

## Estimating direct and indirect rebound effects for U.S. households

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When energy efficiency investments yield net energy cost savings, this leads to a decrease in the total price of energy services. In such cases, energy efficiency investments may not yield expected energy- or emission-reductions due to a concept called the rebound effect. The direct rebound effect is an increase in energy consumption due to a rise in the demand for end-use energy services with an efficiency investment (Greening et al., 2000, Berkhout et al, 2000, Sorrell et al., 2008). The indirect rebound effect describes the changes in energy consumption due to the embodied energy of the reinvestment or re-spending of energy cost savings and the shift out of less energy-intensive goods and services (Greening et al., 2000, Berkhout et al, 2000). There is also an economy-wide rebound effect which describes a variety of mechanisms such as energy demand induced by a decline in the market price of energy which might result with widespread efficiency investments, an economy-wide shift into energy-intensive sectors due to the lower price of energy services and energy with efficiency (Greening et al., 2000, Saunders, 2010), disinvestment in the energy-supply sector (Turner et al., 2009), and other changes in the structure of an economy. All of these rebound effects, direct, indirect, or economy-wide, can be studied in a short-term or long-term time horizon, and for consumers, producers, or the government. In my research, I quantify a subset of these effects -- the short-run direct and indirect rebound effects for efficiency investments by residential households in the U.S.

While there is a growing literature on the various mechanisms of the rebound effect, the papers most related to my study, and reviewed here, are those focused on the rebound effects from energy efficiency improvements by households. Brannlund et al. (2007) employ an Almost Ideal Demand System (AIDS) framework to estimate own-price elasticities for energy and cross-price elasticities for the consumption bundle of a typical Swedish household. By simulating an exogenous (and costless) 20% improvement in end-use energy efficiency, they estimate changes in household budget shares and corresponding rebound effects in CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>2</sub> emissions. However, the drivers of the rebound effect are not analyzed in their study. Mizobuchi et al. (2008) use the same methodology as Brannlund et al., with the additional consideration of capital costs of efficient equipment for households in Japan, but exclude consideration of time preferences and how the tradeoffs between the capital cost and energy savings of an efficiency investment might change rebound effects. Druckman et al. (2011) consider the indirect rebound in carbon dioxide from respending cost savings from conservation measures by estimating expenditure elasticities and emissions intensities for spending by the typical U.K. household, yet do not consider direct rebound effects. My study will address these gaps in the literature with an analytical rebound definition, which identifies the sub-additivity and drivers of direct and indirect rebound effects, and will consider the role of time preferences and the cost-effectiveness of efficiency investments in the extent of the direct and indirect rebound effect for households.

Rebound effects are defined as the percentage difference between expected and actual energy savings (Allan et al, 2006, Guerra and Sancho, 2010). Actual energy savings may deviate from expected energy savings due to changes in demand for energy services,  $Q_{es}$  as efficiency,  $\tau$  (in energy service units, such as lm/W for lighting or mi/gal for driving) increases, characterized by the efficiency elasticity of the demand for energy services,  $\epsilon_{\tau, Q_{es}}$  (Berkhout et al, 2000, Sorrell et al., 2008). If market energy prices,  $P_e$ , (i.e. \$/kWh or \$/gal gasoline) are constant, and given that the price of energy services,  $P_{es} = P_e/\tau$ , the direct rebound effect can be characterized by the own-price elasticity of energy services,  $\epsilon_{P_{es}, Q_{es}}$  (Sorrell et al., 2008).

The Slutsky decomposition depicts the change in the demand for energy services and other goods by consumers (Berkhout et al., 2000) following a decline in the price of energy services from an efficiency investment with zero incremental capital cost relative to a baseline technology. Assuming the market price of energy,  $P_e$ , is constant, the decline in the price of energy services is driven solely by the increase in the efficiency. The Slutsky decomposition reveals that the change in demand for energy service and other goods, parameterized by the own-price elasticity,  $\epsilon_{P_{es}, Q_{es}}$ , which is typically negative, and the cross-price elasticity,  $\epsilon_{P_{es}, Q_{es}^c}$  of energy services, is

equal to the sum of substitution and income effects. The energy demand (or emissions) implications of a change in the demand for energy service and other goods will depend on the embodied energy (or emissions) intensity (or lifecycle energy per dollar of expenditure) of energy services,  $E_{es}$ , and other goods,  $E_{\bar{e}}$  [e.g. BTU/\$, kg CO<sub>2</sub>e/\$].

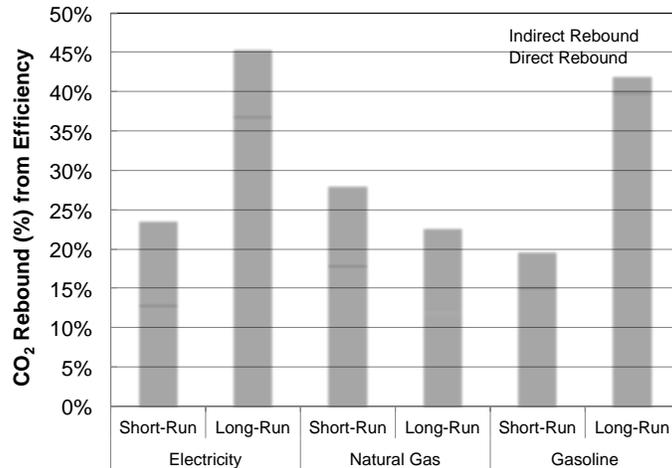
The elasticities of relevance for calculating the rebound effect, own-price and cross price elasticities for a variety of energy service and other goods, are unavailable due to the lack of data on the demand for energy services, particularly for end-uses of electricity. When cross-price elasticities are available, they are estimated with own-price elasticities of energy which are much higher than estimates from the energy economics literature due to the limited detail of the energy price data included in the econometric models (Taylor and Houthakker, 2010). Thus, assuming that the basic properties of elasticities hold (i.e. Engel aggregation or the budget constraint, Cournot aggregation which limits the extent of substitution effects permissible by the budget constraint, and Slutsky decomposition), I make a few simplifying assumptions on cross-price elasticities for non-energy goods, to yield Eq 1.

- 1) Energy service price elasticities,  $\epsilon_{P_{es}, Q_{es}}$  and  $\epsilon_{P_{es}, Q_{\bar{e}}}$ , can be approximated by energy price elasticities,  $\epsilon_{P_e, Q_e}$  and  $\epsilon_{P_e, Q_{\bar{e}}}$ . This will be an overestimate of the direct and indirect rebound because (in absolute value) energy price elasticities are an upper bound for energy service price elasticities due to the dependence of the demand for efficiency on energy prices (Hanly et al, 2002).
- 2) All energy service and other goods have equal compensated (constant-utility) cross-price elasticities with respect to energy prices. Differences in the (uncompensated) cross-price elasticities will then be driven by expenditure elasticities for energy goods,  $\epsilon_{I, Q_e}$  and other goods,  $\epsilon_{I, Q_{\bar{e}}}$ , and budget shares for energy goods,  $s_e$ , and other goods,  $s_{\bar{e}}$ .

$$R = -\epsilon_{P_e, Q_e} + (\epsilon_{P_e, Q_e} + s_e \epsilon_{I, Q_e}) \frac{(\sum_{\bar{e}} E_{\bar{e}} s_{\bar{e}}) / (\sum_{\bar{e}} s_{\bar{e}})}{E_e} + \frac{\sum_{\bar{e}} E_{\bar{e}} s_{\bar{e}} \epsilon_{I, Q_{\bar{e}}}}{E_e} \quad (1)$$

Key input parameters to calculate the rebound effect are obtained from several sources. Own-price elasticities for electricity, natural gas, and gasoline are obtained from the energy economics literature (Reiss et al., 2005, Bernstein et al., 2006, Gillingham, 2011). Embodied emissions intensities of expenditure (for rebound in CO<sub>2</sub>e emissions; similar to energy intensities) on energy and non-energy goods are obtained from the 2002 version of the economic input-output lifecycle assessment (EIO-LCA) model developed by Carnegie Mellon's Green Design Institute (the model and documentation are available at [www.eiolca.net](http://www.eiolca.net)). Initial demand for energy and other goods are obtained from the 2004 U.S. Consumer Expenditure Survey, which contained expenditures by households by income level and other demographic characteristics (Bureau of Labor Statistics, 2004).

Preliminary results shown in Figure 1 demonstrate that the greenhouse gas (GHG) rebound effect in percentage terms will vary depending on the fuel saved with the efficiency investment, driven by differences in the own-price elasticity for the fuel, the household's expenditure share on the fuel, the energy intensity per expenditure on the fuel, and the GHG emissions intensity of expenditure on other goods. Electricity has higher GHG emissions intensity per dollar and higher own-price elasticity, which leads to a higher rebound in percentage terms (the relative rebound effects by fuel are similar in physical or kg CO<sub>2</sub>e units). I have also explored the variation in rebound effects by income bracket, which shows higher rebound effects (in % but not physical units) for lower-income groups due to their higher price-responsiveness.



**Figure 1:** Rebound effects (in %) vary by fuel

In future work, I will consider explore how rebound effects vary when capital costs and time preferences are taken into account. I hypothesize that cost-effective (over the lifecycle) efficiency investments will have a higher rebound effect than those investments for which the annualized capital cost is greater than the annual energy cost savings.

These preliminary results show that direct and indirect rebound effects for U.S. households could be significant, but are highly dependent on the household’s price responsiveness on energy services. In using energy price elasticities in these results, I may be overestimating the rebound effect for the average household because (1) energy price elasticities are greater than energy service price elasticities (Hanly et al., 2002), (2) price responsiveness has been shown to decline as income rises (Small and Van Dender, 2007; Gillingham, 2011) and time costs increase (Jalas, 2002) so if household incomes rise with economic growth, rebound effects should decline over time, and (3) the higher capital costs of efficient equipment may reduce rebound effects in energy service demand, which I will quantify in future research. Even with these positive biases, I do not find direct and indirect rebound effects for households that are greater than 100% (or “backfire”), representing the case of greater energy consumption that prior to the efficiency investment (Saunders, 2000, Sorrell, 2009). Rebound effects less than 100% suggest that policies to improve end-use efficiency for the household, such as appliance or fuel economy standards, energy efficiency tax credits, or voluntary labels, can reduce energy consumption. However, the reduction in energy consumption will depend both on the efficiency improvements in technology as well as the price-responsiveness of consumers, which varies due to issues such as income level and time costs, and the level of saturation in a particular energy service (Khazzoom, 1980).

The rebound results shown are for the average U.S. household, however the effect for individual households may differ due to lifestyle choices and other factors of “energy culture” not captured by price elasticities, which depict average historical spending patterns. For example, the “green” household choosing to reinvest energy cost savings from efficiency into more efficiency investments could have an even lower, or potentially negative rebound effect (i.e. greater than expected energy savings). Other households may choose to reinvest energy savings from efficiency entirely on increased energy services, possibly leading to backfire. Understanding the variation in consumer behavior and designing incentives to shift preferences in energy consumption is as important, if not more so, as modeling technological progress and average economic responses in modeling the costs and benefits of energy efficiency and, more generally, the dynamics of energy demand.

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