3)$$

The scale parameter B converts units (from A to K), and the exponent β represents cost curvature. If $\beta = 1$, then cost is linear, so additional fuel efficiency can be achieved at a flat marginal cost. But we generally assume $\beta > 1$, to capture the likely case that additional efficiency can be obtained only by using successively more expensive materials or technologies. The parameter A_0 provides flexibility to shift the intercept of the cost function, and this shifted cost function is used in most engineering studies reviewed below and in our calibration appendix.⁸ The general idea is that any car must generate some positive miles per gallon (mpg), even when *no* costs are incurred trying to raise mpg. Some energy efficiency (A_0) comes with any car, while costs of additional efficiency could be quadratic (e.g., $\beta=2$).

The model abstracts from various taxes on inputs or outputs, just as it abstracts from government expenditures.⁹ The essential function of government modeled here includes only a required target total energy efficiency of household appliances, a target that can be stated in miles/gallon or degrees of cooling/kwh. That standard can be represented as $\epsilon A \geq \eta$, for a policy scalar η . We assume the existing policy is binding, so fuel efficiency matches the scalar: $\epsilon A = \eta$. For a given value of the technology parameter, government has essentially set A , which costs K_A . Thus, a new regulation that raises the required fuel efficiency must raise costs in this model, where the cost of A rises at an increasing rate (increasing marginal cost).¹⁰

Because the initial equilibrium has a pre-existing efficiency standard that is both costly and binding, we have no need to describe how a consumer facing no standard would maximize $U = U(\epsilon A E_S, X; nE)$ by their choices of A , E_S , and X . Instead, we assume that the government “distorts” those choices by requiring more A than unconstrained consumers would choose – presumably to reduce the negative effect on U from total energy use nE . Our

⁸ Those studies include NRC (2002, 2015), DOE (2011, 2016a, 2016b), and Lutsey *et al.* (2017). Our cost function allows A_0 to be zero, and we later determine whether a positive A_0 is necessary to fit the data.

⁹ Our model could be extended to include other taxes and second-best effects, but those topics are well covered already (see papers collected in Goulder, 2002). Such extensions would complicate our analysis and modify our solutions by adding more rebound terms of either sign, but it would not remove the key terms we discuss below. It might confuse readers to discuss old second-best results that are not the topic of this paper. We prefer the simplest model necessary to demonstrate our new results (as summarized above and in propositions below).

¹⁰ These costs follow from our assumption that consumers are well-informed optimizers facing a costly mandate. In a behavioral model where consumers miss opportunities to reduce their own overall costs by choosing more energy efficiency, a mandate could raise welfare – with effects very similar to the CTS analyzed below. Here we use the simplest model to show how increased stringency can raise costs and thus have negative rebound.

linearization below can analyze small changes, so we also assume that a small increase in technology ϵ would not be enough to make the policy non-binding (discussed more below).

In Proposition 2 below, we solve for a condition on parameters that must hold for our assumption that rational and fully-informed consumers are being forced to purchase more A than they would desire if unconstrained. When we assume this condition holds, then any increase in the stringency of the energy efficiency requirement must be costly and therefore must reduce real income (ignoring the benefits of reduced external damages).¹¹

Since ϵ and A are given, and K_A is a fixed cost, the household chooses only energy use E_S (at price P_E) and other goods X (at price P_X). Their only income is from a fixed total factor endowment, \bar{K} , which earns the rate of return P_K . Thus, the budget constraint is:

$$I = P_K \bar{K} = P_X X + P_K K_A + P_E E_S$$

Then, because $S = \epsilon A E_S$, the maximization of $U(S, X)$ subject to this budget yields first order conditions that can be solved for the marginal rate of substitution: $\frac{\partial U}{\partial X} / \frac{\partial U}{\partial S} = P_X / (P_E / \epsilon A)$. In other words, given the fixed cost $P_K K_A$, the *effective marginal price of appliance services* is $P_E / \epsilon A$. For example, if P_E is the price of gasoline in \$/gallon, and ϵA is fuel efficiency in miles/gallon, then the cost of an additional mile ($P_E / \epsilon A$) is in dollars per mile.

This model abstracts from the fact that the choice of car or air conditioner is before the choice of miles or cooling. It collapses that dynamic problem to a year in which the economy is in long-run equilibrium, so the household pays the annualized cost of the car plus annual cost of miles. But this model captures exactly the aspect of the problem that gives rise to rebound: once the car or appliance is purchased with a particular energy efficiency, the only marginal cost is energy use. Energy efficiency may rise through a costless shock to ϵ , or a requirement that raises the fixed cost of A , but either such shock *reduces* marginal cost ($P_E / \epsilon A$) per mile driven or per degree of cooling from the air conditioner.

On the producer side, competitive firms are price takers in all markets, with constant returns to scale (CRTS) production. Firms in sector X use K_X and energy E_X as inputs. Energy E is generated from input of factor K_E . We choose units of measurement such that one unit of the primary factor K_E can produce one unit of E . Thus, the production functions are:

$$X = X(K_X, E_X) \tag{1.4}$$

¹¹ Or, if that condition is not satisfied, then a policy to increase energy efficiency can raise real income. That case would require a model of how consumers choose energy efficiency (A) that does not maximize utility.

$$E = K_E \tag{1.5}$$

Perfect competition and CRTS imply zero-profit conditions stating that the value of each sector’s output produced and sold must equal the sum of amounts spent on inputs:

$$P_X X = P_K K_X + P_E E_X \tag{1.6}$$

$$P_E E = P_K K_E \tag{1.7}$$

All markets must clear in equilibrium. That is, energy supply must equal the sum of all demands, and the factor endowment must equal the sum of all factor uses:

$$E = E_X + E_S \ , \tag{1.8}$$

$$\bar{K} = K_X + K_A + K_E \ . \tag{1.9}$$

2. Linearization

We totally differentiate and linearize all equations at the initial equilibrium, and we use a “hat” to denote a proportional change (e.g., $\hat{X} \equiv dX/X$). The resulting N linear equations are solved in later sections for N unknowns, the changes in quantities and prices that result from a small exogenous change in technology ($\hat{\epsilon}$) or policy ($\hat{\eta}$). The analysis of small changes does not mean results are small, however. Pre-existing standards act like taxes that raise the cost of appliances, so they create deadweight losses that rise disproportionately with the implicit tax rate. While the initial small standard or tax has only second-order effects on welfare, successive increases have first-order effects. Moreover, our linearization captures exactly the sort of the policy debates about small legislative changes that are most common.

Large new regulations are rare, as actual policy proceeds incrementally. When first enacted in 1975, for example, CAFE rules required new passenger cars by 1978 to average 18 miles per gallon (mpg). The standards increased to 27.5 mpg for model year 1985, and they were raised again in 2011 (NHTSA, 2011a). By model year 2025, vehicles with footprint over 55 square feet need to meet a standard of 46 mpg, while those 41 square feet or smaller must achieve 60 mpg (NHTSA, 2011b). Rules for household appliances similarly face periodic debates about incremental changes.¹²

To proceed, total differentiation of production functions for the three goods shows

¹² A standard enacted in 1988 required top-loading clothes washers manufactured between 1988 and 1994 to have an unheated rinse option, and it required those manufactured after 1994 to have a “modified energy factor” (cu.ft./kWh/cycle) of at least 1.18. This DOE standard was raised in 2007 to 1.26, in 2015 to 1.29, and in 2018 to 1.57. See <https://www.gpo.gov/fdsys/browse/collectionCfr.action?selectedYearFrom=2018&go=Go> . For another example, the 1992 standard for split system central air conditioners required a “seasonal energy efficiency ratio” (SEER) of at least 10. It was raised in 2006 to 13, and in many states again in 2015 to 14.

how the change in each output is determined from changes in each set of inputs:

$$\hat{S} = \hat{\epsilon} + \hat{A} + \hat{E}_S \quad (2.1)$$

$$\hat{X} = \theta_{KX}\hat{K}_X + \theta_{EX}\hat{E}_X \quad (2.2)$$

$$\hat{E} = \hat{K}_E. \quad (2.3)$$

For sector X , the factor share for input K is θ_{KX} , the factor share for energy is θ_{EX} , and $\theta_{KX} + \theta_{EX} = 1$. The elasticity of substitution in sector X between inputs to production is defined as σ_X , the percentage change in the input use ratio in response to a one percent change in the input price ratio. For small changes, the definition of σ_X implies:

$$\hat{K}_X - \hat{E}_X = \sigma_X(\hat{P}_E - \hat{P}_K). \quad (2.4)$$

Since the marginal price of services S is $P_E/\epsilon A$, differentiation yields the proportional change in that price as $(\hat{P}_E - \hat{A} - \hat{\epsilon})$. The elasticity of substitution in utility between X and S is σ_U , defined as the percentage change in the ratio of those quantities for a one percent change in the marginal price ratio. For small changes, we get:

$$\hat{X} - \hat{S} = \sigma_U[(\hat{P}_E - \hat{A} - \hat{\epsilon}) - \hat{P}_X]. \quad (2.5)$$

Then, we differentiate $K_A = B(A - A_0)^\beta$ and manipulate:

$$\hat{K}_A = \frac{\beta}{1-\alpha}\hat{A}, \quad (2.6)$$

where $\alpha \equiv A_0/A$ is minimum energy efficiency as a fraction of total initial energy efficiency ($0 \leq \alpha < 1$). We interpret $\beta/(1-\alpha)$ in this equation as the ‘‘cost elasticity of energy efficiency’’, because it is the percent change in cost for one percent more efficiency. Next, totally differentiate zero-profit equations (1.6) - (1.7), and use the firm’s FOC’s:

$$\hat{P}_X = \theta_{KX}\hat{P}_K + \theta_{EX}\hat{P}_E \quad (2.7)$$

$$\hat{P}_E = \hat{P}_K \quad (2.8)$$

Finally, total differentiation and linearization of the market-clearing condition in (1.8) and the resource constraint in (1.9) yield:

$$\hat{E} = \lambda_X\hat{E}_X + \lambda_S\hat{E}_S \quad (2.9)$$

$$0 = \gamma_X\hat{K}_X + \gamma_A\hat{K}_A + \gamma_E\hat{K}_E \quad (2.10)$$

where λ_i denotes the ratio of energy use in sector i to the total use of energy ($\lambda_X + \lambda_S = 1$), and γ_i is the ratio of capital used in sector i to total capital in all sectors ($\gamma_X + \gamma_A + \gamma_E = 1$).

We define the primary factor K as numeraire, so $\hat{P}_K = 0$.

3. Rebound from a Costless Technological Shock with No Binding Mandate

A costless technology shock (CTS) is represented in our model by a small exogenous change in efficiency technology, $\hat{\epsilon} > 0$. Many prior papers study rebound from this kind of technology shock in a world with no efficiency mandate and assuming no change in spending on appliances. The analysis in this section is designed to represent prior literature by similarly assuming no efficiency mandate nor change in appliance spending. This case is *not* “general equilibrium” in nature, because we assume no change in A . Yet, consumers do react to greater energy efficiency by changing their fuel use, their appliance services, and other goods.¹³ We use this representation of prior literature below for direct comparisons with results for general equilibrium rebound from either a CTS or a policy shock in a world *with* a pre-existing energy efficiency mandate that is both costly and binding. This section also provides a detailed walkthrough of how we decompose rebound into its various components.

Thirteen changes ($\hat{X}, \hat{S}, \hat{A}, \hat{E}, \hat{E}_X, \hat{E}_S, \hat{K}_X, \hat{K}_A, \hat{K}_E, \hat{P}_X, \hat{P}_E, \hat{P}_K, \hat{\epsilon}$) appear in the ten linearized equations (2.1) – (2.10). This section takes $\hat{\epsilon} > 0$ as an exogenous change in technology and assumes that A is unchanged ($\hat{A} = 0$). Thus, with K as numeraire ($\hat{P}_K = 0$), we can solve for the other ten outcomes (in proportional changes). In addition, we unpack the solution for \hat{E} into different terms. Each such term can show a particular rebound effect as a function of parameters and of the exogenous increase in the efficiency scalar, $\hat{\epsilon} > 0$.

For this CTS with no mandate and unchanged A , some of the solutions are easy to see. For example, the simple production function for E uses only the numeraire primary factor, so our first result is $\hat{P}_E = \hat{P}_K = 0$. Production of X uses both K and E , but neither input price changes, so CRTS implies $\hat{P}_X = 0$. Also, the two inputs change in the same proportion as output, $\hat{E}_X = \hat{K}_X = \hat{X}$. Next, the effective marginal price of S is $P_E/\epsilon A$, but ϵ rises while A and P_E are unchanged. Therefore, the cost per additional unit of S falls ($\hat{P}_E - \hat{\epsilon} - \hat{A} = -\hat{\epsilon}$). Appendix A shows derivations for all outcomes, but here are solutions for four of them:

$$\hat{X} = \left(-(\gamma_A + \gamma_E \lambda_S) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \right) \hat{\epsilon} \quad (3.1)$$

$$\hat{S} = \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \right) \hat{\epsilon} \quad (3.2)$$

¹³ Our simple model is not designed to determine consumer choice of A optimally in a world with no mandate. Instead, we want to compare rebound from the CTS with and without a mandate, “all else equal” (including A).

$$\widehat{E}_S = \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - 1 \right) \hat{\epsilon} \quad (3.3)$$

$$\hat{E} = \left((\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \lambda_S \right) \hat{\epsilon} \quad (3.4)$$

The last equation for the overall change in energy use (\hat{E}) will be re-arranged to decompose it into key components, but we first gain some intuition by looking at the other outcomes.

The positive technology shock increases real incomes, so consumers buy more goods and services.¹⁴ They also respond to the fall in the marginal cost of services by substituting toward S from X (in a way that depends on σ_U). The simplicity of our model allows us to separate income from substitution effects for both services and the other good. Specifically, in Appendix B, we derive the substitution effect as the change in consumption while consumers face the new prices but are as happy as in the old equilibrium. The income effect is the remaining change in consumption. In fact, Appendix B shows that the first term in equation (3.1) is the substitution effect on X , which depends on σ_U and is negative. The income effect on X is the remaining term in (3.1) and is positive. Similarly, the first term in (3.2) is the positive substitution effect on S . The income effect on S is the remaining term in (3.2), and it matches the positive income effect on X (because of homothetic preferences).

Next, our model enables us to solve for the welfare gain from this shock, given by the overall change in utility (dU) divided by the marginal utility of income (μ). This dollar value of the change in utility is then divided by total income (I) to express it in relative terms. As shown in Appendix C, this measure of the change in welfare is:

$$\begin{aligned} \frac{dU}{\mu I} &= \frac{P_X X}{I} \hat{X} + \frac{P_K K_A + P_E E_S}{I} \hat{S} \\ &= (\gamma_X + \gamma_E \lambda_X) \hat{X} + (\gamma_A + \gamma_E \lambda_S) \hat{S} = \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \hat{\epsilon} > 0 \end{aligned}$$

In the first line, the relative change in welfare is a weighted average of the changes in consumption of goods and services, where the weight for each is its share of income.¹⁵ Using solutions for \hat{X} and \hat{S} above, the closed-form solution for $dU/(\mu I)$ is shown on the far right. As confirmation of these two derivations, we note that this relative change in real income is

¹⁴ Utility is homothetic, so both the commodity X and services S are normal goods.

¹⁵ We can show that $(\gamma_X + \gamma_E \lambda_X)$ is the income share of the composite good X : $\gamma_X + \gamma_E \lambda_X = \frac{K_X}{\bar{K}} + \frac{K_E E_X}{\bar{K} E} = \frac{K_X + E_X}{\bar{K}} = \frac{P_K K_X + P_E E_X}{P_K \bar{K}} = \frac{P_X X}{I}$. Similarly, $(\gamma_A + \gamma_E \lambda_S) = \frac{K_A}{\bar{K}} + \frac{K_E E_S}{\bar{K} E} = \frac{P_K K_A + P_E E_S}{I}$ is the income share for S .

identical to the earlier-derived income effect on goods and on services.

Income and substitution effects alter the consumption bundle and thus change energy use. As shown above, the proportional change in energy used in production of the composite good, \widehat{E}_X , matches the proportional change in that good, \widehat{X} shown in (3.1), because of CRTS with unchanged input prices. Thus, the income effect causes the same proportional increase in X and E_X . Also, the substitution effect reduces E_X by the same percentage as it reduces X in (3.1). The substitution effect increases E_S by the first term in (3.3), and the income effect increases E_S by the second term in (3.3). But (3.3) for \widehat{E}_S has a third term that reduces energy use for appliance services (by $-\hat{\epsilon}$). This last term is the *direct effect* of the CTS that allows consumers to produce the same services using less energy.

The general solution for \widehat{E} in (3.4) has an ambiguous sign, and it is hard to interpret, so we unpack the effect on total energy use into three major components: a direct efficiency effect, a direct rebound, and an indirect rebound. We then further decompose both the direct and indirect rebound effects into income and substitution effects, in general equilibrium.¹⁶

These components appear in the first column of Table 1, Panel A, which decomposes effects of a CTS on total energy use in this case (with no policy, and fixed A). The sum of all terms in the first column is \widehat{E} in equation (3.4). The other columns and panel – discussed later – show general equilibrium effects of a CTS *with* a pre-existing standard, and effects of increased stringency of an energy efficiency standard (EES).

In column (1), with no policy, consumers could exploit the efficiency improvement to get the same services using less energy. That is, even if households were to choose unchanged X and S , the energy used to produce this bundle would fall. We define this energy saving as the “direct efficiency effect” (DEE), identified in the first term of the column. This energy saving would be the only effect if relative prices and real incomes held constant – as it might be calculated by engineers. Thus, the DEE reduces energy used *for services* by the full amount of the technology shock ($-\hat{\epsilon}$). It reduces the total energy use in the economy by the shock times the fraction of total energy used for those services ($-\lambda_S \hat{\epsilon} < 0$).

Next, in column (1) of Panel A, we define the “direct rebound effect” (DRE) as the change in energy use resulting from the combined substitution and income effects on the demand for services S (as in Gillingham *et al.* 2016). The income effect component of that

¹⁶ Most PE empirical studies estimate only the uncompensated direct rebound effect, without separate income and substitution effects. Thomas and Azevedo (2013) and Borenstein (2015) use PE theory models to decompose direct and indirect rebound effects into substitution and income effects. We follow their lead, but in a GE model.

DRE is the next term in the column (λ_S times the income effect on E_S in eq. 3.3). The real income gain allows consumers to get more S using more E_S . The DRE through the substitution effect is the next term down. It is λ_S times the substitution effect on E_S in (3.3), and it is also positive. Its absolute size depends on σ_U , the elasticity of substitution in utility. The DRE is the sum of the income and substitution effects and thus must be positive.

The “indirect rebound effect” (IRE) then refers to the effect of the technology shock on the equilibrium change in demand for the *other* good, X , and thus on *its* energy use, E_X . The second-to-last term in this first column of Panel A is the change in energy use from the income effect on demand for X . It is $\lambda_X \equiv E_X/E$ times the income effect on E_X in (3.1), and it is positive. The last term is the change in energy use through the substitution effect on X . Consumers substitute away from X , which implies less energy use E_X , a *negative* effect on rebound. The total IRE is the sum of a positive income effect and negative substitution effect:

$$\frac{\lambda_X((\gamma_X + \gamma_E \lambda_X)\sigma_U \gamma_A + \lambda_S \gamma_E)}{1 - \gamma_A} \hat{\epsilon} - \lambda_X(\gamma_A + \gamma_E \lambda_S)\sigma_U \hat{\epsilon} = \frac{\lambda_X \lambda_S \gamma_E (1 - \sigma_U)}{1 - \gamma_A} \hat{\epsilon}.$$

The sign of this expression depends on the size of σ_U . If goods X and S are not substitutable enough ($\sigma_U < 1$), then the income effect dominates, and the indirect rebound is positive. If the substitution effect dominates ($\sigma_U > 1$), however, then the IRE is negative.

Alternatively, we can decompose rebound into an “overall income effect” and an “overall substitution effect”. The real income gain increases demands for both E_X and E_S and thus always adds positively to rebound. The overall income effect is the sum of the two income effects in the first column of Table 1, or $((\gamma_X + \gamma_E \lambda_X)\sigma_U \gamma_A + \lambda_S \gamma_E)\hat{\epsilon}/(1 - \gamma_A) > 0$ (because $\lambda_S + \lambda_X = 1$). It is the second term in the solution for \hat{E} in (3.4). Similarly, we can calculate an overall substitution effect on rebound through both E_S and E_X by adding the two substitution effects. This sum is $(\lambda_S \gamma_X - \lambda_X \gamma_A)\sigma_U \hat{\epsilon}$, and it is the first term in (3.4). It has an ambiguous sign because the substitution effect increases E_S but decreases E_X .

We can show that $\lambda_S \gamma_X - \lambda_X \gamma_A > 0$ implies that appliance services are more energy-intensive than the composite good sector.¹⁷ If this inequality holds, then the overall income effect and overall substitution effect both increase energy use. If S is less energy-intensive, however, then the substitution effect is a “negative” component of rebound, and the sign of

¹⁷ Rearrange the inequality $\lambda_S \gamma_X - \lambda_X \gamma_A > 0$ to get $\frac{\lambda_S}{\gamma_A} > \frac{\lambda_X}{\gamma_X} \leftrightarrow \frac{E_S/E}{K_A/\bar{K}} > \frac{E_X/E}{K_X/\bar{K}} \leftrightarrow \frac{E_S}{K_A} > \frac{E_X}{K_X}$, which implies that the S sector is more energy intensive than sector X .

the total rebound depends on whether the income effect dominates the substitution effect.

These analytical results and their signs in the second column of Table 1 are consistent with results in prior literature. Technological progress generally improves energy efficiency of the economy, so its direct efficiency effect is to reduce total energy use. The direct rebound effect is expected to be positive, through substitution, while indirect rebound can be positive or negative. The next section distinguishes between these effects of a CTS with no existing mandate from those of a CTS with a pre-existing mandate. (Later, we distinguish these results from those following the increased stringency of a binding energy efficiency standard.)

4. Rebound from a Costless Technological Shock with a Binding Mandate

Unlike existing papers, we now study general equilibrium rebound effects from a costless technology shock in the case with a pre-existing efficiency mandate that is both costly and binding. The CTS is still modeled as an increase in the technology parameter, $\hat{\epsilon} > 0$, but as mentioned above, we assume that the pre-existing mandate requires enough additional purchase of energy efficiency beyond the unconstrained amount that a small change in ϵ would not make the policy non-binding.¹⁸

In general equilibrium, if consumers care about fuel efficiency ϵA and are given an exogenous increase in ϵ , then they can choose to spend less on A . If they do so, then the CTS may not improve efficiency by the full amount of the exogenous shock. This behavior is particularly important with a pre-existing mandate that is costly and that remains binding. Since consumers still have to purchase more A than desired, they respond to the technology shock by cutting back as much as possible on purchase of A . If consumers spend only enough to satisfy the unchanged mandate, then the CTS results in no additional energy efficiency at all.¹⁹ The unchanged policy still requires $\epsilon A \geq \eta$, so consumers can reduce purchase of costly A such that $\hat{A} = -\hat{\epsilon}$, and energy efficiency ϵA is unchanged.²⁰

¹⁸ Using our linearization method requires the assumption that all equations are differentiable, and thus the solutions are differentiable. Results are only valid for small changes, so the technology shock $\hat{\epsilon}$ must be small. We assume it small enough that it does not change the binding nature of the pre-existing policy. If an actual shock were large enough to make the policy non-binding, then the outcome would include some effects of this section with a binding mandate and some effects of the previous section without a binding mandate.

¹⁹ In a similar result, though not about rebound, Goulder *et al* (2012) look at a subset of states that adopt a vehicle fuel efficiency standard that is more stringent than the federal standard requiring automakers to meet a nationwide corporate average fuel economy (CAFE). Those automakers can sell more fuel efficient cars in the more-stringent states and sell less efficient cars in other states, with no overall change in average fuel efficiency.

²⁰ Empirical evidence in Knittel (2012) suggests that improvements in fuel efficiency technology over time were offset by spending on other vehicle characteristics that reduce fuel efficiency, such as vehicle weight and power.

We use the ten linearized equations in Section 2 to solve for the same ten unknowns as above. The exogenous shock is still $\hat{\epsilon} > 0$, and the numeraire is still $\widehat{P}_K = 0$, but all outcomes are now different because $\hat{A} = -\hat{\epsilon}$. Appendix D derives a closed-form expression for each of these ten equilibrium changes resulting from a small CTS with a binding energy efficiency standard, including the change in total energy use, \hat{E} , but then we unpack that solution for \hat{E} into the same rebound effects as before, as shown in column (3) of Table 1.

Many of the results are both easy to solve and intuitive. The primary factor K is the only input to the production of E , and it is numeraire, so $\widehat{P}_E = \widehat{P}_K = 0$. Production of X uses both K and E , but neither input price changes, so CRTS implies $\widehat{P}_X = 0$. Therefore, the two inputs change in the same proportion as output, $\widehat{E}_X = \widehat{K}_X = \hat{X}$. Next, the CTS does not change overall energy efficiency, ϵA , so $\hat{S} = \widehat{E}_S$. The effective marginal price of S is $P_E/\epsilon A$, where $\widehat{P}_E = 0$, and A falls by the same percentage that ϵ rises. Therefore, the marginal cost of S does not change ($\widehat{P}_E - \hat{\epsilon} - \hat{A} = 0$). Unchanged relative prices of services S and good X implies no substitution between these goods. Yet the CTS helps consumers to cut spending on A while they still meet the unchanged standard. Thus, it has a positive income effect that increases X and S by the same percentage as the income gain (as shown in Appendix D):

$$\hat{X} = \hat{S} = \frac{\gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon} > 0.$$

As a consequence, the relative welfare gain, measured by the dollar value of the change in utility divided by total income as in Appendix C, is:

$$\frac{dU}{\mu l} = \frac{P_X X}{I} \hat{X} + \frac{P_K K_A + P_E E_S}{I} \hat{S} = \hat{X} = \hat{S} = \frac{\gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon}$$

Increases in consumption of X and S lead to an increase in energy use by the same percentage:

$$\hat{E} = \widehat{E}_X = \widehat{E}_S = \frac{\gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon} > 0.$$

These positive rebound effects depend positively on the fraction of K used in the appliance sector ($\gamma_A \equiv K_A/\bar{K}$), and on the cost elasticity of additional energy efficiency [$\beta/(1-\alpha)$]. This elasticity depends on the curvature of the cost function β and the fraction $\alpha \equiv A_0/A$.

In fact, all effects on energy use in column (3) of Table 1 are either zero or positive. The economy stays at the same mandated efficiency level after the technology shock, so the direct efficiency effect is zero. And rebound through substitution effects is zero, so the direct and indirect rebound effects have only their positive income effect. The *total* effect of the CTS is to increase total energy use, as shown in Table 1. This result could be defined as a

“backfire”, since the positive rebound effect swamps the zero direct efficiency effect. We state these results formally in Proposition 1.

PROPOSITION 1: *For a positive costless technology shock (CTS) in this model with a pre-existing energy efficiency mandate that is costly and still binding after the shock, then:*

- (i) *The direct efficiency effect is zero.*
- (ii) *Rebound substitution effects are zero.*
- (iii) *The only nonzero rebounds are through income effects and are positive.*

The proof for Proposition 1 is the derivation above and in Appendix D. It follows from the assumption that the unchanged energy efficiency standard is still binding after the CTS.

These results are strikingly different from those in prior rebound literature. For the CTS with no pre-existing mandate, the prior literature shows that the direct efficiency effect is a reduction in energy use, only partly offset by a positive direct rebound effect (as in the first two columns of Table 1). For the CTS *with* a pre-existing mandate, the next two columns show the CTS has no direct energy savings at all, and no rebound through substitution effects. In essence, the energy efficiency innovation reduces the cost of achieving the unchanged pre-existing standard. Then “direct rebound” is the positive income effect on energy for S , and “indirect rebound” is the positive income effect on energy for production of other goods, X .

A glance down column (3) shows that if the fraction of K in services (λ_S) is less than the fraction of K used in other goods (λ_X), as could be expected, then the indirect rebound effect ($\frac{\lambda_X \gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon}$) is greater than the direct rebound effect ($\frac{\lambda_S \gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon}$). Most empirical papers based on partial equilibrium models measure only direct rebound, using the elasticity of demand for services, but they ignore mandates. In contrast, our general equilibrium model can show *indirect* rebound. And for the CTS with a pre-existing efficiency mandate, the positive indirect effect likely exceeds the positive direct rebound effect.

An additional possibility ignored here is that policy makers set standards based on costs and benefits, such that this reduction of costs could induce them eventually to tighten the standard. We do not analyze endogenous policy, but we do analyze a tighter standard (in the next section). We also ignore endogenous technology, but another possibility is that the costly policy can *induce* improvements in technology that then cause positive rebound effects. Finally, we assume the exogenous CTS is not large enough to make the mandate nonbinding, but footnote 18 above describes intuition for the effects of a larger CTS.

5. Rebound Effects from a Change in the Energy Efficiency Standard

We now solve for effects of a costly increase in EES stringency, decompose it into types of rebound, and compare these results to those above. Since the policy is represented by $\epsilon A \geq \eta$, we model the policy shock as a small exogenous change, $\hat{\eta} > 0$ (with no change in technology, $\hat{\epsilon} = 0$). Because purchase of A is costly, and consumers are already required to purchase more than they would if unconstrained, they will not buy more than necessary to satisfy the new requirement. Therefore the chosen \hat{A} will exactly equal the required $\hat{\eta}$.

Here again, we use the ten linearized equations (2.1) - (2.10) to solve for equilibrium changes in energy consumption, \hat{E} , and nine other unknowns. Then we decompose that effect on total energy use into separate terms. Each term shows a particular rebound effect as a function of parameters and of the exogenous change, $\hat{\eta} > 0$. As in other sections, some results are easy to show. For example, energy is produced using only the numeraire, so its production cost does not change ($\widehat{P}_E = \widehat{P}_K = 0$). The commodity X uses both K_X and E_X as inputs, so the relative price of X also does not change ($\widehat{P}_X = 0$). Thus, inputs change in the same proportion as output: $\widehat{E}_X = \widehat{K}_X = \hat{X}$. The marginal cost of S falls in the same proportion as energy efficiency rises ($\widehat{P}_E - \hat{A} - \hat{\epsilon} = -\hat{\eta} < 0$). Appendix E explains in detail the derivations for all unknowns. Here, we show the general solutions for only four of them:

$$\hat{X} = \left(-(\gamma_A + \gamma_E \lambda_S) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \right) \hat{\eta} \quad (5.1)$$

$$\hat{S} = \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \right) \hat{\eta} \quad (5.2)$$

$$\widehat{E}_S = \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} - 1 \right) \hat{\eta} \quad (5.3)$$

$$\hat{E} = \left((\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} - \lambda_S \right) \hat{\eta} \quad (5.4)$$

Again we discuss outcomes in (5.1)-(5.3) to help understand effects on total energy in (5.4).

Similar to the analysis of the CTS, the reduction in marginal cost of S has both income and substitution effects on X and S . Substitution leads to more consumption of services and less of other goods. The first term in (5.1) is the substitution effect on X , and it is negative. The substitution effect on S is the first term in (5.2), and it is positive. The size of substitution effects depends positively on σ_U . In addition, the total income effect has two terms. On the one hand, consumers get a positive income effect from the service cost reduction, captured by

the second terms in (5.1) and (5.2). On the other hand, they get a negative income effect because the more stringent policy ($\hat{\eta} > 0$) also requires more resources K_A to produce A (that is, $\widehat{K}_A = \frac{\beta}{(1-\alpha)} \hat{A} = \frac{\beta}{(1-\alpha)} \hat{\eta} > 0$). This second portion of the income effect ($-\frac{\gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\eta} < 0$) has a magnitude that depends on existing resource use for fuel efficiency ($\gamma_A \equiv K_A/\bar{K}$), curvature of its cost β , and the fraction α .

The policy shock alters relative prices, the consumption bundle, and thus energy use. The change in production of X in (5.1) results in the same percentage change in E_X . The change in E_S in (5.3) is ascribable to both the change in S and an additional negative term, $-\hat{\eta}$. This additional term is the direct energy savings from the mandated increase in efficiency.

To interpret the effect of the EES on total energy use, we now re-arrange (5.4) into the components shown in column (5) of Table 1, in Panel B. The first entry shows the direct efficiency effect, which is the reduction in use of energy with more-efficient appliances that would occur if households were to consume an unchanged bundle of X and S . This DEE reduces energy use in production of S , and thus reduces the economy-wide aggregate energy consumption by $\lambda_S \equiv E_S/E$ times the policy shock $\hat{\eta}$.

But households do change their bundle of X and S . We define the direct and indirect rebound effects of the EES in the same way as for the CTS, which enables us to compare the same concept for the two different exogenous shocks. Both the CTS and the EES shocks allow consumers to get the same services using less energy, so results in the fifth column are consistent with existing findings that the substitution effect increases consumption of S but reduces X . In particular, the direct rebound through the substitution effect is positive (see the third entry in the fifth column: $\lambda_S(\gamma_X + \gamma_E \lambda_X) \sigma_U \hat{\eta} > 0$). The last entry in that column is the negative indirect rebound through the substitution effect on X , $-\lambda_X(\gamma_A + \gamma_E \lambda_S) \sigma_U \hat{\eta} < 0$. Substitution effects decrease E_X but increase E_S . Adding the two substitution terms in the fifth column yields the overall substitution effect on energy use, $(\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U \hat{\eta}$, which has ambiguous sign. Thus, if services S are more energy-intensive than X , $(\lambda_S \gamma_X - \lambda_X \gamma_A) > 0$, then the overall substitution effect increases E , with a positive rebound effect. But if the X -sector is *more* energy intensive than the S -sector, the substitution effect increases E_S less than it decreases E_X , so the overall substitution effect could reduce total energy use.

The income effect is the main difference between the EES and CTS (with or without pre-existing mandate). The income effect for the CTS is always positive, as consumers get

“free money” from reduced need to spend on A or E_S . Under our assumptions that the EES is binding and costly, the real income effect of this policy shock must be negative.

The change in real income (i.e., the change in welfare) is given by the overall change in utility (dU) divided by the marginal utility of income (μ) and total income (I). As shown in Appendix C, using solutions for \hat{X} and \hat{S} above, we can measure this income change as:

$$\begin{aligned} \frac{dU}{\mu I} &= \frac{P_X X}{I} \hat{X} + \frac{P_K K_A + P_E E_S}{I} \hat{S} \\ &= (\gamma_X + \gamma_E \lambda_X) \hat{X} + (\gamma_A + \gamma_E \lambda_S) \hat{S} = \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \end{aligned}$$

Our assumption that the policy is binding therefore means that the change in real income on the far right must be negative. A slight re-arrangement of this condition implies:

PROPOSITION 2: *In this model, the pre-existing energy efficiency standard is costly and binding if and only if $\gamma_A \beta > (1 - \alpha)((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)$.*

Our assumption that the EES is binding means that the inequality holds. It means we assume a large enough fraction of resources is used for energy efficiency (γ_A), or a large enough curvature in its cost function (β), or both. If so, then the total income effect is negative.

The direct rebound effect is the sum of substitution and income effects on E_S . The substitution effect on S and E_S is always positive, but the income effect is negative. Therefore, the DRE can be negative or positive. The indirect rebound effect on E_X includes a negative substitution effect and a negative income effect, so its sign is clearly negative.

Also, some prior studies find evidence for “backfire” from energy efficiency – where the direct energy savings from increased energy efficiency are more than offset by positive rebound effects (Khazzoom, 1980; Brannlund *et al.*, 2007; Fouquet and Pearson, 2012; Saunders, 2013). This backfire is less likely for a *mandated* increase in energy efficiency, because the mandate is costly and thus has negative income effects on rebound. Here, we show exact conditions under which backfire is impossible for the efficiency mandate.

PROPOSITION 3: *For increased stringency of an energy efficiency standard (EES) in this model with a pre-existing efficiency mandate that is costly and always binding:*

- (i) *The direct rebound is negative if and only if $\gamma_A \beta > (1 - \alpha)((\gamma_E \lambda_X + \gamma_X) \sigma_U + \gamma_E \lambda_S)$ (in which case, $\gamma_A \beta$ is even larger than required for the EES to bind).*
- (ii) *The total rebound is negative if and only if $\gamma_A \beta > (1 - \alpha)(\lambda_S \gamma_X \sigma_U + \gamma_E \lambda_S)$ (less strict*

- than in (i)). A sufficient condition is when X is energy-intensive ($\lambda_S \gamma_X - \lambda_X \gamma_A < 0$).
- (iii) Backfire is impossible if and only if $\gamma_A \beta > (1 - \alpha) \lambda_S \gamma_X (\sigma_U - 1)$ (less strict than in (ii)). Sufficient conditions are X is energy-intensive ($\lambda_S \gamma_X - \lambda_X \gamma_A < 0$), or $\sigma_U < 1$.

Appendix F provides a detailed proof, but here we provide some intuition. The direct rebound effect on S is the sum of a positive substitution effect and a negative income effect, so it will be negative if the income effect dominates (a large enough γ_A or β , a small enough σ_U , or a combination of these). Total rebound is the sum of that DRE and the unambiguously negative IRE, so it can be negative under a looser condition. It is trivial to show that the condition in (i) is stricter than the one in (ii), and either is more strict than in (iii). If (ii) holds, so the *total* rebound effect is negative, then direct energy savings are augmented by further energy savings, and backfire is impossible. The condition $\sigma_U < 1$ is sufficient to rule out backfire, because the right side of the inequality in (iii) is negative, while the left side is positive. With $\sigma_U < 1$, the positive substitution effect is small and is swamped by the negative income effect, so the total rebound effect cannot offset direct energy savings.

Other sufficient conditions can guarantee that total rebound is negative (which also makes backfire impossible). The costs of a more stringent EES certainly make the income effect negative, but the substitution effect *can* be positive when E_S rises. If the X -sector is *more* energy-intensive than the S -sector, however, then E_X falls by more than E_S rises, and the overall substitution effect must also be negative. That is a case where total rebound under the energy efficiency standard *must* be negative.

Empirical studies of rebound often ignore or underestimate the indirect rebound effect.²¹ Yet we find above for the CTS that the indirect rebound effect can exceed the direct rebound effect. The same can hold for increased stringency of the EES. For example, Proposition 3 shows that the condition under which the DRE is positive is compatible with the condition where the TRE is negative. If so, then the magnitude of the negative IRE must be greater than the magnitude of the positive DRE. Thus, again, the indirect effect can swamp the direct effect. Moreover, as shown in Appendix F, we can use the proposition to find conditions under which indirect rebound is more negative than direct rebound.

6. Calibration

As shown in Table 1, the direct efficiency effect and rebound effects from an energy

²¹ One difficulty for empirical studies is to define a complete set of substitutes and complements to a particular product. Second, most ignore indirect income effects and use only cross-price elasticity estimates.

efficiency improvement depend on elasticities, on fractions of productive factors used in each sector, and on parameters in the cost function for energy efficiency. To illustrate numerical magnitudes, we calibrate these parameters and use them in our formulas to show how the size of results depend on parameters. Our benchmark dataset approximates the U.S. economy in the year 2015, the most recent year for which relevant data are available.

Our model has one primary factor, K , and two final outputs: appliance services S and a composite good X . Two other outputs are used as intermediate inputs, including energy E and appliances A . Yet, an actual car or appliance is a combination of energy efficiency features plus many aesthetic and functional features not related to energy use. We observe spending on appliances, but not on each feature. Added costs to improve energy efficiency may also vary by appliance. Yet, the energy efficiency mandate requires that $\epsilon_A \leq \eta$, for policy scalar η , so spending on A is best calibrated and interpreted as spending on energy efficiency rather than on other features not related to energy use. Here, we arbitrarily assume a fraction of actual expenditures on appliances is for energy efficiency (e.g. extra insulation or higher quality parts). We initially assume one-half, but we test sensitivity of results to this assumption. That is, if an Energy Star freezer-refrigerator costs \$600, then \$300 is spent on energy efficiency (A). The remaining \$300 is part of the other composite good, X .

Using partial equilibrium models, Borenstein (2015) or Chan and Gillingham (2015) can calculate rebound for particular examples like vehicles, electric lighting, or refrigerators. We wish to take a broader perspective, and our general equilibrium model is most useful for a large sector of the economy. Therefore, we analyze energy efficiency in a general way for all household appliances, an aggregation of everything of households that use energy – including washer, dryer, furnace, refrigerators, lights, air conditioners, and electric space heaters. Since household vehicles are also subject to fuel efficiency standards, they are also included.²² Then energy for appliance services (E_S) is an aggregation of all household purchase of electricity, natural gas, heating oil, propane, gasoline, and other motor fuels.

We obtain residential energy expenditure data from the State Energy Data System (SEDS), through which the Energy Information Administration (EIA) provides historical time

²² Actual appliances also have standards with differing history and stringency. With more disaggregation and complexity, this model could represent each of them separately. If $\beta > 1$, those with more stringency have more negative income effects and negative rebound. In our sensitivity analysis, we analyze cars and appliances separately (but with the same stringency). Each is about half the total, so effects of each are about half the total.

series of energy production, consumption, prices, and expenditures across sectors.²³ We get consumer expenditure data on gasoline and other motor fuels from the Bureau of Economic Analysis (BEA).²⁴ Energy expenditure by households for 2015 is 248 (\$B), and expenditure on gasoline and other motor fuels is 270 (\$B). So, the total energy used for appliance services is the sum, 518 (\$B). We define a unit of E in the initial equilibrium as the amount that costs \$1, so $P_E = 1$ (dollars per unit of E). Household energy use is $E_S = 518$ billion units, where energy E_S is the sum of all fuels used by household appliances (e.g. natural gas for heating, electricity for cooling, and propane for cooking).

To calculate the annual cost of appliances for energy efficiency, $P_K K_A$, we start with household expenditures on new appliances for 2015 from the BEA (675 \$B) and then perform a user cost calculation to arrive at the annualized cost of these capital assets.²⁵ We assume annual depreciation (δ) equal to 10% of total appliances, and annual maintenance (ω) equal to another 5%. We also assume no growth, so that all new appliance purchases are replacement investment (10% of the existing appliance stock each year). Then the existing appliance stock is $675 \times 10 = 6,750$ (\$B). If the annual discount rate (ρ) is 5%, then the annual user cost of appliances in \$B is $6,750 \times (\delta + \omega + \rho) = 1,350$ (\$B).²⁶ For the portion of appliances representing energy efficiency features, the annual user cost is: $P_K K_A = (0.5) \times 1,350 = 675$ (\$B).

Next, we use the EIA's SEDS to obtain economy-wide energy use for 2015 as \$1,127 billion.²⁷ The ratio of energy use for household appliances to total energy use ($\lambda_S \equiv E_S/E$) is $518/1,127 = 0.460$. Then, $\lambda_X \equiv E_X/E = 1 - \lambda_S = 0.540$ is the fraction of energy used in production of the composite good X . Next, we define a unit of K as the amount that earns \$1 per year, and so the initial $P_K = 1$, and we note that national income is $P_K \bar{K}$. For data, we use U.S. gross domestic product (GDP) for 2015 from BEA, so $I = 18,037$ (\$B).²⁸ The fractions of K used in production of energy and for energy efficiency are:

²³ https://www.eia.gov/state/seds/sep_sum/html/pdf/sum_ex_res.pdf

²⁴ https://www.bea.gov/national/consumer_spending.htm

²⁵ These assets include televisions, major household appliances (e.g., refrigerator, freezer, washer, dryer, stove, range, and air conditioners), small electric appliances (e.g., vacuum cleaner and electric kettle), equipment for house and garden (e.g., lawn mowers and propane grills), plus new motor vehicles and parts.

²⁶ Here, we assume perfect markets and ignore taxes, so the market rental price per year would be the same as the annualized cost to the owner of the appliances.

²⁷ https://www.eia.gov/state/seds/sep_sum/html/pdf/sum_ex_tot.pdf

²⁸ Available at:

<https://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=3&isuri=1&904=2015&903=5&906=a&905=2015&910=x&911=0>

$$\gamma_E \equiv \frac{K_E}{\bar{K}} = \frac{P_K K_E}{P_K \bar{K}} = \frac{P_E E}{P_K \bar{K}} = \frac{1,127}{18,037} = 0.063$$

$$\gamma_A \equiv \frac{K_A}{\bar{K}} = \frac{P_K K_A}{P_K \bar{K}} = \frac{675}{18,037} = 0.037$$

Since the fractions of K used in all sectors add to one, $\gamma_X = 1 - \gamma_A - \gamma_E = 0.900$.

No one has estimated the elasticity of substitution in utility between appliance services and all other goods. To calibrate this σ_U , we use estimates of the own-price demand elasticity for appliance services, ξ_{SS} . As shown in Baylis *et al.* (2014), these parameters are related to each other by $\xi_{SS} = -(\zeta_S + \sigma_U(1 - \zeta_S))$, where ζ_S is the calibrated share of income spent on services. Estimates range between -0.1 to -0.3, both for the price elasticity of vehicle-miles-traveled and for the price elasticity of electricity demand.²⁹ Using that range, the calculated elasticity of substitution in utility ranges from 0.05 to 0.25. For our central parameter, we use the center of that range, $\sigma_U = 0.15$, and we vary it to see the sensitivity of results.

For our cost function $K_A = B(A - A_0)^\beta$, linearized equations depend on the parameter $\alpha \equiv A_0/A$. We do not need to calibrate B , because it drops out of $\widehat{K}_A = \frac{\beta}{1-\alpha} \hat{A}$. Appendix G describes in detail the calibration of α and β using engineering studies of the added costs associated with adding to energy efficiency. These costs are calculated for selected vehicles by the National Research Council (NRC, 2002, 2015) and the International Council on Clean Transportation (Lutsey *et al.*, 2017), and for selected appliances by the Department of Energy (DOE, 2011, 2016a, 2016b). Looking at specific measures of energy efficiency (such as mpg), our overall strategy is as follows. (1) Choose A_0 in the low-efficiency range for the vehicle or appliance, and use observed energy efficiency A to calculate the ratio α . (2) Vary that choice to check sensitivity, and include $\alpha = 0$ to see if we could dispense with this extra parameter. (3) Use their calculations of changes in cost for changes in energy efficiency to recover β . (4) Show in appendix tables the various resulting combinations of A_0 , α , and β . (5) Choose the most reasonable combination of α and β for our primary parameters. (6) Use those values for our aggregation of cars and appliances, and show sensitivity of results to alternatives.

The value of β can vary along a single cost curve, and the whole curve can differ between datasets, cars, and different appliances. This heterogeneity is confirmed across five selected vehicles and appliances for which engineering studies are used in Appendix G to

²⁹ See Allcott (2011), Gillingham (2014), Ito (2014), and Deryugina *et al.* (2017).

calibrate α and β shown in Tables G1-G5.³⁰ The two tables for cars and light trucks each show two methods, so the five tables show seven different calculations. These tables are not available for every appliance and vehicle, so these examples only show a plausible range of values. We choose a pair α and β to best represent all appliances and cars in our aggregation. Our numerical results below are only illustrative; the same calculation could be undertaken for any particular vehicle or household appliance, as in a partial equilibrium model.

In the five tables, we see that β can range widely, though all exceed one. Empirical studies of energy efficiency costs often find $\beta=2$ (quadratic costs).³¹ But appendix tables also show how α depends on β , so they need to be chosen in concert.³² Starting with $\alpha=0$ in these tables, the implied values of β are unstable, varying from 1.25 to 5.82. Indeed, this instability is what induced us to add the intercept A_0 to the cost function. When α is about one-half, the values of β vary less, from about 1.75 to 2.75. The implied elasticity $\frac{\beta}{1-\alpha}$ ranges from 3.5 to 5.5, but that range in our model would yield costly standards and large negative rebound. To be conservative, we choose $\alpha=0.5$ and $\beta=1.5$ (so $\frac{\beta}{1-\alpha}$ is only 3.0).³³ This choice is equivalent to the combination where α is one-third and $\beta=2$, since the implied $\frac{\beta}{1-\alpha}$ is still 3.0.

Finally, we check the condition in Proposition 2 to make sure that the EES is binding as our model assumes. The chosen parameter values imply $\gamma_A\beta$ is 0.06, while $(1 - \alpha) \times [(\gamma_X + \gamma_E\lambda_X)\sigma_U\gamma_A + \lambda_S\gamma_E]$ is 0.02, so these values are indeed consistent with our assumption that the EES is binding and costly. Also, with all the calibrated parameters, β must be at least 0.45 to ensure that the EES is binding. For sensitivity analysis, we vary β from 1 to 5.

7. Numerical Illustrations

³⁰ The examples in Appendix G are based on two different datasets for vehicles, which yield somewhat different results, plus three different appliances (central air conditioners, furnaces, and refrigerator-freezers).

³¹ Greene and DeCicco (2000) find that a quadratic cost function for fuel economy improvement can be a good fit to the data. Also see NRC (2002) for various estimates of fuel economy cost curves. Our calibration of β uses more recent studies from the NRC and the International Council on Clean Transportation.

³² In the tables, a higher α is always associated with a smaller β . We take as given the engineering calculation of the incremental cost of improving energy efficiency, but matching that incremental cost with a higher α requires a smaller β . But, the overall cost elasticity $\frac{\beta}{1-\alpha}$ does not vary as much as α or β individually. Appendix Tables G1-G5 show that virtually any combination of α and β yield an overall elasticity of 3.0 or higher.

³³ If the overall cost elasticity of 3.0 seems large, remember that it is the percent change in cost for a one percent increase in *total* energy efficiency. In the vehicle example, suppose the required mpg rises from $A=30.0$ to 30.3 (a 1% increase in mpg). Manufacturers had no extra cost of achieving the initial “minimum” 15 mpg, so our cost function applies to the mpg in excess of $A_0=15$. The same increase of 0.3 mpg is a 2% increase in the *extra* 15 mpg (from 15 to 30 mpg). With our $\beta=1.5$, that 2% addition means a 3% increase in cost.

For any costless technology shock, we assume a 10% increase in energy efficiency technology, $\hat{\epsilon} = 0.10$. In the CTS case with no policy and no change in purchased energy efficiency ($\hat{A} = 0$), 10% better technology implies 10% better energy efficiency. For the EES, we assume the government raises the efficiency standard for all appliances by 10%, so it generates the same impact on energy efficiency. Inserting all calibrated parameters into each expression in Table 1 yields the size of each effect in percentage points. The direct efficiency effect (DEE) is calculated as if relative prices and incomes were constant. For example, a 10% change in ϵ might lead to a 4.6% DEE (because $\lambda_S \equiv E_S/E = 0.460$). If the total rebound effect (TRE) is about +1%, then total use of energy E falls by about 3.6%.

Using our calibrated parameters, we calculate and plot in Figure 1 not only the direct efficiency effect, but also the direct rebound effect (DRE), the indirect rebound effect (IRE), the total rebound effect (TRE), and the total effect (TE). The first five bars on the left are the effects on energy use from the CTS with no energy efficiency policy. The five bars in the middle present the CTS case with a binding pre-existing efficiency standard, and the last five bars are the effects on energy use from increased stringency of the EES policy.

For the CTS with no policy, the fourth bar shows that the free 10% gain in appliance energy efficiency leads to a 4.6% “direct effect” decrease in economy-wide energy use. More than one-fifth of that direct energy saving is offset by the positive total rebound effect in the third bar. Comparing the DRE in the first bar to the TRE in the third bar suggests that nearly 90% of total rebound is attributable to the direct rebound effect on appliance services. Though not shown in Figure 1, both the income and substitution effects increase consumption of S . For the other goods in X , however, the substitution effect reduces consumption, while the income effect increases it. The IRE in the second bar is a net positive rebound effect, which means the positive income effect dominates the negative substitution effect on X . As intended, these numerical results are consistent with most findings in the prior rebound literature that mostly study the exogenous costless technology change in energy efficiency.

A new consideration in this paper is a pre-existing energy efficiency mandate that remains binding after the costless technology shock (in the middle bars of Figure 1). Then the CTS allows consumers to pay less for energy efficiency in their appliances or cars but still meet the unchanged energy efficiency requirement. Appliances maintain the same required energy efficiency, so the reduced spending on energy efficiency perfectly offsets the increase in energy efficiency technology (i.e., $\hat{A} = -\hat{\epsilon}$, and $\widehat{A\epsilon} = \hat{A} + \hat{\epsilon} = 0$). The savings can be

spent on energy for more services (E_S) and on other goods (X). Visually, in the middle bars for the CTS with existing policy, the bar for DEE seems missing, but energy efficiency stays at the original level, so the DEE is literally zero. The total effect on energy is exactly the total rebound effect, +1.17%. Both the DRE and IRE are positive, and the IRE is slightly greater than the DRE. The income effect (not shown in Figure 1) through the cost savings on energy efficiency explains all the DRE and IRE (i.e., no substitution effect).

The “stricter EES” case shows the effects on energy use when the pre-existing energy efficiency standard becomes more stringent. The 10% change to this EES means that efficiency increases by 10%. As normalized, the CTS with no policy and the stricter EES have identical direct energy efficiency effects – as might be calculated by engineers. But the DRE from the EES (the dotted bar on the right) is less than half of the DRE from the CTS with no policy (the dotted bar on the left). The IRE from the EES case (the diagonal stripe bar on the right) is negative and larger in magnitude than the positive DRE. Therefore, total rebound is negative: total energy saving in the last bar is greater than direct energy saving. Substitution effects (not shown) are the same for both the EES and CTS with no policy. Therefore, the real income effect is a main difference in numerical results between the CTS and EES shocks. The CTS provides an income gain, while policy presents a real income loss.

Since the income effect is a key factor that distinguishes the CTS and the EES, we next consider sensitivity of results first for β and γ_A and then for other parameters.

8. Sensitivity Analysis

Figure 2A investigates sensitivity of rebound effects as we vary the assumed curvature of the cost function for energy efficiency (β). Then Figure 2B shows these same rebound effects through income and substitution effects. We use the central-case values for all other parameters. In Figure 2 and others, we generally use dash-dot lines for the CTS with no policy, dashed lines for the CTS with policy, and solid lines for the EES.

For the costless energy efficiency gain with no pre-existing policy, Figure 2A shows that the DRE and the IRE are completely flat: they do not depend on the cost of policy (β). Similarly, the income rebound effect (IncRE) and the substitution rebound effect (SubRE) in Figure 2B also do not depend on β . These results for the CTS with no existing policy match the prior literature that ignores the cost of requiring more energy efficiency: the same positive income shock and positive rebound that partly offsets the direct efficiency effect.

By contrast, the rebound effects from the CTS with policy and from the EES shock are

more responsive to β , but they respond in opposite directions. First, for the CTS with policy (dashed lines), the DRE and IRE are positive and rise with β . Why? A larger β means that more is already being spent on energy efficiency, and the CTS allows consumers to meet the unchanged mandate by use of new free technology instead, so it provides a larger positive income shock (allowing more use of energy for both S and X). In contrast, for the stricter EES (solid lines), the DRE and IRE both fall with β . A larger β in this case means that the additional required energy efficiency is more expensive, which causes a larger negative income shock and negative rebound effects. In fact, Figure 2B shows that all sensitivity of the DRE and IRE comes from the income effect. Substitution effects for the CTS with no policy and for the EES are the same and are completely flat lines (solid flat line in Figure 2B).

Figure 2 does not show the direct efficiency effect, because it does not depend on β . The DEE from the CTS with policy is zero. For both the CTS with no policy and EES shock, the DEE are normalized to be the same reduction in energy use, 4.6% for all value of β . Backfire is impossible in this EES case, since the only positive rebound effect is from substitution, which is much less than the DEE and also offset by the negative income effect. In the CTS case with no policy, backfire is also unlikely for reasonable values of β .

Next, Figures 3A and 3B show results as the intercept in the cost function, $\alpha \equiv A_0/A$, varies between 0.2 and 0.8. Results are almost identical to those in Figure 2, because α and β affect only the overall added cost in $\widehat{K}_A = \frac{\beta}{1-\alpha} \hat{A}$. The difference is that β affects that added cost linearly (as also shown in Figure 2), whereas α affects it nonlinearly (as also shown in Figure 3). Just as for β in Figure 2, the choice of α in Figure 3 does not affect the CTS with no existing policy. In both figures, when $\frac{\beta}{1-\alpha}$ gets larger, rebound effects are more positive for a CTS with existing policy and more negative for an EES. Again, all of this sensitivity occurs through the income effect. The substitution effect is completely flat (orange solid line in 3B). Sensitivity results in the figures show that our central values of $\beta=1.5$ and $\alpha=0.5$ appear to be both reasonable and conservative, as well as compatible with each other.

Next, we undertake sensitivity analysis for the arbitrary assumption that one-half of expenditures on appliances is for features that enhance energy efficiency. This assumed fraction primarily affects $\gamma_A \equiv K_A/\bar{K}$, the fraction of K used for energy efficiency.³⁴ Because

³⁴ This assumption also affects $\gamma_X \equiv 1 - \gamma_A - \gamma_E$. We directly observe $\gamma_E \equiv K_E/\bar{K}$, but $\gamma_X \equiv K_X/\bar{K}$ is assumed to include the fraction of total appliance spending that is not for energy efficiency.

the relationship between this assumed fraction and γ_A is monotonic, however, our sensitivity analysis for γ_A is equivalent to testing the sensitivity of results to this assumed fraction.

In our central calibration above, γ_A is 0.037, but Figure 4 varies it from 0.02 to 0.06 (or equivalently, the assumed fraction of appliance spending that is for energy efficiency varies from 0.25 to 0.8). As shown, rebound effects from the CTS with no policy do not depend on the value of γ_A , because again this parameter pertains to the cost of policy. In contrast, rebound effects from both the EES and the CTS with policy are responsive to γ_A . Figure 4 looks a lot like Figure 2, because γ_A affects the cost of policy as does β . Total rebound from the EES shock can be negative if γ_A is larger than 0.036, and our central estimate is 0.037. As depicted in Figure 4B, the substitution effect (orange solid line) has almost no slope, so the income effect explains most of how rebounds depend on γ_A .

Prior studies focus overwhelmingly on the responsiveness of rebound effects to the elasticity of substitution between energy services and other goods, and to the elasticity of substitution between appliances and energy in the production of energy services. They ignore the cost curvature parameter β and the fraction γ_A , which we show here can explain much of the difference between rebound effects from the CTS and EES.

Nonetheless, to compare our results with prior literature, Figure 5 plots rebound effects from the CTS and EES shock against the elasticity of substitution in utility (σ_U). First, recall that rebound effects from the CTS with a binding policy depend only on income effects, not on substitution effects, so its rebound effects are flat in this figure.

In contrast, rebound effects from both the CTS without policy and the EES are indeed sensitive to σ_U . In Figure 5A, both direct rebound effects rise steeply with σ_U , which is both intuitive and consistent with prior literature. Regardless of whether it is cost-free or costly, an increase in energy efficiency reduces the marginal cost of energy services and thus causes a positive direct rebound effect that rises with σ_U . Also in Figure 5A, the indirect rebound effects in these two cases change only slightly with σ_U , because of offsetting income and substitution effects on energy use in X . In addition, Figure 5B shows that the income effect from the EES shock is always negative, while the income effects from both CTS cases are always positive. Thus, for every value of σ_U in 5A, the DRE from the EES shock is always smaller than the DRE from the CTS without policy.³⁵

³⁵ In Figure 5B, income effects (in all three black lines) slightly rise with σ_U , because consumers are better able to substitute towards cheaper energy services. But most of the response to σ_U comes through the substitution effect, as the orange solid line in Figure 5B is strongly upward sloping.

Next, we note that our model could be extended to capture the fact that firms in sector X also face energy standards on their business equipment and vehicles. A complete model of that fact would include several more equations, with more complicated expressions and more effects in the solution expressions. Using an *ad hoc* approach, however, we can approximate the effects in that more-complex model within our simple model. Figure 6 plots rebound effects for larger values of the parameter λ_S , the fraction of total energy used with regulated appliances to produce energy services. Our central parameter values include λ_S of about one-half, so Figure 6 varies λ_S between one-third and two-thirds.

The figure includes a steeply falling grey line for the *direct* energy effect, indicating that more energy subjected to efficiency standards means more reduction in energy use. But the other lines all indicate that percentage *rebound* effects from either the CTS or the EES shock are not very sensitive to λ_S . Thus, backfire is more unlikely when λ_S is large.

9. Effects for Vehicles Separately from other Household Appliances

We now investigate the effect of assumptions about what to include in “appliances.” Above, we aggregated all household appliances and vehicles for two reasons. First, additional sectors would make our analytical model more difficult to solve and to interpret. Second, a general equilibrium model is not necessary to analyze a small sector. For example, a policy that applies only to freezers that constitute 0.1% of the economy would have tiny indirect effects on the other 99.9% of the economy. Here, however, we can investigate effects separately for vehicles vs. all other household appliances.

Using calibration procedures exactly analogous to those in section 6 above, Appendix H derives share parameters (γ_A and λ_S) for household vehicles and energy use (motor fuel). It also aggregates all household appliances other than vehicles, such as refrigerators, furnaces, and air conditioners. The calculated share parameters are shown in the first two columns of Table 2. We continue to use the previous cost function parameters for both cases.³⁶ In any case, sensitivity results above show just how α or β affects results.

Using the parameters in Table 2 for vehicles *separately* from other appliances, we calculate bar graphs just like Figure 1 (showing bars for the direct efficiency effect, direct rebound effect, indirect rebound effect, total rebound effect, and total energy). Those bar

³⁶ The calibration of α and β in Appendix G for cars and for appliances are not much different from each other. In four calculations for cars and light trucks, when α is about one-half, the values of β vary from 1.75 to 2.71. Three calculations for appliances with the same α about one-half yield β between 2.18 and 2.78.

graphs are in Appendix H rather than here, however, because they look almost exactly like Figure 1. The only difference is the vertical scale. Table 2 shows that the share parameters for vehicles are very nearly half the size of the shares for appliances and vehicles together (and so appliances alone are the other half). As a consequence, the bars for the direct efficiency effect extend downward to just over 2% change in energy instead of 4.6% change in energy. Each type of positive rebound extends up to 0.5% more energy instead of 1.0% more energy; and each type of negative rebound is also half the size of those in Figure 1.

The lesson here is that the size of the sector determines the size of all effects similarly. Table 2 shows that both share parameters (γ_A and λ_S) are halved, so all results are halved. The relative size of the direct efficiency effect would be different if *only* λ_S changed (as in Figure 6), and the relative size of rebound effects would be changed if only γ_A changed (as in Figure 4). The relative sizes of the effects for vehicles separately from appliances would also differ if those two categories faced mandates with different stringency (different β as shown in Figure 2), or have different demand elasticities (based on σ_U , varied in Figure 4). The main point here is that the relative size of each rebound effect depends in a primary way on whether (1) the improvement in energy efficiency is from a costless technology shock, (2) that CTS comes with or without a pre-existing energy efficiency standard, or (3) the greater energy efficiency is achieved by increased stringency of an energy efficiency standard.

10. Conclusions

We use a simple analytical general equilibrium model to analyze and to compare rebound effects from an EES to those from a CTS. In both cases, we consider the economy with a pre-existing energy efficiency standard that is both costly and binding. Also, we decompose each total effect on the use of energy into various components, including a direct efficiency effect, a direct rebound effect, and an indirect rebound effect. Each rebound term is composed of substitution and income effects. Results show that the magnitude and sign of rebound for *both* the CTS and EES depend strongly on the costliness of efficiency mandates.

As found in prior literature, a CTS raises real incomes and thus has positive rebound effects on energy use that offset part of the reduction in energy use from the improvement in technology. Some studies have interpreted such results to indicate effects of energy efficiency policies. Here, however, we show that energy efficiency standards have costs and therefore reduce income, which can reduce energy use and cause *negative* rebound effects (reducing energy use even further than the direct effect). Also, the prior literature gives much attention

to cross-price elasticities between energy services and their complements or substitutes, and to rebound through the substitution effect. Here, we point to the importance of the curvature of the cost curve for energy efficiency improvements, which helps determine the magnitude and sign of the total rebound effect in the case of the costly energy efficiency policy.

Our analytical results compare a CTS such as in prior literature to a CTS with a pre-existing efficiency standard, and show that the CTS may have no direct efficiency effect at all. We also show that a stricter EES can reverse the sign of total rebound. Numerical illustrations use reasonable values for all parameters including the energy efficiency cost parameters, the fraction of the factor endowment used for energy efficiency, and the elasticity of substitution in utility. With these plausible parameters, total rebound from a CTS is strictly positive, but total rebound from energy efficiency standards switch from positive to negative. The analytical findings and numerical example both suggest that using the estimated rebound effect from a zero-cost efficiency gain as the effect of an energy efficiency mandate could greatly overstate rebound from the mandate.

Table 1: Decomposition of the Effect of Energy Efficiency on Total Energy Use

Panel A: Costless Efficiency Improvement ($\hat{\epsilon} > 0$)				
Effects on Energy Use	No Existing Policy (with $\hat{A} = 0$)		Pre-existing policy (so $\hat{A} = -\hat{\epsilon}$)	
	(1)	(2)	(3)	(4)
Direct Efficiency Effect	$-\lambda_S \hat{\epsilon}$	(-)	0	0
Direct Rebound Effect		(+)	(+)	(+)
Income Effect	$\frac{\lambda_S((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)}{1 - \gamma_A} \hat{\epsilon}$	(+)	$\frac{\lambda_S \gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \hat{\epsilon}$	(+)
Substitution Effect	$\lambda_S(\gamma_X + \gamma_E \lambda_X) \sigma_U \hat{\epsilon}$	(+)	0	0
Indirect Rebound Effect		(+/-)	(+)	(+)
Income Effect	$\frac{\lambda_X((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)}{1 - \gamma_A} \hat{\epsilon}$	(+)	$\frac{\lambda_X \gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \hat{\epsilon}$	(+)
Substitution Effect	$-\lambda_X(\gamma_A + \gamma_E \lambda_S) \sigma_U \hat{\epsilon}$	(-)	0	0
Panel B: Efficiency Mandate ($\hat{\eta} > 0$)				
Effects on Energy Use	Pre-existing policy (so $\hat{A} = \hat{\eta} > 0$)			
	(5)			(6)
Direct Efficiency Effect	$-\lambda_S \hat{\eta}$			(-)
Direct Rebound Effect				(+/-)
Income Effect	$\left(\frac{\lambda_S((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)}{1 - \gamma_A} - \frac{\lambda_S \gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \right) \hat{\eta}$			(+/-)
Substitution Effect	$\lambda_S(\gamma_X + \gamma_E \lambda_X) \sigma_U \hat{\eta}$			(+)
Indirect Rebound Effect				(+/-)
Income Effect	$\left(\frac{\lambda_X((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)}{1 - \gamma_A} - \frac{\lambda_X \gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \right) \hat{\eta}$			(+/-)
Substitution Effect	$-\lambda_X(\gamma_A + \gamma_E \lambda_S) \sigma_U \hat{\eta}$			(-)

Table 2: Parameters for Vehicles only and Household Appliances Only

	Share of Capital	Share of Energy	Elasticity Parameters		
	$\gamma_A \equiv K_A/\bar{K}$	$\lambda_S \equiv E_S/E$	α	β	σ_U
Both together	0.037	0.460	0.5	1.5	0.15
Vehicles only	0.019	0.240	0.5	1.5	0.15
Appliances only	0.018	0.220	0.5	1.5	0.15

**Figure 1: Effects on Energy Use from the CTS and EES
(central parameter values)**

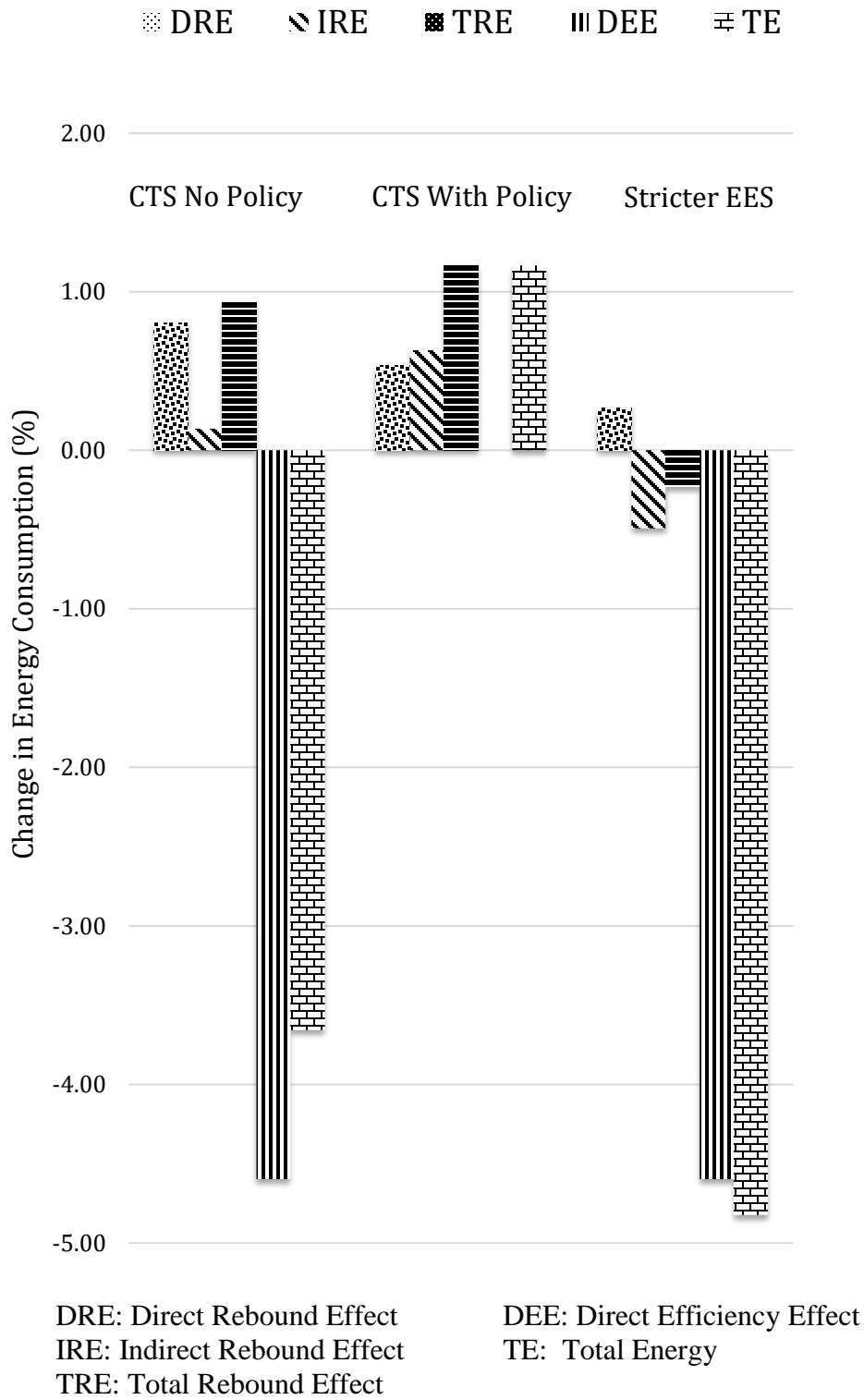


Figure 2: Rebound Effects from the CTS and EES, Varying β

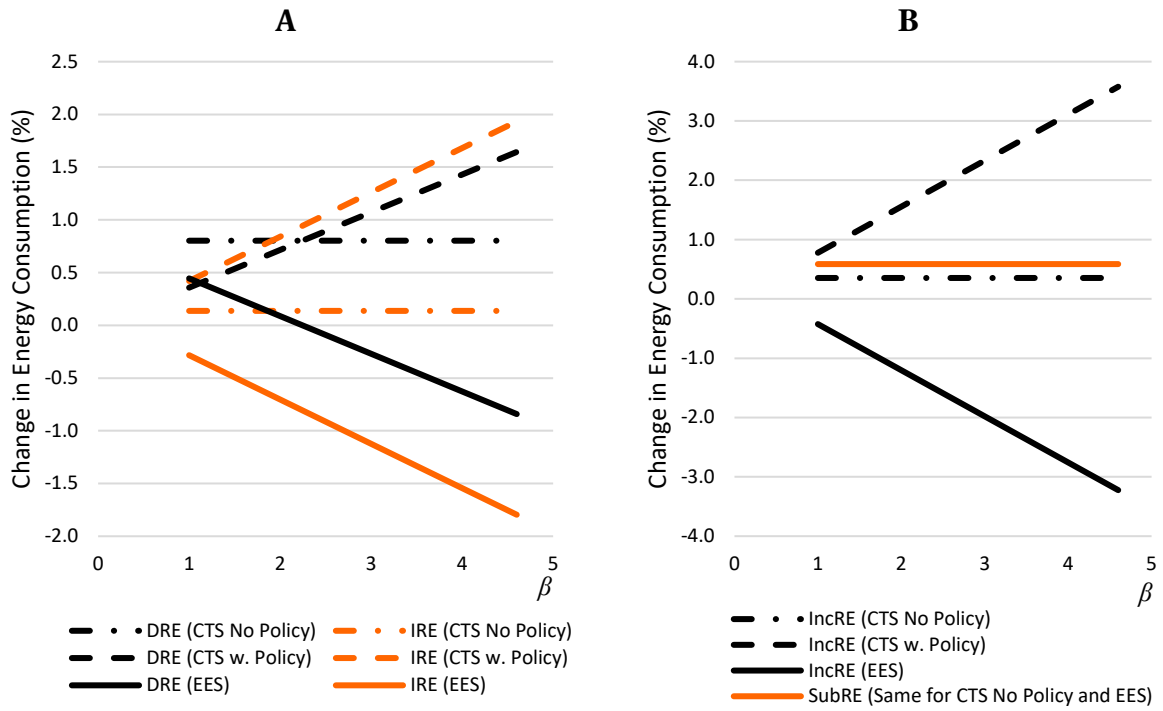


Figure 3: Rebound Effects from the CTS and EES, Varying α

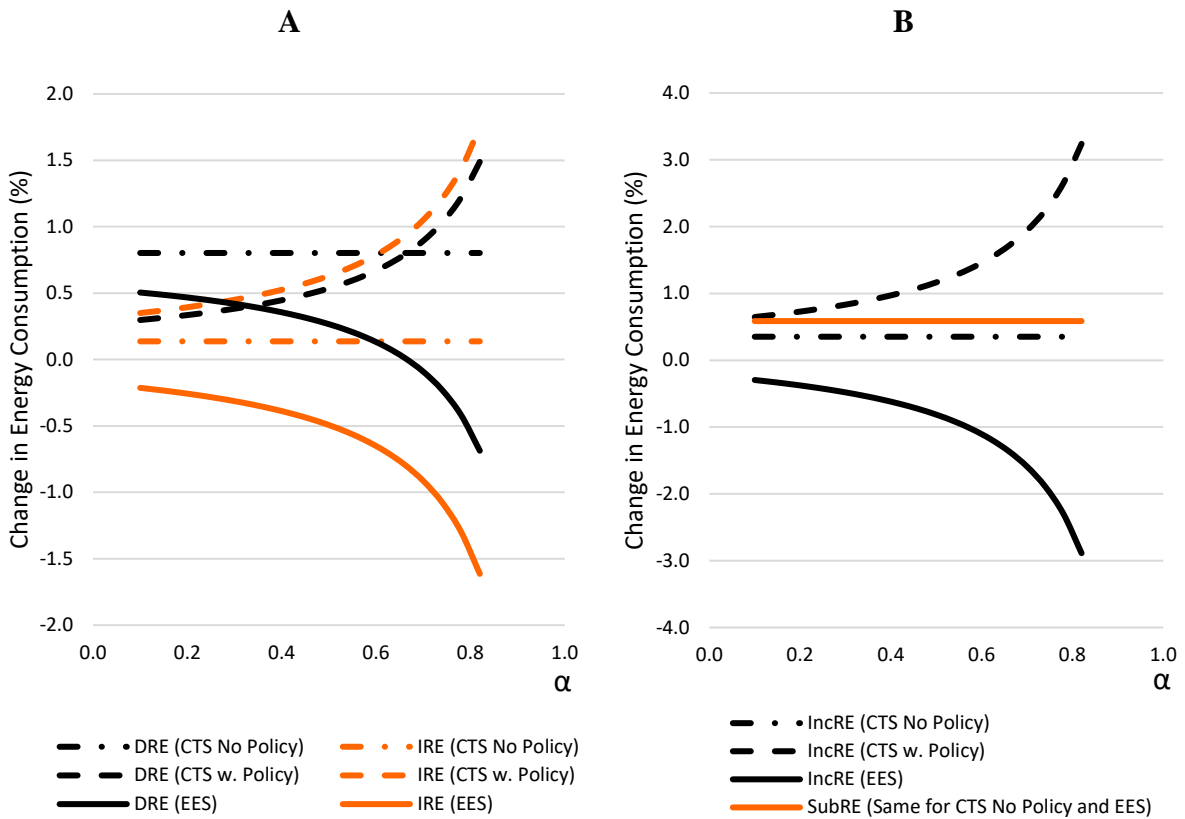


Figure 4: Rebound Effects from the CTS and EES, Varying γ_A

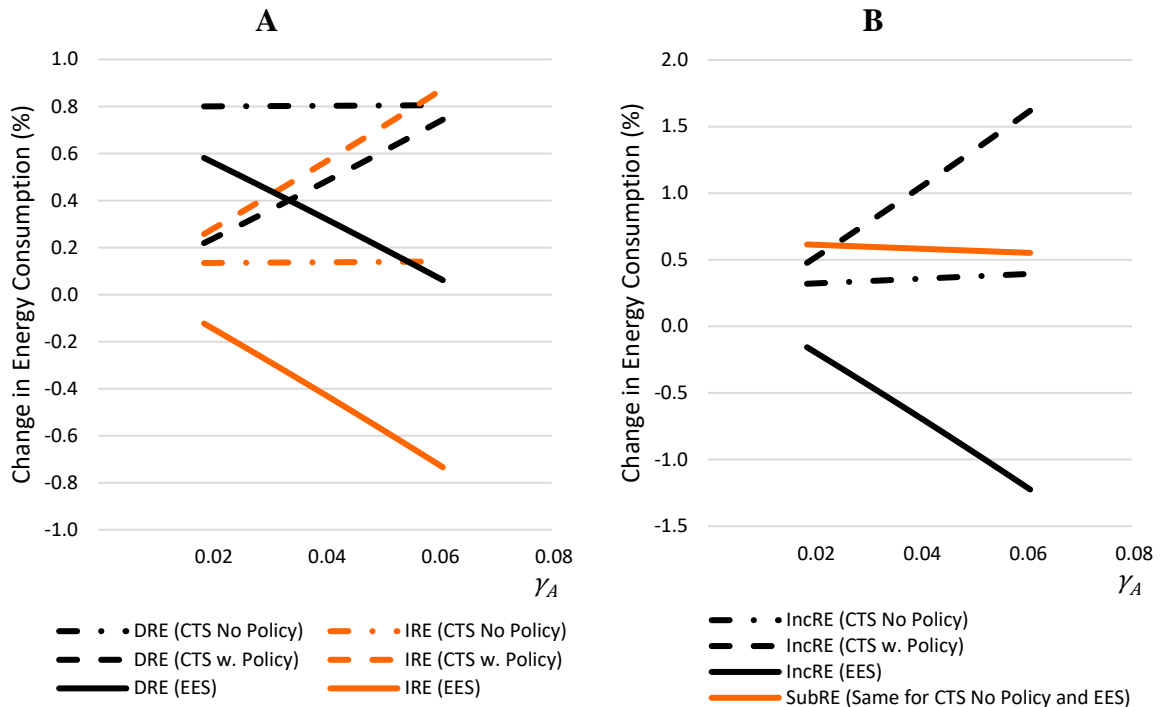


Figure 5: Rebound Effects from the CTS and EES, Varying σ_U

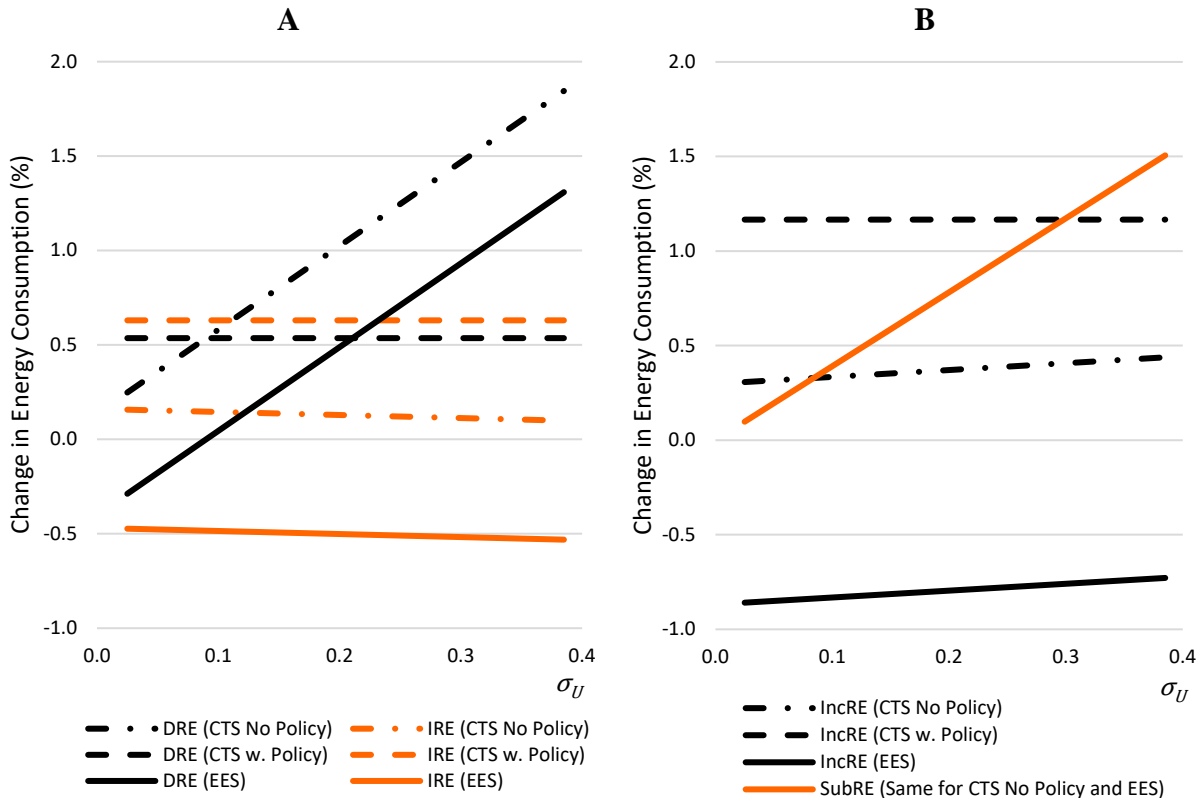
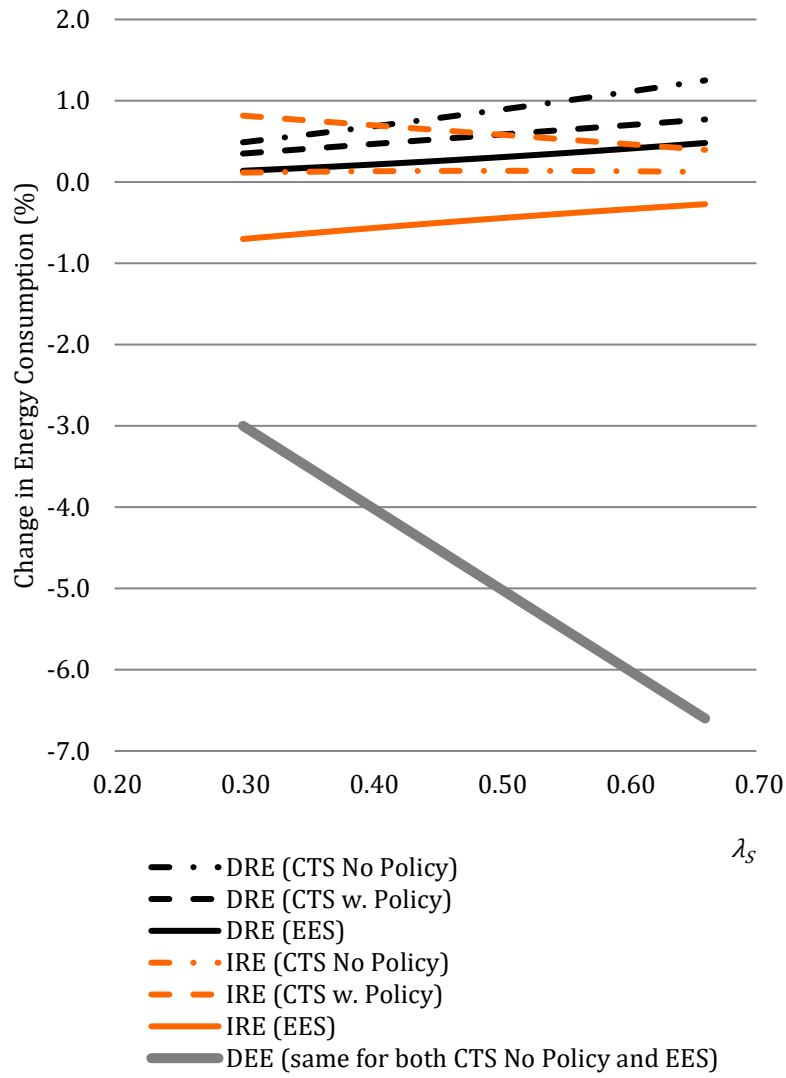


Figure 6: Rebound Effects from the CTS and the EES, Varying λ_S



References

- Abdessalem, Tahar, and Etidel Labidi. 2016. Economic analysis of the energy-efficient household appliances and the rebound effect. *Energy Efficiency* 9: 605-620.
- Allan, Grant, Nick Hanley, Peter McGregor, Kim Swales, and Karen Turner. 2007. The impact of increased efficiency in the industrial use of energy: A computable general equilibrium analysis for the United Kingdom. *Energy Economics* 29 (4): 779-798.
- Allcott, Hunt. 2011. Rethinking real-time electricity pricing. *Resource and Energy Economics* 33 (4): 820-840.
- Barker, Terry, Athanasios Dagoumas, and Jonathan Rubin. 2009. The macro-economic rebound effect and the world economy. *Energy Policy* 2 (4): 411-427.
- Barker, Terry, Paul Ekins, and Timothy Foxon. 2007. The macro-economic rebound effect and the UK economy. *Energy Policy* 35 (10): 4935-4946.
- Baylis, Kathy, Don Fullerton, and Daniel H. Karney. 2014. Negative leakage. *Journal of the Association of Environmental and Resource Economists* 1(1): 51-73.
- Borenstein, Severin. 2015. A microeconomic framework for evaluating energy efficiency rebound and some implications. *Energy Journal* 36 (1): 1-21.
- Brannlund, Runar, Tarek Ghalwash, and Jonas Nordstrom. 2007. Increased energy efficiency and the rebound effect: Effects on consumption and emissions. *Energy Economics* 29: 1-17.
- Chan, Nathan W., and Kenneth Gillingham. 2015. The microeconomic theory of the rebound effect and its welfare implications. *Journal of the Association of Environmental and Resource Economists* 2 (1): 133-159.
- Chang, Juin-Jen, Wei-Neng Wang, Jhy-Yuan Shieh. 2018. Environmental rebounds/backfires: Macroeconomic implications for the promotion of environmentally-friendly products. *Journal of the Environmental Economics and Management* 88: 35-68.
- Department of Energy. 2011. Energy Conservation Program: Energy Conservation Standards for Residential Refrigerator, Refrigerator-Freezers, and Freezers. Docket No. EE-2008-BT-STS-0021. Retrieved 05/22/2018 from https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrigerators_standards_final_rule_08_25_2011.pdf.
- Department of Energy. 2016a. Energy Conservation Program: Energy Conservation Standards for Residential Central Air Conditioners and Heat Pumps. Docket No. EERE-2014-BT-STD-0048. Retrieved 05/22/2018 from https://www.energy.gov/sites/prod/files/2016/12/f34/CAC_HP_Direct_Final_Rule.pdf.
- Department of Energy. 2016b. Energy Conservation Program: Energy Conservation Standards for Residential Furnaces. Docket No. EERE-2014-BT-STD-0031. Retrieved 05/22/2018, <https://www.energy.gov/sites/prod/files/2016/09/f33/Residential%20Furnaces%20SNOPR.pdf>.
- Deryugina, Tatyana, Alexander Mackey, and Julian Reif. 2017. The long-run dynamics of

- electricity demand: Evidence from municipal aggregation. NBER Working Paper 23483. National Bureau of Economic Research, Cambridge, MA.
- Fouquet, Roger, and Peter J.G. Pearson. 2012. The long run demand for lighting: Elasticities and rebound effects in different phases of economic development. *Economics of Energy and Environmental Policy* 1: 83-100.
- Gillingham, Kenneth. 2014. Identifying the elasticity of driving: Evidence from a gasoline price shock. *Regional Science & Urban Economics* 47 (4): 13-24.
- Gillingham, Kenneth, David Rapson, and Gernot Wagner. 2016. The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy* 10 (1): 68-88.
- Goulder, Lawrence H., ed. 2002. *Environmental policy making in economies with prior tax distortions*. Cheltenham, UK: Edward Elgar Publishers.
- Goulder, Lawrence H., Mark R. Jacobsen, and Arthur A. van Benthem. 2012. Unintended consequences from nested state and federal regulations: The case of the Pavley greenhouse-gas-per-mile limits. *Journal of Environmental Economics and Management* 63 (2): 187-207.
- Greene, David L. and John DeCicco. 2000. Engineering-economic analyses of automotive fuel economy potential in the United States. *Annual Review of Energy and the Environment* 25: 477-535.
- Greening, Lorna A., David L. Greene, and Carmen Difiglio. 2000. Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy* 28 (6-7): 389-401.
- Grepperud, Sverre, and Ingeborg Rasmussen. 2004. A general equilibrium assessment of rebound effects. *Energy Economics* 26 (2): 261-282.
- Hanley, Nick, Peter G. McGregor, J. Kim Swales, and Karen Turner. 2009. Do increases in energy efficiency improve environmental quality and sustainability. *Ecological Economics* 68 (3): 389-401.
- Ito, Koichiro. 2014. Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing. *American Economic Review* 104 (2): 537-563.
- Khazzoom, Daniel J. 1980. Economic implications of mandated efficiency in standards for household appliances. *The Energy Journal* 1 (4): 21-40.
- Knittel, Christopher R. 2012. Automobiles on steroids: Product attribute trade-offs and technological progress in the automobile sector. *American Economic Review* 101 (7): 3368–3399.
- Lemoine, Derek. 2017. General equilibrium rebound from improved energy efficiency. University of Arizona Department of Economics Working Paper 14-02. Available at SSRN: <https://ssrn.com/abstract=2443593> or <http://dx.doi.org/10.2139/ssrn.2443593>.
- Lutsey, Nic, Dan Meszler, Aaron Isenstadt, John German, and Josh Miller. 2017. Efficiency technology and cost assessment for U.S. 2025-2030 light-duty vehicles. [White Paper] Retrieved from https://www.theicct.org/sites/default/files/publications/US-LDV-tech-potential_ICCT_white-paper_22032017.pdf.
- Mizobuchi, Kenichi. 2008. An empirical study on the rebound effect considering capital costs.

Energy Economics 30 (5): 2486-2517.

National Highway Transportation Safety Administration. 2011a. Summary of fuel economy performance. Retrieved from http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cape/2011_Summary_Report.pdf.

National Highway Transportation Safety Administration. 2011b. 2017-2025 model year light-duty vehicle GHG emissions and CAFE standards: Supplemental. Retrieved from http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cape/2017-2025_CAFE-GHG_Supplemental_NOI07292011.pdf

National Research Council. 2002. *Effectiveness and impact of Corporate Average Fuel Economy (CAFE) Standards*. Washington, DC: The National Academies Press.

National Research Council. 2015. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. Washington, DC: The National Academies Press.

Nässén, Jonas, and John Holmberg. 2009. Quantifying the rebound effects of energy efficiency improvements and energy conserving behavior in Sweden. *Energy Efficiency* 2 (3): 221-231.

Saunders, Harry D. 2013. Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. *Technological Forecasting & Social Change* 80: 1317-1330.

Sorrell, Steve, and John Dimitropoulos. 2008. The rebound effect: Microeconomic definitions, limitations, and extensions. *Ecological Economics* 65 (3): 636-649.

Sorrell, Steve, John Dimitropoulos, and Matt Sommerville. 2009. Empirical estimates of the direct rebound effect: A review. *Energy Policy* 37 (4): 1356-1371.

Thomas, Brinda A., and Inês L. Azevedo. 2013. Estimating direct and indirect rebound effects for U.S. households with input-output analysis. Part 1: Theoretical Framework. *Ecological Economics* 86: 199-210.

Turner, Karen. 2009. Negative rebound and disinvestment effects in response to an improvement in the UK economy. *Energy Economics* 31 (5): 648-666.

Wei, Taoyuan. 2007. Impact of energy efficiency gains on output and energy use with cobb-douglas production function. *Energy Policy* 35 (4): 2023-2030.

Wei, Taoyuan. 2010. A general equilibrium view of global rebound effects. *Energy Economics* 32 (3): 661-672.

Appendices to Be Placed Online

Appendix A. Solve for Changes in Energy from a CTS with No Policy

This appendix uses equations (2.1) - (2.10) in the text to solve for changes in prices and quantities that result from a small CTS, $\hat{\epsilon} > 0$, but to compare these results with the previous literature, we calculate the effects of the alternative assumption that: $\hat{A} = \hat{K}_A = 0$. With the numeraire choice, $\hat{P}_K = 0$, relative prices of E and X does not change because the production of E uses only K and the production of X uses K and E . Substitute $\hat{P}_E = \hat{P}_X = 0$ into (2.2), (2.4), (2.7), and (2.8) and manipulate to derive:

$$\hat{K}_X = \hat{E}_X = \hat{X} = -\sigma_U \hat{\epsilon} + \hat{\epsilon} + \hat{A} + \hat{E}_S = (1 - \sigma_U) \hat{\epsilon} + \hat{E}_S \quad (\text{A.1})$$

Then substitute (A.1) into (2.9):

$$\hat{E} = \lambda_X \hat{\epsilon} (1 - \sigma_U) + \hat{E}_S \quad (\text{A.2})$$

Substitute (A.1), (A.2), and $\hat{K}_A = 0$ into (2.10) to obtain the closed form solution for \hat{E}_S (equation (3.3) in the text):

$$\begin{aligned} \hat{E}_S &= \frac{(\gamma_X + \gamma_E \lambda_X)(\sigma_U - 1)}{1 - \gamma_A} \hat{\epsilon} = \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - 1 \right) \hat{\epsilon} \\ &= \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - 1 \right) \hat{\epsilon} \end{aligned} \quad (\text{A.3})$$

Substitute (A.3) into (2.1), (A.1) and (A.2) to obtain equations (3.1), (3.2), and (3.4) in the text for the closed form solutions of \hat{X} , \hat{S} and \hat{E} .

Appendix B: Separating Income and Substitution Effects for the CTS

We take the overall effect on energy use from a small exogenous CTS and separate it into income and substitution effects. This shock changes consumers' costs, real incomes, and consumption choices. We measure the substitution effect for each commodity as a change in that quantity within the overall consumption bundle that makes the consumers as happy as before the price change but while facing new prices. The income effect is the remaining change in the consumption bundle due to the change in real income.

We use superscript "0" to denote the initial equilibrium and superscript "1" to denote the new equilibrium. Also, the superscript "C" refers to the "compensated" quantity needed to measure the substitution effect, and the superscript "I" refers to the remaining change in

quantity from the income effect. We start with equations from Appendix A that show solutions for \hat{X} and \hat{S} as functions of the shock and parameters:

$$\hat{X} = \left(-(\gamma_A + \gamma_E \lambda_S) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \right) \hat{\epsilon}$$

$$\hat{S} = \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \right) \hat{\epsilon}$$

Decompose the effect of the shock on S into two components:

$$\hat{S} \equiv \frac{S^1 - S^0}{S^0} = \tilde{S}^C + \tilde{S}^I \quad (\text{B.1})$$

where $\tilde{S}^C \equiv (S^C - S^0)/S^0$ defines the substitution effect, and $\tilde{S}^I \equiv (S^1 - S^C)/S^0$ is the income effect. We define \tilde{X}^C and \tilde{X}^I similarly as the substitution and income effects on \hat{X} :

$$\hat{X} = \frac{X^1 - X^0}{X^0} = \tilde{X}^C + \tilde{X}^I \quad (\text{B.2})$$

By definition, the substitution effect implies that consumers stay at their original utility level facing the new price, so we observe zero change in utility:

$$dU^C = \frac{\partial U}{\partial X} (X^C - X^0) + \frac{\partial U}{\partial S} (S^C - S^0) = 0$$

$$dU^C = \frac{\partial U}{\partial X} X^0 \tilde{X}^C + \frac{\partial U}{\partial S} S^0 \tilde{S}^C = 0$$

$$\frac{dU^C}{\mu I} = \frac{P_X^0 X^0}{I} \tilde{X}^C + \frac{P_K^0 K_A^0 + P_E^0 E_S^0}{I} \tilde{S}^C = 0$$

$$\frac{dU^C}{\mu I} = (\gamma_X + \gamma_E \lambda_X) \tilde{X}^C + (\gamma_A + \gamma_E \lambda_S) \tilde{S}^C = 0 \quad (\text{B.3})$$

where μ is the marginal utility of income, and we use first order conditions from consumer optimization ($\partial U / \partial X = \mu P_X$).

With homothetic preferences, the income effect changes the consumption bundle proportionately, so we get:¹

$$\tilde{X}^I = \tilde{S}^I \quad (\text{B.4})$$

Equations (B.1) - (B.4) yield a system of four linear equations and four unknowns

¹ Homotheticity implies: $\frac{X^C - X^1}{X^1} = \frac{S^C - S^1}{S^1}$, which can be written as $\tilde{X}^I \frac{X^0}{X^1} = \tilde{S}^I \frac{S^0}{S^1}$, so $\frac{\tilde{X}^I}{\tilde{S}^I} = \frac{X^1}{X^0} / \frac{S^1}{S^0} = \frac{\hat{X}+1}{\hat{S}+1} \approx 1$.

$(\tilde{S}^C, \tilde{S}^I, \tilde{X}^C$ and $\tilde{X}^I)$. We solve this system of linear equations by successive substitution:

$$\begin{aligned}\tilde{S}^C &= (\gamma_X + \gamma_E \lambda_X) \sigma_U \hat{\epsilon} \\ \tilde{S}^I &= \tilde{X}^I = \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \hat{\epsilon} \\ \tilde{X}^C &= -(\gamma_A + \gamma_E \lambda_S) \sigma_U \hat{\epsilon}\end{aligned}$$

Appendix C: Derivation of the Welfare Change from a CTS

Here, we derive the welfare change from the CTS. Consumers maximize utility by their choices of the composite good, X , and appliance services, S , subject to their budget:

$$\max_{X,S} U(S, X; nE) \text{ subject to } P_X X + P_E E_S + P_K K_A \leq I$$

Assuming interior solutions (the budget constraint holds as an equality), first order conditions for this maximizing problem are:

$$U_X - \mu P_X = 0 \text{ or } U_X / \mu = P_X \quad (C.1)$$

$$U_S - \mu P_E / (\epsilon A) = 0 \text{ or } U_S / \mu = P_E / (\epsilon A) \quad (C.2)$$

where a subscript on U indicates a partial derivative (marginal utility), and μ is the shadow price on the budget constraint (marginal utility of income).

The CTS affects prices and outputs, so it affects utility. Totally differentiate the utility function and divide by μ to obtain the dollar value of the change in utility:

$$\frac{dU}{\mu} = \frac{U_X}{\mu} dX + \frac{U_S}{\mu} dS$$

Substitute (C.1) and (C.2) into the above equation and divide by the total income (I). Then multiply and divide by appropriate terms, and rearrange:

$$\begin{aligned}\frac{dU}{\mu I} &= \frac{P_K K_X + P_E E_X}{I} \hat{X} + \frac{P_K K_A + P_E E_S}{I} \hat{S} = \frac{P_K K_X + P_E E_X}{P_K \bar{K}} \hat{X} + \frac{P_K K_A + P_E E_S}{P_K \bar{K}} \hat{S} \\ &= (\gamma_X + \gamma_E \lambda_X) \hat{X} + (\gamma_A + \gamma_E \lambda_S) \hat{S}\end{aligned}$$

The left-hand side is a measure of the welfare change from the shock, the dollar value of the change in utility divided by total income. Substitute the closed form solutions for \hat{X} and \hat{S} into the above equation to get the closed form change in welfare:

$$\frac{dU}{\mu I} = (\gamma_X + \gamma_E \lambda_X) \hat{X} + (\gamma_A + \gamma_E \lambda_S) \hat{S} = \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} \hat{\epsilon}$$

Appendix D: Solve for Changes in Energy from a CTS with a Pre-existing EES

To solve for changes in prices and quantities from a small CTS, $\hat{\epsilon} > 0$, we assume no change in the EES. The pre-existing EES is still binding, so we get:

$$\widehat{\epsilon A} = \hat{\eta} = 0 \text{ or } \hat{A} = -\hat{\epsilon} \quad (\text{D.1})$$

Given (D.1), linearized equations (2.1) - (2.10) yield a system of 10 equations and 10 unknowns ($\widehat{E}, \widehat{X}, \widehat{S}, \widehat{E}_X, \widehat{E}_S, \widehat{K}_X, \widehat{K}_A, \widehat{K}_E, \widehat{P}_X, \widehat{P}_E$). We are interested in closed-form solutions for changes in energy use in sectors S and X as functions of parameters and the shock $\hat{\epsilon} > 0$. The easiest way to solve this system is to find expressions for changes in all quantities in term of \widehat{E}_S and $\hat{\epsilon}$, and then substitute those expressions into equation (2.10) to get the closed-form solution of \widehat{E}_S .

Our numeraire choice ($\widehat{P}_K = 0$) simplifies the mathematical derivations significantly, and combined with (2.7) - (2.8), it yields: $\widehat{P}_K = \widehat{P}_E = \widehat{P}_X = 0$. We substitute these zero changes and (D.1) into (2.1), (2.2), (2.4), and (2.5) to obtain:

$$\widehat{K}_X = \widehat{E}_X = \widehat{X} = \widehat{S} = \widehat{E}_S \quad (\text{D.2})$$

Thus, the percentage change in E equals the percentage change in E_X and E_S , then use (2.3) and (2.9) to get:

$$\widehat{K}_E = \widehat{E} = \lambda_X \widehat{E}_X + \lambda_S \widehat{E}_S = \widehat{E}_X = \widehat{E}_S \quad (\text{D.3})$$

Combine (D.1) and (2.6) to obtain:

$$\widehat{K}_A = -\beta \hat{\epsilon} \quad (\text{D.4})$$

Substitute (D.2) - (D.4) into (2.10) and solve for \widehat{E}_S :

$$\widehat{K}_X = \widehat{E}_X = \widehat{X} = \widehat{S} = \widehat{E} = \widehat{E}_S = \frac{\gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon}$$

We can solve for the welfare gain from this shock by following the same step in Appendix C, given by the overall change in utility (dU) divided by the marginal utility of income (μ). This dollar value of the change in utility is then divided by total income (I) to express it in relative terms. This measure of welfare is:

$$\begin{aligned} \frac{dU}{\mu I} &= \frac{P_X X}{I} \widehat{X} + \frac{P_K K_A + P_E E_S}{I} \widehat{S} \\ &= (\gamma_X + \gamma_E \lambda_X) \widehat{X} + (\gamma_A + \gamma_E \lambda_S) \widehat{S} = \widehat{X} = \widehat{S} = \frac{\gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \hat{\epsilon} > 0 \end{aligned}$$

Appendix E: Solve for Changes in Energy from a Small EES Policy Shock

This appendix uses equations (2.1) - (2.10) in the text to solve for changes in prices and quantities that result from a tighter efficiency standard ($\hat{\eta} > 0$). We assume no change in energy efficient technology, so $\hat{\epsilon} = 0$. Because purchase of A is costly, households will not buy more than necessary to satisfy the new requirement. Therefore the chosen \hat{A} will equal the required $\hat{\eta}$. Substitute the choice of numeraire ($\widehat{P}_K = 0$) into (2.7) - (2.8) to get $\widehat{P}_E = \widehat{P}_X = 0$. We want the closed-form expression for \widehat{E} as a function of parameters and the policy shock $\hat{\eta}$. To do so, we first find all quantity changes in terms of \widehat{E}_S and $\hat{\eta}$, and then substitute those expressions into equation (2.10) to get the closed-form solution for \widehat{E}_S .

From (2.2) and (2.4), no change in relative prices of K , E , and X implies that:

$$\widehat{K}_X = \widehat{E}_X = \widehat{X}$$

Then substitute (2.1) into (2.5) to get:

$$\widehat{K}_X = \widehat{E}_X = \widehat{X} = -\sigma_U \hat{\eta} + \hat{\eta} + \widehat{E}_S \quad (\text{E.1})$$

Substitute (E.1) into (2.9) and (2.3):

$$\widehat{K}_E = \widehat{E} = \lambda_X (-\sigma_U \hat{\eta} + \hat{\eta}) + \widehat{E}_S \quad (\text{E.2})$$

Substitute (E.1), (E.2), and (2.6) into (2.10) to solve for \widehat{E}_S (equation (5.3) in the text):

$$\begin{aligned} 0 &= \gamma_X \hat{\eta} + \frac{\gamma_A \beta}{(1-\alpha)} \hat{A} + \gamma_E \lambda_X (-\sigma_U \hat{\eta} + \hat{\eta}) + \gamma_E \widehat{E}_S \\ \widehat{E}_S &= \left(\frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U - (\gamma_X + \gamma_E \lambda_X)}{(\gamma_E + \gamma_X)} - \frac{\gamma_A \beta}{(\gamma_E + \gamma_X)(1-\alpha)} \right) \hat{\eta} \\ &= \left((\gamma_X + \gamma_E \lambda_X) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} - 1 \right) \hat{\eta} \end{aligned} \quad (\text{E.3})$$

Substitute (E.3) into (2.1), (E.1), and (E.2) to get equations (5.1), (5.2), and (5.4) in the text.

Appendix F: Proof of Proposition 3

Proof of (3.i):

The direct rebound effect (*DRE*) from the EES shock is the sum of the substitution and income effects on E , so it can be written and shorten as:

$$DRE = \left(\frac{\lambda_S ((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)}{1 - \gamma_A} - \frac{\lambda_S \gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \right) \hat{\eta} + \lambda_S (\gamma_X + \gamma_E \lambda_X) \sigma_U \hat{\eta}$$

$$\begin{aligned}
&= \left(\lambda_S((\gamma_X + \gamma_E \lambda_X)\sigma_U \gamma_A + \lambda_S \gamma_E) - \frac{\lambda_S \gamma_A \beta}{(1-\alpha)} + \lambda_S(\gamma_X + \gamma_E \lambda_X)\sigma_U(1-\gamma_A) \right) \frac{\hat{\eta}}{1-\gamma_A} \\
&= \left(\lambda_S \gamma_E - \lambda_S \gamma_E \lambda_X - \frac{\lambda_S \gamma_A \beta}{(1-\alpha)} + \lambda_S \gamma_X \sigma_U + \lambda_S \gamma_E \lambda_X \sigma_U \right) \frac{\hat{\eta}}{1-\gamma_A} \\
&= \left((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S - \frac{\gamma_A \beta}{(1-\alpha)} \right) \frac{\lambda_S \hat{\eta}}{1-\gamma_A}
\end{aligned}$$

Because $1 - \gamma_A > 0$, $\lambda_S > 0$, and $\hat{\eta} > 0$, the sign of DRE has the sign of the whole expression in big parentheses. That is, if $\gamma_A \beta > (1 - \alpha)((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S)$, then $DRE < 0$. In such a case, $\gamma_A \beta$ is even larger than required for the EES to bind as $\gamma_A \beta > (1 - \alpha)((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S) > (1 - \alpha)((\gamma_E \lambda_X + \gamma_X)\gamma_A \sigma_U + \gamma_E \lambda_S)$.

We can also show that under the condition $\gamma_A \beta > (1 - \alpha)((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S)$, the indirect rebound effect (IRE) is also negative and more negative than the DRE. We can write the indirect rebound effect as:

$$\begin{aligned}
IRE &= \left(\frac{\lambda_X[(\gamma_X + \gamma_E \lambda_X)\sigma_U \gamma_A + \lambda_S \gamma_E]}{1-\gamma_A} - \frac{\lambda_X \gamma_A \beta}{(1-\gamma_A)(1-\alpha)} \right) \hat{\eta} - \lambda_X(\gamma_A + \gamma_E \lambda_S)\sigma_U \hat{\eta} \\
&= \frac{\hat{\eta} \lambda_X}{1-\gamma_A} \left((\gamma_X + \gamma_E \lambda_X + \gamma_A + \gamma_E \lambda_S)\sigma_U \gamma_A + \lambda_S \gamma_E - \frac{\gamma_A \beta}{(1-\alpha)} - (\gamma_A + \gamma_E \lambda_S)\sigma_U \right) \\
&= \frac{\hat{\eta} \lambda_X}{1-\gamma_A} \left(\lambda_S \gamma_E - \gamma_E \lambda_S \sigma_U - \frac{\gamma_A \beta}{(1-\alpha)} \right) < 0
\end{aligned}$$

Subtract DRE by IRE and consider the result:

$$\begin{aligned}
DRE - IRE &= \left((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S - \frac{\gamma_A \beta}{(1-\alpha)} \right) \frac{\lambda_S \hat{\eta}}{1-\gamma_A} - \frac{\hat{\eta} \lambda_X}{1-\gamma_A} \left(\lambda_S \gamma_E - \gamma_E \lambda_S \sigma_U - \frac{\gamma_A \beta}{(1-\alpha)} \right) \\
&= \left((\gamma_E \lambda_X + \gamma_X + \gamma_E)\lambda_S \sigma_U + (\lambda_S - \lambda_X)\gamma_E \lambda_S + \frac{\lambda_X \gamma_A \beta}{(1-\alpha)} \right) \frac{\hat{\eta}}{1-\gamma_A}
\end{aligned}$$

If $(1 - \alpha)((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S) < \gamma_A \beta$, then

$$DRE - IRE > \left((\gamma_E \lambda_X + \gamma_X + \gamma_E)\lambda_S \sigma_U + (\lambda_S - \lambda_X)\gamma_E \lambda_S + \lambda_X((\gamma_E \lambda_X + \gamma_X)\sigma_U + \gamma_E \lambda_S) \right) \frac{\hat{\eta}}{1-\gamma_A}$$

$$\text{and } DRE - IRE > ((\gamma_E + \gamma_X)\sigma_U + \lambda_S \gamma_E \lambda_S) \frac{\hat{\eta}}{1-\gamma_A} > 0$$

Because $DRE < 0$ and $IRE < 0$, then the absolute size of the indirect rebound effect is greater than the absolute size of the direct rebound effect.

Proof of (3.ii):

From Column (5) of Table 1, the total rebound effect (TRE) is the sum of direct and indirect substitution and income effects:

$$\begin{aligned} TRE &= \left((\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} \right) \hat{\eta} \\ &= \frac{\hat{\eta}}{1 - \gamma_A} \left((\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U + \lambda_X \sigma_U \gamma_A + \lambda_S \gamma_E - \frac{\gamma_A \beta}{(1 - \alpha)} \right) \\ &= \frac{\hat{\eta}}{1 - \gamma_A} \left(\lambda_S \gamma_X \sigma_U + \lambda_S \gamma_E - \frac{\gamma_A \beta}{(1 - \alpha)} \right) \end{aligned}$$

The fraction of K used in production of A to \bar{K} , γ_A , is less than one, so $1 - \gamma_A > 0$. The sign of TRE depends on the term in big parentheses. That is, if $\gamma_A \beta > (1 - \alpha)(\lambda_S \gamma_X \sigma_U + \gamma_E \lambda_S)$, then $TRE < 0$.

First, we must meet the minimum requirement such that the pre-existing energy efficiency standard is costly and binding: that is, $\gamma_A \beta > (1 - \alpha)((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E)$. If energy service sector is less energy intensive (i.e., $\lambda_S \gamma_X - \lambda_X \gamma_A < 0$), then we can show:

$$\lambda_S \gamma_X \sigma_U + \gamma_E \lambda_S < (\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A - \lambda_S \gamma_E$$

by subtracting the left hand side terms from the right hand side terms in the above inequality and rearranging the result as :

$$\lambda_S \gamma_X \sigma_U + \gamma_E \lambda_S - (\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A - \lambda_S \gamma_E = \sigma_U (1 - \gamma_A) (\lambda_S \gamma_X - \lambda_X \gamma_A) < 0$$

Then in such a case, the minimum requirement to ensure the pre-existing energy efficiency standard is costly and binding implies the condition such that $TRE < 0$.

If energy service sector is more energy intensive (i.e., $\lambda_S \gamma_X - \lambda_X \gamma_A > 0$), then the minimum costly and binding EES condition is less strict than the condition that is required for the TRE to be negative:

$$\gamma_A \beta > (1 - \alpha)(\lambda_S \gamma_X \sigma_U + \gamma_E \lambda_S) > (1 - \alpha)((\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A - \lambda_S \gamma_E)$$

Proof of (3.iii):

Backfire occurs when the direct energy savings from increased energy efficiency are more than offset by the positive rebound effects, or the total effect on energy use is positive. It's trivial to show that if the energy service sector is less energy intensive than the other good sector, backfire is impossible as the total rebound effect is actually a negative rebound.

Consider if the energy service sector is more energy intensive, then from equation (5.4), the total effect on energy use can be shortened as:

$$\begin{aligned}\hat{E} &= \left((\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U + \frac{(\gamma_X + \gamma_E \lambda_X) \sigma_U \gamma_A + \lambda_S \gamma_E}{1 - \gamma_A} - \frac{\gamma_A \beta}{(1 - \gamma_A)(1 - \alpha)} - \lambda_S \right) \hat{\eta} \\ &= \frac{\hat{\eta}}{1 - \gamma_A} \left((\lambda_S \gamma_X - \lambda_X \gamma_A) \sigma_U + \lambda_X \sigma_U \gamma_A - \frac{\gamma_A \beta}{(1 - \alpha)} - \lambda_S \gamma_X \right) = \frac{\hat{\eta}}{1 - \gamma_A} \left(\lambda_S \gamma_X (\sigma_U - 1) - \frac{\gamma_A \beta}{(1 - \alpha)} \right)\end{aligned}$$

If $\gamma_A \beta > (1 - \alpha) \lambda_S \gamma_X (\sigma_U - 1)$, $\hat{E} < 0$ and there is no backfire!

One special case is that if $\sigma_U < 1$, then $\lambda_S \gamma_X (\sigma_U - 1) - \frac{\gamma_A \beta}{(1 - \alpha)} < -\frac{\gamma_A \beta}{(1 - \alpha)} < 0$. Since $1 - \gamma_A > 0$ and $\hat{\eta} > 0$, $\hat{E} < 0$. So, there exists no backfire if $\sigma_U < 1$.

Appendix G: Calibration of Cost Function Parameters (α and β)

Recall that the annual cost, K_A , of achieving more energy efficiency, A , is a function of the extra energy efficiency beyond some A_0 which we call “minimum” energy efficiency:

$$K_A = B(A - A_0)^\beta, \text{ with } B > 0 \text{ and } \beta \geq 1$$

This minimum A_0 is essentially an engineering concept, but it is better interpreted as a parameter of the cost function – a fixed number that needs to be calibrated for the model to fit the facts we want to capture.² Various sources below are used to set α , defined as $\alpha \equiv A_0/A$.

For convenience of notation, we define $A_1 \equiv A - A_0$. Then the above cost equation can be written as: $K_A = B A_1^\beta$, and it can be differentiated with respect to the chosen extra energy efficiency A_1 to obtain the marginal cost of energy efficiency:

$$MC \equiv \frac{dK_A}{dA} = \frac{dK_A}{dA_1} = B\beta A_1^{\beta-1} \quad (\text{G.1})$$

Note that $dA_1 = dA$, since A_0 is a fixed parameter. Totally differentiate equation (G.1) with respect to A_1 to get:

$$dMC = B\beta(\beta - 1)A_1^{\beta-2} dA_1 \quad (\text{G.2})$$

Divide equation (G.2) by equation (G.1) to obtain:

$$\begin{aligned}\frac{dMC}{MC} &= \frac{(\beta - 1)dA_1}{A_1} \\ \widehat{MC} &= (\beta - 1)\widehat{A}_1 \\ \beta &= \frac{\widehat{MC}}{\widehat{A}_1} + 1\end{aligned} \quad (\text{G.3})$$

² This A_0 is not the cost-minimizing energy efficiency that un-regulated firms and consumers would choose. Existing mandates mean that firms start with A above A_0 , and our model is used only for small changes. This A_0 just shifts the cost curve, so that A_0 and β can be chosen jointly to obtain the best fit for available information.

where we can rewrite $\widehat{A}_1 \equiv dA_1/A_1 = dA/(A - A_0) = \widehat{A}/(1 - \alpha)$. If we have enough data on both the *levels* and *changes* in both marginal cost and energy efficiency, then we could use equation (G.3) to calibrate our cost curve parameter β .

For light-duty vehicles, given some initial fuel efficiency A in miles per gallon (mpg), calculations of incremental costs (dK_A) associated with improved fuel efficiency (dA) are provided by the International Council on Clean Transportation (Lutsey *et al.*, 2017) and the National Research Council (NRC, 2015). For several major appliances, the Department of Energy (DOE, 2011, 2016a, and 2016b) provides similar cost calculations for changes in energy efficiency (as measured for appliances). We use those additional costs to calculate the marginal cost of energy efficiency (MC , per unit dA) and its percentage change (\widehat{MC}).

Then, to calibrate β using equation (G.3), we also need to know $\widehat{A}_1 = dA/(A - A_0)$, where A_0 is not observed. In the model, A and A_0 are in services S per unit of energy, where S is an aggregation. In the data, energy efficiency is reported in mpg for cars, or Annual Fuel Utilization Efficiency (AFUE) for furnaces, or Seasonal Energy Efficiency Ratio (SEER) for air conditioners. Our text lists the six steps of our approach.

Table G1 shows calibration results for midsize cars with spark-ignition (SI) engines, as studied in NRC (2015). Panel A shows their “low-technology cost scenario”, and panel B shows their “high-technology cost scenario”. Fuel efficiency improvements and associated incremental costs in the first two columns of Table G1 are taken from NRC (2015). All incremental costs are relative to the “null vehicle” which has the lowest technology in the 2008 model year.³ The third column shows our calculated marginal cost of energy efficiency, MC , the change in incremental cost divided by the change in fuel economy. Using the first two rows, we have $(1,388-321)/(52.1-36.5) = 68$ (in dollars per additional mpg). Then we calculate the proportional *change* in marginal cost ($\widehat{MC} = dMC/MC$). For the same example, the percentage change in the marginal cost from 36.5 to 52.1 mpg is $(153-68)/68 = 1.24$ (or, 124%). Our calibrated β in either the low- or high-cost scenarios is only a point calculation (at 36.5 mpg or 36.4 mpg). These mpg’s are between the 2015 CAFE standard and the 2016 CAFE standard for passenger cars (i.e., between 36.2 mpg and 37.8 mpg).

The last four columns of Table G1 show the calculation of β for each A_0 and α . The table shows that a smaller minimum fuel economy α tends to yield a larger β . The calculated

³ Technologies are added to improve the fuel economy of the null vehicle in order to meet the current and future CAFE standards. See NRC (2015) for more technical descriptions of the null vehicle.

β is generally higher in the low-cost scenario than in the high-cost scenario. In either panel, and in our other calculations below, $\alpha=0$ can yield high and unstable values of β . When α is near one-half, tables show a range of β that are all around 2 (quadratic costs).

Table G1: Calibration of β for Midsize Cars with SI Engine

A. Low Cost

Fuel Economy (mpg)	Incremental Cost (\$)	MC (\$/mpg)	\widehat{MC}	β			
				$A_0 = 0$ ($\alpha = 0$)	$A_0 = 10$ ($\alpha = .27$)	$A_0 = 15$ ($\alpha = .41$)	$A_0 = 20$ ($\alpha = .55$)
36.5	321	68	124%	3.91	3.11	2.71	2.32
52.1	1388	153					
57.9	2278						

B. High Cost

Fuel Economy (mpg)	Incremental Cost (\$)	MC (\$/mpg)	\widehat{MC}	β			
				$A_0 = 0$ ($\alpha = 0$)	$A_0 = 10$ ($\alpha = .27$)	$A_0 = 15$ ($\alpha = .41$)	$A_0 = 20$ ($\alpha = .55$)
36.4	325	104	79%	2.84	2.33	2.08	1.83
52.1	1956	186					
56.1	2701						

Note: Fuel economy improvements and their associated incremental costs are extracted from Tables 8.4a and 8.4b in NRC (2015). Panel A shows their low-cost scenario, and panel B is their high-cost scenario. According to U.S. EPA statistics, the combined mpg of the least-efficient midsize cars sold in U.S. in 2018 is 14. Choices of A_0 for sensitivity analysis are 0, 10, 15, and 20.

Table G2: Calibration of β for Passenger Cars and Light Trucks

A. Passenger Car

Fuel Economy (mpg)	Incremental Cost (\$)	MC (\$/mpg)	\widehat{MC}	β			
				$A_0 = 0$ ($\alpha = 0$)	$A_0 = 10$ ($\alpha = .28$)	$A_0 = 15$ ($\alpha = .42$)	$A_0 = 20$ ($\alpha = .56$)
35.7	378	92	24%	2.80	2.30	2.05	1.79
40.4	811	113					
44.4	1255						

B. Light Truck

Fuel Economy (mpg)	Incremental Cost (\$)	MC (\$/mpg)	\widehat{MC}	β			
				$A_0 = 0$ ($\alpha = 0$)	$A_0 = 10$ ($\alpha = .26$)	$A_0 = 15$ ($\alpha = .42$)	$A_0 = 20$ ($\alpha = .58$)
28.8	416	131	47%	2.98	2.43	2.09	1.75
35.7	900	193					
44.1	1621						

Note: Fuel economy improvements and their associated incremental costs are extracted from Tables A.1 – A.4 in Lutsey *et al.* (2017). Panel A shows calculations for passenger cars, and panel B is for light trucks. According to U.S. EPA statistics, the combined mpg of the least-efficient passenger cars and light-duty trucks is about 11 to 14. Choices of A_0 for passenger cars are 0, 10, 15, and 20. For light trucks, choices of A_0 are 0, 8, 13, and 18.

Table G2 shows our calibration for passenger cars and light trucks using results from Lutsey *et al.* (2017), where targets are stated as percentages of carbon dioxide emission reductions of 0% up to 100% from the 2008 baseline year. We convert those emission reduction targets into equivalent mpg goals using the common conversion factor of 8,887 grams of CO₂ emissions per gallon of gasoline consumed.⁴ We report equivalent mpg goals in the first column of Panels A and B. Incremental costs are taken from Lutsey *et al.* (2017), from which we calculate marginal costs and percentage changes in *MC*. For these passenger cars and light trucks, we vary A_0 just as in the case of midsize cars above. Our calculated β shown in the last four columns of Panel A and B are very close to those in Table G1.

Table G3: Calibration of β for Residential Packaged Central Air Conditioner

Energy Efficiency (SEER)	Installed Cost (\$)	<i>MC</i> (\$/SEER)	\widehat{MC}	β			
				$A_0 = 0$ ($\alpha = 0$)	$A_0 = 8$ ($\alpha = .57$)	$A_0 = 9$ ($\alpha = .64$)	$A_0 = 10$ ($\alpha = .71$)
14.0	4779	156	26%	4.66	2.57	2.31	2.05
15.0	4935	197					
17.5	5427						

Note: Data are taken from the DOE (2016a). SEER stands for Seasonal Energy Efficiency Ratio, which is a measure of an air conditioner’s efficiency. A SEER rating is the ratio of cooling in British thermal unit (BTU) to the energy consumed in watt-hours. The federally regulated minimum SEER for air conditioners are 13 or 14 depending on geographical locations. Choices of A_0 for sensitivity analysis are 0, 8, 9, and 10.

Next, we show calibration results for residential central air conditioning units in Table G3, furnaces in Table G4, and refrigerator-freezers in Table G5. These selections are major appliances that consume much household energy, and ones for which incremental costs are available from DOE (2011, 2016a, 2016b). The first column in Tables G3 and G4 shows the measured energy efficiency (the SEER rating for air conditioners and AFUE rating for furnaces).⁵ Their associated installed costs are provided by DOE (2016a, 2016b) and shown in the second column of both tables. To calculate marginal costs of energy efficiency in the third column, we divide the difference between installed costs in the second column by the increase in energy efficiency in the first column. For example, in the third column of Table G3, the marginal cost $156 = (4,935 - 4,779)/(15.0-14.0)$. Then, the table shows the percentage change

⁴ The conversion rate can be found on the U.S. Environmental Protection Agency (EPA)’s website: <https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references>.

⁵ A SEER rating is the ratio of cooling in British thermal unit (BTU) to the energy consumed in watt-hours. A furnace with an AFUE rating of 90 would mean that it can convert 90% of its fuel into usable heat.

in marginal costs, followed by the cost curve parameter β (in the last four columns). The minimum energy efficiency A_0 is a technological parameter, not related to policy, so we vary it below the federally required minimum energy efficiency. For $A_0 > 0$, our calculated β for central air conditioners and furnaces varies around 2.

Table G4: Calibration of β for Residential Non-weatherized Furnace

Energy Efficiency (AFUE)	Installed Cost (\$)	MC (\$/AFUE)	\widehat{MC}	β			
				$A_0 = 0$ ($\alpha = 0$)	$A_0 = 50$ ($\alpha = .54$)	$A_0 = 60$ ($\alpha = .65$)	$A_0 = 70$ ($\alpha = .76$)
92	2635	36	8%	3.58	2.18	1.90	1.62
95	2742	39					
98	2858						

Note: Data are taken from the DOE (2016b). AFUE stands for Annual Fuel Utilization Efficiency, which is a measure of furnace efficiency. A furnace with an AFUE rating of 90 would mean that it can convert 90% of its fuel into usable heat. A low-efficiency heating system has 56% to 70% AFUE. The minimum federal energy efficiency standard for residential furnaces is 80. Choices of A_0 for sensitivity analysis are 50, 60, and 70.

Table G5: Calibration of β for 16 Cubic Foot Top-Mount Refrigerator-Freezers

Maximum Energy Use [kWh/yr]	Energy Efficiency [ft3/(kWh/day)]	Incremental Cost [\$]	MC [\$/(ft3/kWh/day)]	\widehat{MC}	β			
					$A_0 = 0$ ($\alpha = 0$)	$A_0 = 600$ ($\alpha = .63$)	$A_0 = 550$ ($\alpha = .68$)	$A_0 = 500$ ($\alpha = .74$)
410	14.27	6.52	15.03	96%	5.82	2.78	2.53	2.23
341	17.13	49.41	29.50					
296	19.76	127.14						

Note: For each maximum energy use (first column), DOE (2011) calculates incremental cost (third column). The text describes how we convert their maximum energy use to a measure of required energy efficiency for our model (second column), in cubic feet cooled per kWh per day. The last four columns show our calculated β for alternative assumptions about A_0 in kWh/year (namely, 0, 500, 550, and 600).

Table G5 presents calculations for refrigerator-freezers, where efficiency is measured as the annual energy use. The federal standard before September 15, 2014 for top-mount refrigerator-freezers is stated as a maximum energy use, for example 432.8 kWh per year.⁶ DOE (2011) provides calculations for each annual energy consumption (kWh/year) shown in the first column. In our analytical model, however, energy efficiency is measured as services per unit of energy ($\epsilon A = S/E$). Therefore, we convert the efficiency of refrigerator-freezers to volume cooled per unit of electricity per day. To do so, we multiply the size of the appliance (16 cubic feet) by the number of days per year (365.25) and divide by annual energy use. Results are shown in the second column of Table G5. The third column is the incremental cost

⁶ This figure is calculated as 9.80 times the adjusted volume of the appliance in cubic feet, plus 276. If the volume is 16 cubic feet, then the maximum energy use is $9.8 \times 16 + 276 = 432.8$ kWh per year.

of DOE (2011), from which we calculate marginal cost in the fourth column (and change in marginal cost in the fifth column). Using four alternatives for A_0 (in kWh per year), the last four columns show the calibrated β . We generally vary the minimum energy efficiency A_0 below the federally required minimum efficiency for each appliance.

In general, Tables G1-G5 confirm that cost parameters can vary across vehicles and appliances and also depend on methods and assumptions. Our calibration section describes how we choose a pair of parameters that best fit the calculations appearing in all these tables.

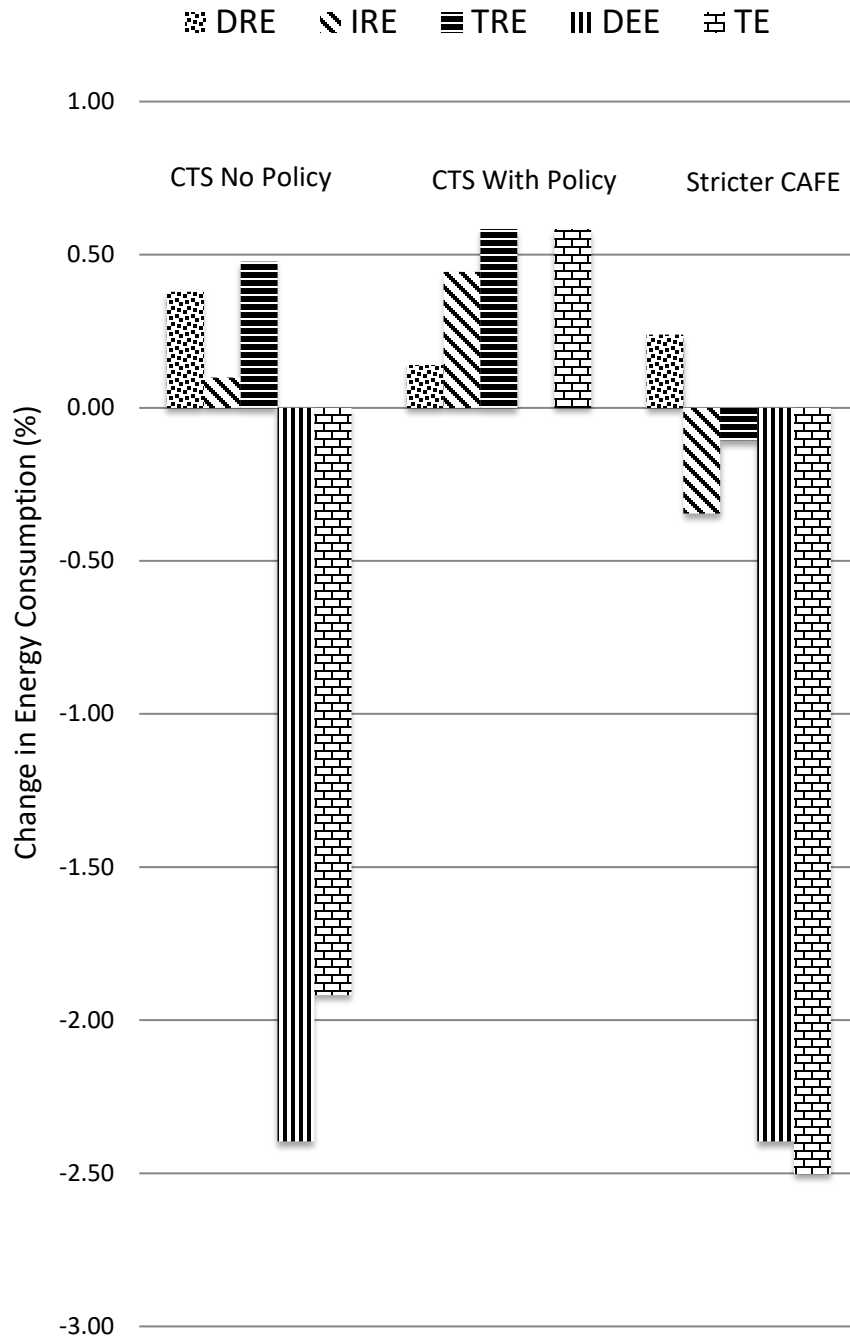
Appendix H: Calibration for Vehicles Separately from Household Appliances

As in the main calibration of section 6, we obtain 2015 residential energy expenditure data from the U.S. Energy Information Administration (EIA). Data on gasoline and other motor fuels are from the Bureau of Economic Analysis (BEA).

For household vehicles and parts, we use EIA data to calculate that the annualized cost for energy efficiency is $P_K K_A = 344.342$ (\$B). Thus, the fraction of K used for energy efficiency ($\gamma_A \equiv K_A/\bar{K}$) is $344.342/18,037 = 0.019$. Total expenditure on gasoline and other motor fuels is 270 (\$B). The ratio of this energy use to total energy use is $\lambda_S \equiv E_S/E = 270/1,127 = 0.240$, and the fraction of energy used in production of the composite good X is 0.760. We keep other parameters the same as in the case with all cars and appliances together, and we check the condition in Proposition 2 to make sure that the fuel efficiency standard is binding. All direct and rebound effects are shown in the figure below.

For household appliances other than vehicles, our calibrated annual cost for energy efficiency is $P_K K_A = 330.658$ (\$B), so the fraction of K used for energy efficiency is $\gamma_A \equiv K_A/\bar{K} = 330.658/18,037 = 0.018$. The total energy used for these appliance services (without motor fuel costs) is 248 (\$B). Thus the ratio of this energy use to total energy use is $\lambda_S \equiv E_S/E = 248/1,127 = 0.220$, and the fraction of energy used in production of the composite good is 0.780. We keep other parameters the same as in the case with household vehicles, and we check the condition in Proposition 2 to make sure that the appliance standard is binding. All direct and rebound effects are shown in another figure below.

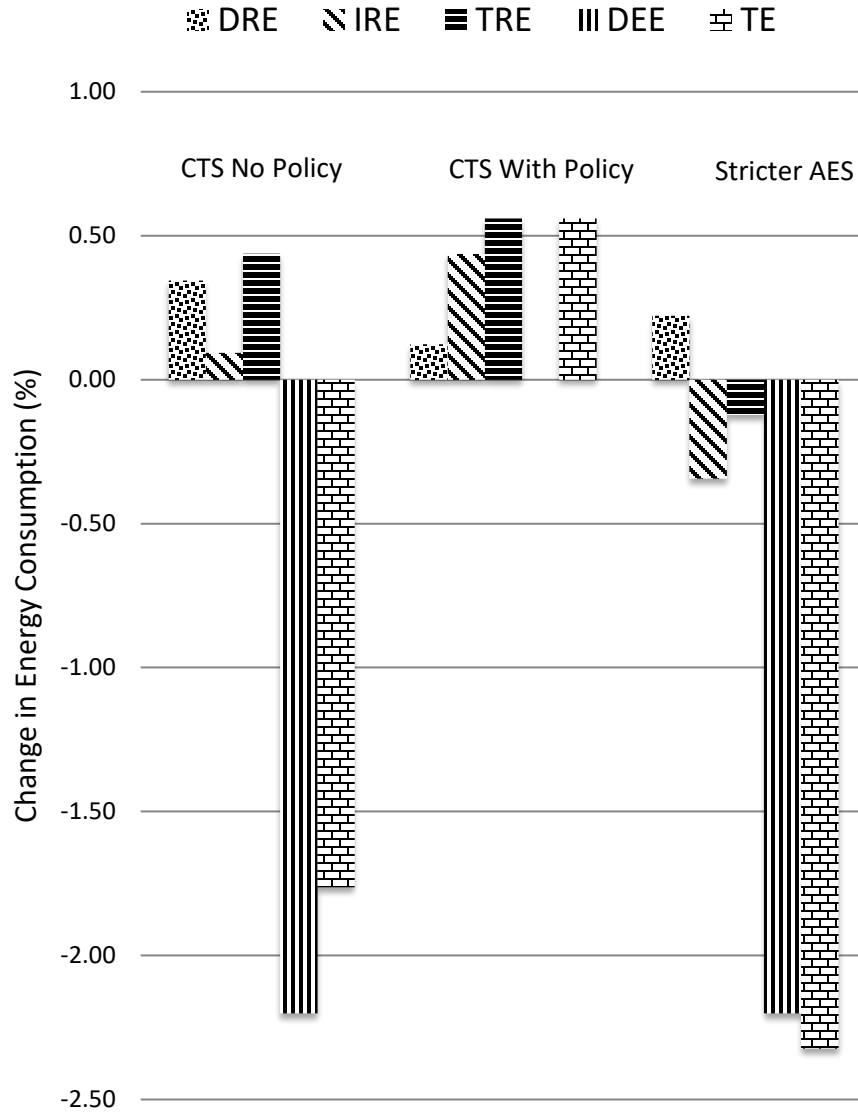
**Effects on Energy Use from the CTS and CAFE Standards – Vehicles Only
(central parameter values)**



DRE: Direct Rebound Effect
 IRE: Indirect Rebound Effect
 TRE: Total Rebound Effect

DEE: Direct Efficiency Effect
 TE: Total Energy

**Effects on Energy Use from the CTS and EES – for Appliances other than Vehicles
(central parameter values)**



DRE: Direct Rebound Effect
IRE: Indirect Rebound Effect
TRE: Total Rebound Effect

DEE: Direct Efficiency Effect
TE: Total Energy