



Analysis

Estimating direct and indirect rebound effects for U.S. households with input–output analysis. Part 2: Simulation

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ABSTRACT

This is the second part of a two-part paper that integrates economic and industrial ecology methods to estimate the indirect rebound effect from residential energy efficiency investments. We apply the model developed in part one to simulate the indirect rebound, given an estimate of the direct rebound, using a 2002 environmentally-extended input–output model and the 2004 Consumer Expenditure Survey (in 2002\$) for the U.S. We find an indirect rebound of 5–15% in primary energy and CO₂e emissions, assuming a 10% direct rebound, depending on the fuel saved with efficiency and household income. The indirect rebound can be as high as 30–40% in NO_x or SO₂ emissions for efficiency in natural gas services. The substitution effect modeled in part one is small in most cases, and we discuss appropriate applications for proportional or income elasticity spending assumptions. Large indirect rebound effects occur as the U.S. electric grid becomes less-carbon intensive, in households with large transportation demands, or as energy prices increase. Even in extreme cases, there is limited evidence for backfire, or a rebound effect greater than 100%. Enacting pollution taxes or auctioned permits that internalize the externalities of energy use would ensure that rebound effects unambiguously increase consumers' welfare.

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1. Introduction

This is the second part of a two-part paper focused on the indirect rebound effect, given an estimate of the direct rebound effect, from energy efficiency investments. The rebound effect, simply defined, is equal to the difference between potential energy savings, PES, often obtained from an engineering estimate, and actual energy savings, AES, after accounting for changes in consumer usage in response to the fall in the price of energy services or operating cost with an efficiency investment (Sommerville, 2007; Guerra and Sancho, 2010), as shown in Eq. (1).

$$1 - \frac{AES}{PES} \quad 1$$

In part one, we provided a critical review of direct and indirect rebound studies from the economics and industrial ecology literatures that differ in assumptions about the definition of the direct rebound effect, average versus marginal spending patterns, and the importance of supply-chain or embodied energy of spending. Using classical consumer demand theory, we developed a framework that integrates marginal spending patterns as incomes rise or the price of energy

services fall with the embodied energy or emissions of that spending. Our analysis demonstrated that the extent of re-spending from the indirect rebound effect is bounded by the direct rebound effect and the household's budget constraint.

In part two of the paper, we apply the framework from part one to simulate direct and indirect rebound effects for the average U.S. household. As we draw upon U.S. data from a number of sources and vintages, the results in this paper form an initial order-of-magnitude estimate of the indirect rebound, given the direct rebound, in the U.S. residential sector, assuming domestically produced goods and services. We also analyze the major sources of variability and uncertainty in the indirect rebound effect to guide future research. Section 2 briefly summarizes the analytical model of the direct and indirect rebound effect in a static general equilibrium framework described in part one of this two-part paper. Section 3 describes the data sources used to simulate the indirect rebound including income elasticities and household spending patterns from the 2004 U.S. Consumer Expenditure Survey (CES). Section 4 applies our model to simulate investments in different types of efficiency (e.g. saving electricity, natural gas, or gasoline expenditures) made by the average U.S. household and the corresponding direct and indirect rebound effects. Policymakers might be interested in achieving various goals with efficiency, such as reducing emissions or the use of imported energy resources, thus we assess the rebound effect measured in terms of indicators such as primary energy consumption, GHG, NO_x, and SO₂ emissions. In addition, this section illustrates interaction between the direct and indirect rebound effect, a sensitivity analysis of key parameters, and variations in rebound effects by income. Section 5 concludes

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with a discussion of the reliability and relevance of our results for policy analysis.

2. Methods

In part one of this two-part paper, we derived models of the direct and indirect rebound effect from microeconomic properties of elasticities, including the Slutsky decomposition of price elasticities into substitution and income effects, combustion energy or emissions from the use phase of fuels and the embodied energy of production for goods from an environmentally-extended economic input–output life-cycle assessment model (Hendrickson et al., 2006; www.eiolca.net). This model assumes that the efficiency investment has no incremental capital cost (or has the same capital cost) compared to a conventional technology, and so our estimates form an upper bound of the indirect rebound effect (Chitnis et al., 2012; Henly et al., 1988; Mizobuchi, 2008; Nässén and Holmberg, 2009).

We derived three possible approximations for the cross-price elasticity parameter for the direct and indirect rebound effect, including the assumption of proportional spending, R_{D+I_PS} , and income elasticity or marginal spending patterns, R_{D+I_IE} , both of which assume no substitution out of other goods spending when the price of energy services (or operating cost) falls with an efficiency investment. We also attempt to bound the substitution effect with the assumption of constant cross-price elasticities for non-energy services, R_{D+I_CS} .

$$R_{D+I_PS} = -\eta_{S,P_S} + \frac{\sum_{O=1;\neq S}^n (v_O(I-A)^{-1} + v_O^C)w_O(1 + \eta_{S,P_S})}{(v_S(I-A)^{-1} + v_S^C)(1-w_S)} \tag{2}$$

$$R_{D+I_IE} = -\eta_{S,P_S} + \frac{\sum_{O=1;\neq S}^n (v_O(I-A)^{-1} + v_O^C)w_O\eta_{O,I}(1 + \eta_{S,P_S})}{(v_S(I-A)^{-1} + v_S^C)(1-w_S\eta_{S,P_S})} \tag{3}$$

$$R_{D+I_CP} = -\eta_{S,P_S} + \frac{\sum_{O=1;\neq S}^n (v_O(I-A)^{-1} + v_O^C)w_O(\eta_{S,P_S} + w_S\eta_{S,I})}{(v_S(I-A)^{-1} + v_S^C)\sum_{O=1;\neq S}^n w_O} + \frac{\sum_{O=1;\neq S}^n (v_O(I-A)^{-1} + v_O^C)w_O\eta_{O,I}}{v_S(I-A)^{-1} + v_S^C} \tag{4}$$

where:

- η_{S,P_S} is the energy service price elasticity which is equal to the (negative) direct rebound.
- $\eta_{S,I}$ is the income elasticity of the demand for an energy service S .
- $\eta_{O,I}$ is the income elasticity of the demand for other good, O .
- V is a vector of direct emissions per dollar of expenditure including the production of energy services, V_S and other goods, V_O .
- w_S is the budget share for energy service S and w_O is the budget share for good O .

$(I-A)^{-1}$ is the Leontief input–output multiplier matrix, written in terms of identity matrix I , and production function A , which we obtain from the 2002 environmentally extended economic input–output life cycle assessment model for the U.S., which assumes domestically produced goods and services (Hendrickson et al., 2006; www.eiolca.net).

V^C is a vector of combustion emissions per dollar of expenditure from the use-phase of a fuel, V_S^C , (and is equal to 0 for non-fuels, V_O^C , including an energy carrier such as electricity). To estimate combustion emissions, we use 2002 U.S. commodity prices of \$1.4/gal for retail gasoline (all grades, all formulations) and \$8.6 per thousand cubic

feet for residential delivered natural gas (EIA, 2012). We conduct a sensitivity analysis on the influence of fuel prices on our indirect rebound effect calculations in Section 4.3. To estimate NO_x emissions from gasoline, which are a function of miles driven, we assume that the household drives vehicles¹ with a fuel economy of 19.6 miles/gal in the base case (BTS, 2012), for a total of 21,800 miles per year.

In addition, we define $Z = V(I-A)^{-1} + V^C$ to be a vector sum of the combustion emissions and supply chain emissions from production, or the embodied emissions per dollar of expenditure.

The models in Eqs. (2)–(4) are for the direct and indirect rebound effect in percentage terms, for the case of electricity, natural gas, or gasoline service efficiency. However, since each fuel or energy carrier has a different level of primary energy or emission intensity per dollar of expenditure, the rebound effect for each fuel is measured against a different baseline or potential energy or emission savings (PES), equal to $z_S w_S \tau Y$ for income level Y and energy service price (or operating cost) reduction τ expressed as a fraction or percentage. In the results in Section 4 we will show both rebound in percent and rebound in primary energy or emissions, which are obtained by multiplying the rebound in percent, shown in Eq. (1), by a given baseline PES.

3. Data

3.1. Energy Service Own-price Elasticities for Direct Rebound Effects

We assume that the range in direct rebound effects is between 0 and 15% for electricity and natural gas services (i.e. space cooling and heating), and between 5 and 20% for gasoline services (i.e. driving), which are consistent with the range of studies of the efficiency elasticity and energy service price elasticity for home heating and cooling and personal transport (see Table 1 in part 1; Davis, 2008; Dinan and Trumble, 1989; Dubin et al., 1986; Gillingham, 2011; Greene, 2012; Haughton and Sarkar, 1996; Hirst et al., 1985; Schwartz and Taylor, 1995; Small and van Dender, 2007). In our mean results, we use a direct rebound parameter of 10%, and use the ranges in the direct (and calculated indirect) rebound effects in the sensitivity analysis. We use the same mean direct rebound estimate for each fuel so that the differences in indirect rebound effects by fuel are clearly apparent.

We also study the variation in the rebound effects for average U.S. households of varying incomes. There are two sources of variation in the rebound effect by income: variations in the direct rebound effect and variations in the re-spending patterns by household income. To examine income variations in the direct rebound effect, we use income quantile regression estimates of electricity price elasticities by Reiss and White (2005). As these are energy price elasticities, they overestimate the direct rebound effect, and underestimate the indirect rebound effect, but are indicative of the trends across income brackets. In addition, these price-elasticities were measured for households in California, and using California utility pricing structures, which limits the validity of these estimates for households outside of the state. Differentiated price response by income is contested, as other researchers (Alberini et al., 2011) do not find such differences by income (and higher price elasticities) using a city-level panel of electricity expenditures. We also use the Gillingham's (2011) estimates of gasoline price elasticity of driving by income quantile to study rebound effects in gasoline efficiency. These estimates also rely on vehicle registration and emissions data for the state of California, which limits its validity to other U.S. states. To our knowledge, own-price elasticities by income quantile are not available for natural gas or its services, or in U.S. states other than California.

¹ On average, each household owns just under 2 vehicles, so that each vehicle is used to drive almost 11,000 miles per year.

Table 1

Houthakker–Taylor expenditure elasticities used in rebound simulations.

Sources: Taylor and Houthakker, 2010; 2004 Consumer Expenditure Survey.

Category	2004 budget share	LES-normalized expenditure elasticity	IA-normalized expenditure elasticity	Marginal spending share (LES)	Marginal spending share (IA)
Food	8%	0.12	0.36	1%	3%
Shelter	15%	0.54	0.87	8%	13%
Appliances	3%	0.54	0.87	1%	2%
Electricity	2%	0.14	0.40	0.3%	1%
Natural gas	1%	0.14	0.40	0.2%	1%
Other utilities	4%	0.14	0.40	1%	2%
Gasoline	4%	2.3	1.3	9%	5%
Transportation equip.	11%	2.3	1.3	26%	14%
Public transit	0.2%	2.3	1.3	0.4%	0.2%
Air travel	1%	2.3	1.3	2%	1%
Health care	4%	0.27	0.52	1%	2%
Financial services	20%	0.27	1.3	22%	24%
Misc.	26%	1.1	1.2	29%	32%

Notes: LES = Linear Expenditure System, IA = Indirect Addilog System. Spending shares may not sum to 100% because of rounding truncation.

3.2. U.S. Consumer Expenditure Survey

We use the U.S. Consumer Expenditure Survey (CES) for 2004 to represent average annual household demand for goods and services, including energy in the U.S. We use 2004 data, the closest year to 2002 for which the Bureau of Labor Statistics (BLS) applied improved procedures for income imputation in the CES, and convert all expenditures into 2002\$ using the U.S. all-urban, all-goods consumer price index (BLS, 2004), except electricity, natural gas, and gasoline, which were converted into \$2002 by the all-urban CPIs specific to each fuel or energy carrier, as input to the EIO-LCA model.

The Consumer Expenditure Survey (CES) is an annual compilation of data from two separate nationally representative samples of households: a bi-weekly Diary survey and a quarterly Interview survey. The Diary survey is conducted as two consecutive 1-week surveys, and collects expenditure data on smaller food, personal care, and household expenses. The Interview Survey is conducted over five consecutive quarters, and collects data on recurring expenses such as rent and utilities, and larger purchases, such as property, automobiles, durable goods, and medical expenses. The Interview Survey also collects before- and after-tax income data, however these are less reliable due to recall errors, privacy concerns, etc.

Respondents to the CES are known to systematically underreport health, clothing, and other expenditures compared with personal consumption expenditures (PCE) collected as part of GDP figures due to issues such as recall errors and sampling bias (Weber and Matthews, 2008). Only about 60% of national personal consumption expenditure (PCE) data are comparable and measured in the CES (Passero et al., 2011), however about 70% of the household carbon footprint is captured (Weber and Matthews, 2008).

The public CES data are divided into 74 expenditure categories, and we use the more detailed 674-sector pre-publication tables which disaggregates air travel expenditures and have to be allocated into the 428 EIO-LCA sectors, and may suffer sector misallocation error. The 428-sector CES data are used to calculate lifecycle household carbon emissions, termed the household carbon footprint (HCF) and measured in ton CO₂e using EIO-LCA. The ratio of lifecycle emissions per dollar spent in a given expenditure category is also listed. We also aggregate these data into $n = 13$ categories for clarity of interpretation of the indirect rebound results. See Appendix A for lifecycle energy and GHG, NO_x, and SO₂ emission intensities per dollar for 13 categories of household expenditures.

3.3. Expenditure Elasticities

We use expenditure/income elasticities from Taylor and Houthakker (2010) which uses four quarters of CES data for 1996, for six exhaustive

categories of expenditures: food, shelter, utilities, transportation, health, and miscellaneous goods. U.S. income (expenditure) elasticities are only available for these 6 categories because of the lack of price indices for a broad number of sectors in the economy, which are required to estimate a set of income and price elasticities within complete demand systems models that is consistent with consumer demand theory (Taylor and Houthakker, 2010). Taylor and Houthakker (2010) estimate expenditure elasticities using five different demand system models: the Linear Expenditure System (LES), Almost Ideal Demand System (AIDS), Direct Addilog (DA), Indirect Addilog (IA) and Double-Log (DL) system. We compute indirect rebound effects using these five sets of elasticities to assess the uncertainty in the indirect rebound effect under differing assumptions about the household's utility function. The Linear Expenditure System (LES) and Indirect Addilog (IA) results, shown in Table 1 correspond to the cases with the highest and lowest estimates of the indirect rebound effect. The expenditure shares in 2004 differ slightly from the average budget shares during the period studied by Taylor and Houthakker, so that Engel aggregation does not hold. We normalize the expenditure elasticities so that the Engel aggregation property does hold, to ensure that the budget constraint is met. These 6 Taylor–Houthakker categories are mapped to our 13 categories to assign income elasticities.

3.4. U.S. Household Expenditures, Spending Patterns, and Environmental Footprints

Fig. 1 shows the expenditures and environmental supply chain emissions (also known as footprints) for the average U.S. household in 2004 (in 2002\$), aggregated to the six Houthakker–Taylor categories. The expenditures and CO₂e footprint are similar to the aggregate U.S. residential figures in 2004 calculated by Weber and Matthews (2008) using the same CES data with a trade-linked, multi-regional version of the 1997 EIO-LCA model.

While transportation and utilities form a small portion of household expenditures, as expected, they are the largest sources of primary energy consumption and GHG, NO_x, and SO₂ emissions, as seen in Fig. 2a. The differences between the proportional spending, income elasticity, and cross-price elasticity re-spending scenarios using the LES and IA sets of income elasticities are shown in Fig. 2b. The differences in gasoline demand across re-spending scenarios will drive indirect rebound results, given the large portion of the household's carbon footprint attributed to gasoline-based transportation. The differences in re-spending patterns between the income elasticity and cross-price elasticity scenarios are minimal given a 10% direct rebound, but as we will show in the next section, appear to be greater if households exhibit a larger direct rebound from efficiency investments.

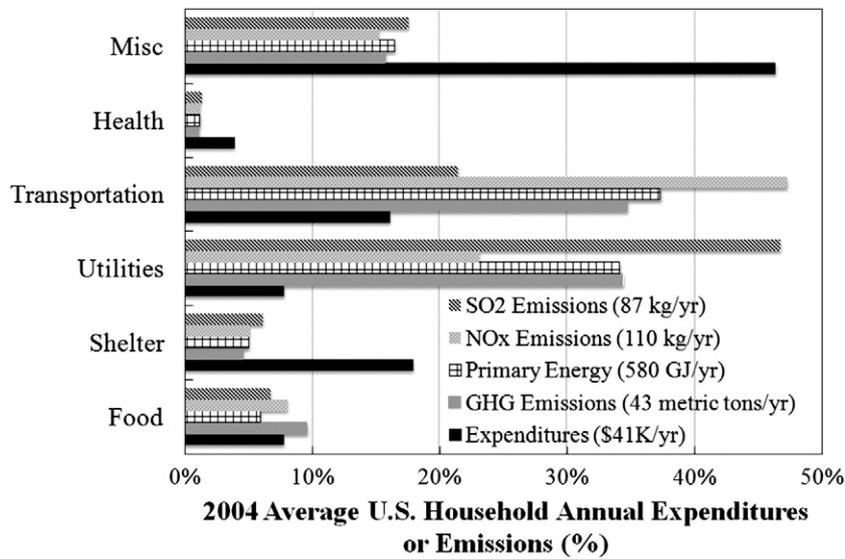


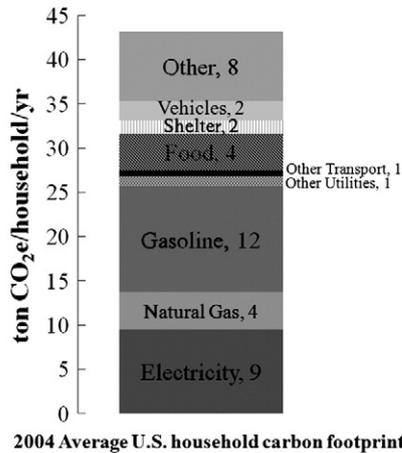
Fig. 1. Annual expenditures and emissions for the average U.S. household in 2004. Notes: Expenditure data are from 2004 Consumer Expenditure Survey (BLS, 2004) converted to 2002\$ by CPI method. Embodied emissions are estimated using the 2002 EIO-LCA model (www.eiolca.net). Annual expenditures, primary energy and emissions for the average U.S. household in 2004 are noted in parentheses.

4. Results

In this section, we demonstrate an application of our model to simulate direct and indirect rebound effects from efficiency investments made by the average U.S. household to achieve various objectives, such as reducing supply-chain and combustion primary energy, and GHG, NO_x, or SO₂ emissions, assuming domestically produced goods and services with 2002 U.S. economic structure, prices, and environmental impacts. We also show how these rebound effects, in physical units or percentages, vary depending on the fuel or energy carrier saved (whether electricity, natural gas, or gasoline), and other parameters in a sensitivity analysis. Not surprisingly, we find that the direct and indirect rebound effects vary with the policy goal and fuel saved as shown in Fig. 3. Since we treat the direct rebound effect as a parameter (10%) across all four energy and emission cases, we will focus the discussion of results on the indirect rebound effect. Under

our assumptions of a 10% direct rebound from an energy efficiency intervention which reduces household expenditures in either electricity, natural gas, or gasoline, and the U.S. economic structure, energy prices, and electric grid mix of 2002 (of 0.64 kgCO₂e/kWh), the indirect rebound is a similar magnitude (≤10%) as seen in Fig. 4, and there is no indication of backfire, or rebound greater than 100%, i.e. increased energy consumption compared to before the efficiency investment. If the direct rebound effect were much larger (close to 100%), backfire would be possible and indirect rebound effects would be small, as seen in Fig. 5. If we had considered a sustainable consumption measure like eating locally-produced food, which also yielded expenditure savings for the household, the embodied emissions of re-spending and indirect rebound effects would be larger because food is not as energy- and emission-intensive as fuels and electricity. In addition, as energy prices and the U.S. electric grid mix changes, the indirect rebound will also change, as seen in Fig. 6.

A) Gasoline and electricity are the largest portions of the average U.S. household carbon footprint



B) Comparison of household re-spending patterns with 10% reduction in electricity expenditures and 10% direct rebound

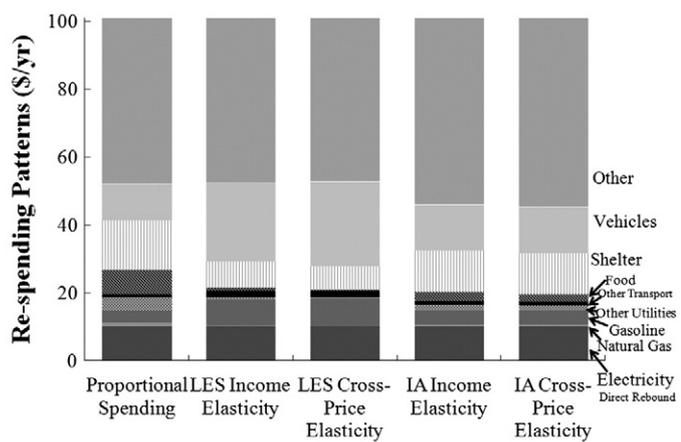


Fig. 2. a–b: (A) 2004 average U.S. household carbon footprint. (B) Comparison of re-spending patterns for electricity service efficiency. Sources/Notes: The 2004 U.S. consumer expenditure survey (CES) data are from BLS (2004) (in \$2002). Embodied emissions are from the 2002 EIO-LCA model (www.eiolca.net). The sets of income elasticities (LES = linear expenditure system; IA = indirect addilog) are from Taylor and Houthakker (2010) using historical U.S. CES data, where LES income elasticities correspond to an upper estimate of the indirect rebound an IA income elasticities correspond to a lower estimate of the indirect rebound.

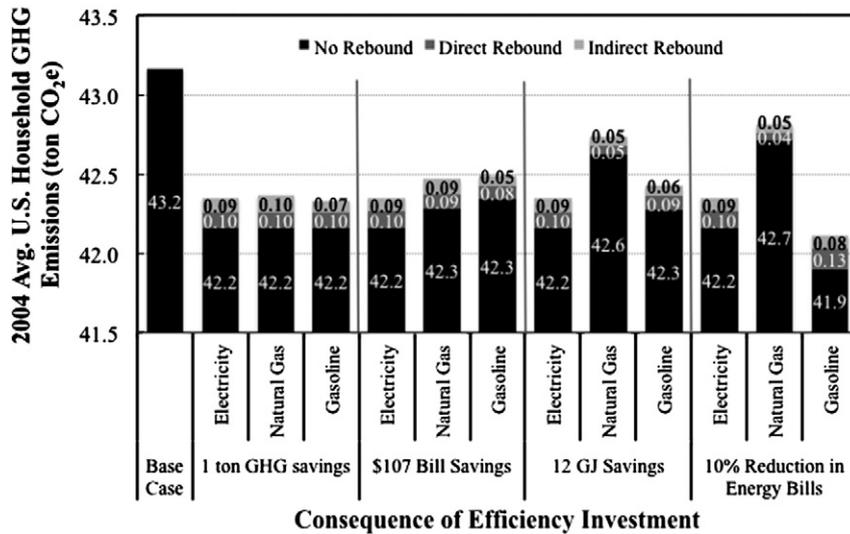


Fig. 3. 2004 average U.S. household embodied GHG emissions with energy efficiency investments in electricity, natural gas, and gasoline services, after accounting for direct and indirect rebound effects. Notes: The base case represents emissions before an efficiency investment, and the four scenarios represent engineering assessments, before accounting for re-spending behavior, of abatement objectives or policy goals to be achieved with efficiency. Sources: Authors' calculations with 2002 purchaser price EIO-LCA model (www.eiolca.net), 2004 Consumer Expenditure Survey (BLS, 2004) in 2002\$, and average of rebound results using five sets of income elasticities from Taylor and Houthakker (2010).

4.1. Indirect Rebound Effects Vary by Policy Goal and Type of Fuel Efficiency

Fig. 3 shows the net embodied (supply chain) CO₂e emissions, after accounting for energy efficiency savings, as well as direct and indirect rebound effects, for four abatement goals or objectives. The abatement objectives, measured from an engineering assessment

and before accounting for the re-spending behavior of households, include energy efficiency measures that lead to

- (1) 1 ton embodied CO₂e emission reductions in a particular fuel
- (2) \$107 (in 2002\$) of annual energy bill savings in a particular fuel

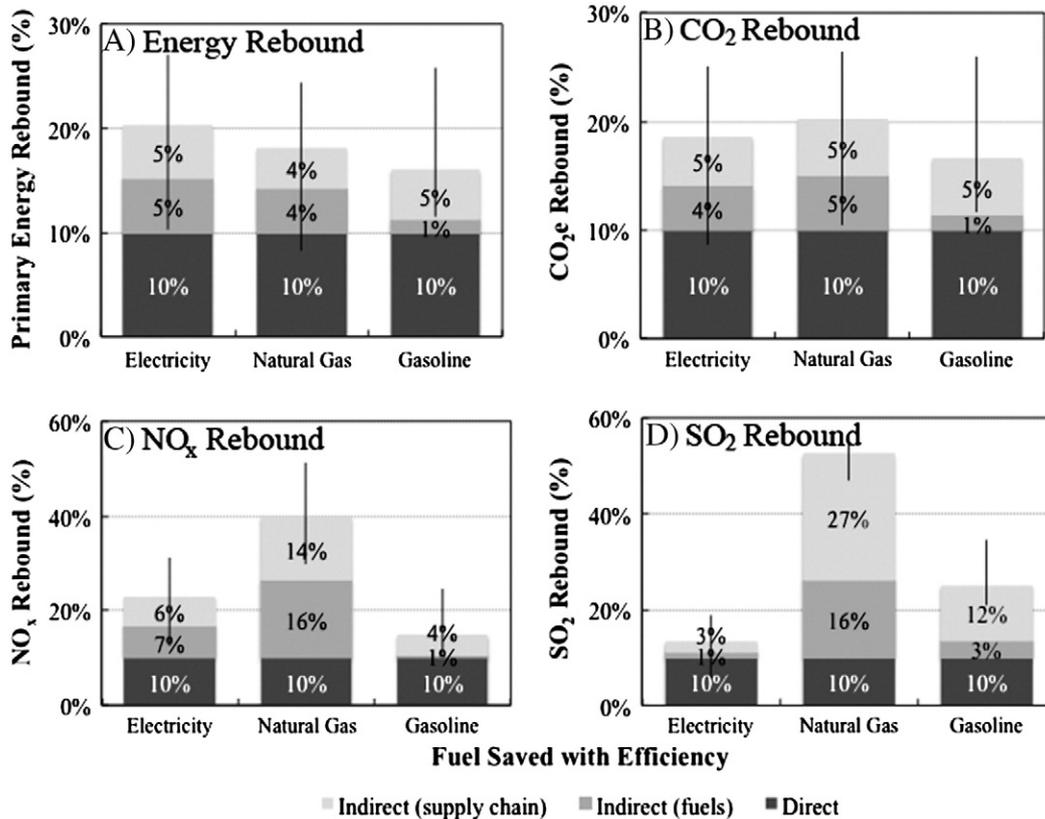


Fig. 4. A–D: Direct and indirect rebound effects vary by fuel type and environmental impact of consumption, whether primary energy or CO₂, NO_x, or SO₂ emissions. Notes: Rebound effects are a percentage of potential energy savings estimated with an engineering or econometric assessment with a static, general equilibrium, fixed price system. Sources: Authors' calculations with www.eiolca.net using 2004 Consumer Expenditure Survey (BLS, 2004). Mean results are the average of indirect rebound effects calculated with five sets of income elasticities, upper error bars use the linear expenditure system (LES) set of income elasticities, and lower error bars use the indirect addilog (IA) set of income elasticities from Taylor and Houthakker (2010). Indirect (fuels) rebound, includes both scope 1 (combustion) and scope 2 (electricity) emissions or primary energy, and indirect (supply chain) rebound also incorporates scope 3 (supply chain) emissions for all goods and services.

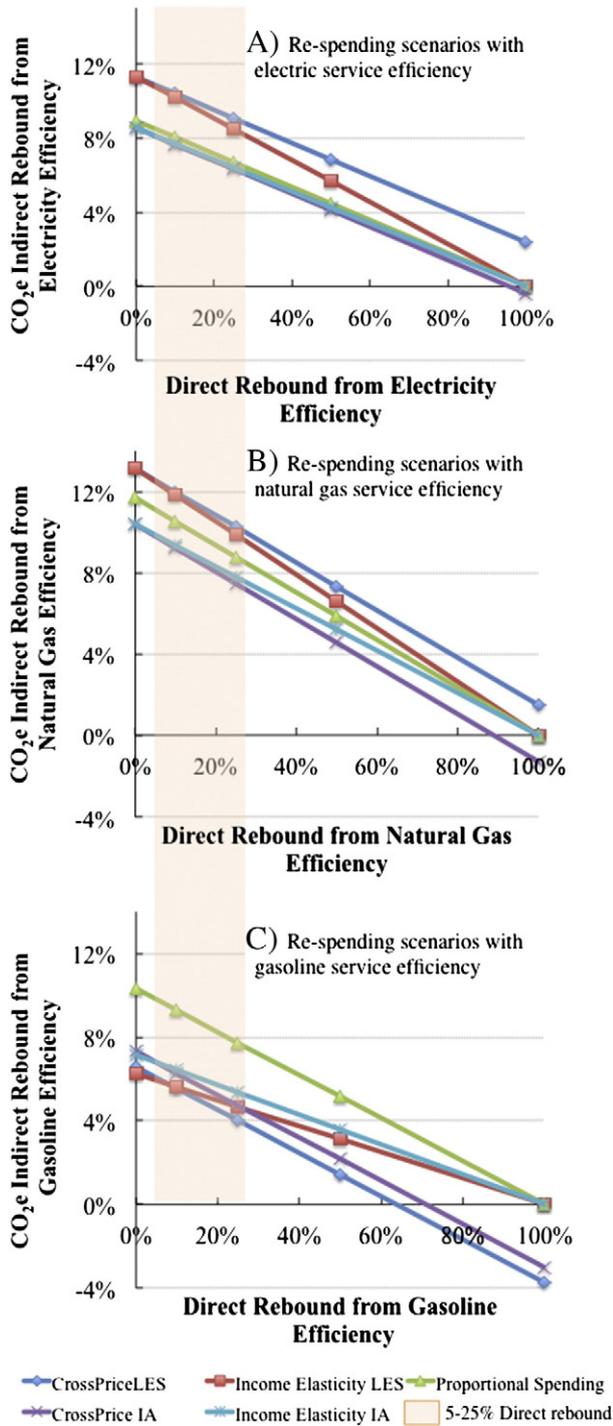
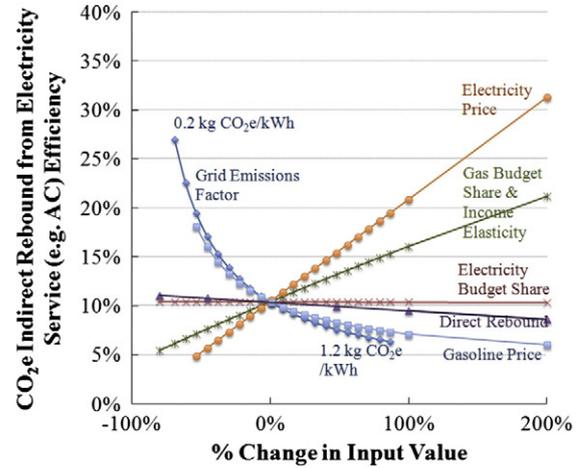


Fig. 5. a–c. Direct and indirect rebound effects for (A) electricity efficiency, (B) natural gas efficiency, and (C) gasoline efficiency under re-spending scenarios using proportional spending, income elasticities, and cross-price elasticities. Sources: Income elasticities using the linear expenditure system (LES) and indirect addilog (IA) demand system models are from Taylor and Houthakker (2010), and budget shares from 2004 Consumer Expenditure Survey (BLS, 2004).

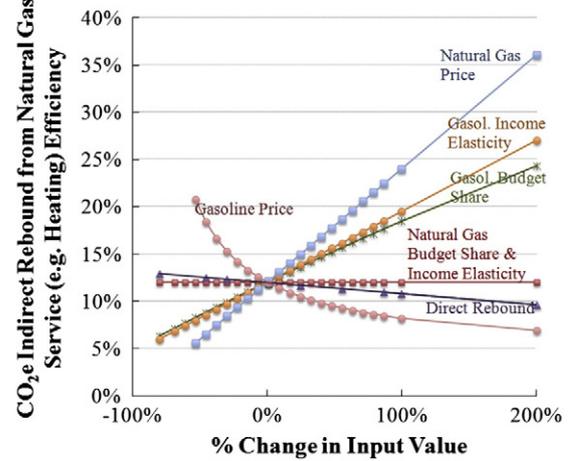
- (3) a 12 GJ reduction in primary energy use with a particular fuel
- (4) a $\tau = 10.5\%$ (rounded to 10%) reduction in energy bills in a particular fuel, assuming constant 2004 energy prices (in 2002\$) and a $\delta = 11.7\%$ improvement in appliance energy efficiency (where $\tau = \delta / (1 + \delta)$; see part 1, Section 4).

The abatement objectives were chosen so that electricity efficiency provides the same level of embodied CO₂e reductions across scenarios,

A) Indirect Rebound for electricity service efficiency



B) Indirect Rebound for natural gas service efficiency



C) Indirect rebound for gasoline service efficiency

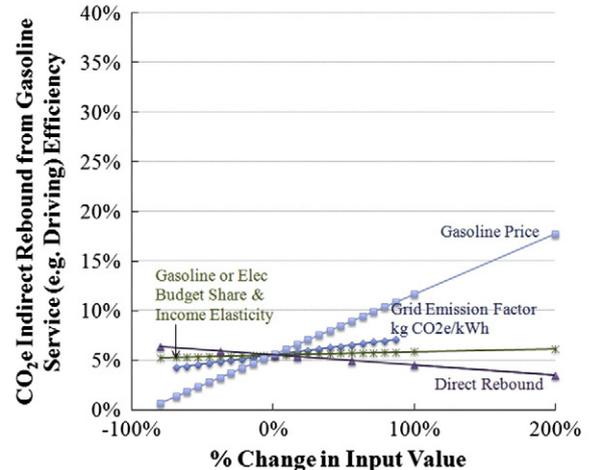


Fig. 6. A–C: Indirect Rebound Effects in CO₂e for efficiency investments reducing average U.S. household expenditures in energy services from (A) electricity, (B) natural gas, and (C) gasoline. Notes: Results assume the 2002 U.S. economic structure and energy prices, and the Linear Expenditure System (LES) set of income elasticities from Taylor and Houthakker (2010). Grid emission factors (GEF) are parametrically varied and used to calculate embodied emissions for other goods in the 2002 EIO-LCA model. Only the most sensitive input parameters are shown.

and to provide a comparison with other types of fuel efficiency investments. The percentage of appliance efficiency improvement, δ , and corresponding percentage of energy cost savings, τ , varies by fuel for each

of these abatement objectives, except for the electricity efficiency cases, and for the fourth objective.

Fig. 3 shows that that the variations in net supply chain CO₂e emission after accounting for direct and indirect rebound effects by type of fuel efficiency are greatest for the third and fourth scenarios, for abatement objectives framed in terms of reductions in primary energy consumption, or as a percentage reduction in energy bills for a fuel.

The differences in net CO₂e emissions across energy efficiency interventions in Fig. 3 largely stem from the relative differences in CO₂e intensity per joule (J) of primary energy of the fuel, household budget share for the fuel, and 2004 commodity prices (in 2002\$), with direct and indirect rebound effects appearing as smaller effects. For example, since the average U.S. household's annual expenditures on gasoline are much higher than for electricity and natural gas, a policy goal framed in terms of percent reductions in residential energy consumption or expenditures will result in the greatest CO₂e emission reductions with efficiency in gasoline-fueled vehicles, even after accounting for responding behavior, i.e. direct and indirect rebound effects. Natural gas efficiency appears to result in the fewest net CO₂e reductions, because it forms a smaller portion of the household's budget (see Appendix A) and is less CO₂e-intensive fuel per joule of primary energy than either electricity or gasoline.

Fig. 4a–d shows the direct and indirect rebound effects in percent, for all three fuels considered in terms of primary energy, CO₂e, NO_x, and SO₂ emissions. The error bars represent a 15% range in direct rebound effects and a smaller 1–3% range in indirect rebound effects computed using different systems of income elasticity estimates from Taylor and Houthakker (2010). As implied by Eq. (4), the percentage rebound does not depend on the percent reduction in energy bills, τ , resulting from an efficiency investment saving a particular fuel under constant market prices for energy.

Indirect rebound effects are divided into an indirect-fuels portion, which includes combustion (scope 1) emissions from re-spending energy cost savings on other fuels and electricity emissions (scope 2) from re-spending on electricity services, and an indirect-supply chain portion, which includes supply chain (scope 3) emissions embodied in purchases of all other goods. Indirect rebound estimates using scope 1–3 emissions can be more than 50% higher than estimates using scope 1 combustion emissions for natural gas or gasoline and scope 2 emissions for electricity alone (labeled the indirect-fuels portion).

Fig. 4a–b shows that rebound effects are modest in primary energy consumption and GHG emissions for all three fuels considered. The indirect rebound effects from electricity and natural gas efficiency are due to re-spending of energy cost savings on transportation and miscellaneous services, which constitute the largest portions of the next dollar spent (see Table 1). Gasoline efficiency results in the smallest indirect rebound effect because re-spending in gasoline is counted as the direct rebound effect, and as household substitutes into gasoline and its complements it also substitutes out of electricity and natural gas, resulting in a lower level of emissions for these expenditure categories than in the no-rebound case. The only potentially large (>20%) indirect rebound effects are in NO_x and SO₂ emissions, shown in Fig. 4c–d, for the case of natural gas efficiency, due to re-spending natural gas cost savings on substitute goods such as electricity, the largest source of SO₂ emissions, or gasoline, the largest source of NO_x emissions per dollar of expenditure.

4.2. Responding Scenarios for Direct and Indirect Rebound Effects

In Fig. 5a–c, we compare three scenarios by which households could respond energy cost savings from an efficiency investment, shown in Eqs. ((2)–(4)). Not surprisingly, the higher the direct rebound effect, the lower the indirect rebound effect, since the greater the increase in household energy service demand, the lower the energy cost savings available for responding on other goods, assuming the same level of expenditures before and after the efficiency investment.

Fig. 5 illustrates the relationship between indirect CO₂e rebound effects from electricity efficiency, and the direct rebound parameter, which varies between 0 and 1.0. Fig. 5 also compares indirect rebound estimates for electricity, gasoline, and natural gas efficiency under assumptions of proportional re-spending (PS), income elasticity re-spending (IE), and our cross-price elasticity model (CP).

The indirect rebound effect depends on the carbon-intensity and pattern of re-spending with different types of efficiency investments, as predicted by the PS, IE, and CP re-spending scenarios. The PS scenario overestimates re-spending on carbon-intensive activities such as food, electricity, and natural gas, and underestimates re-spending on carbon-intensive gasoline, relative to the IE and CP scenarios, as seen in Figure 3. For natural gas and (to a lesser extent) electricity efficiency, these effects largely offset each other and the indirect rebound effects with PS are within range predicted by IE and CP scenarios. However, for gasoline efficiency, re-spending on gasoline is considered part of the direct rebound, and the remaining pattern of spending with the IE and CP assumptions is less carbon intensive than the PS assumption would predict. We consider PS to be a reasonable assumption for natural gas efficiency, but IE or CP to be more appropriate for modeling re-spending of the monetary savings from electricity and gasoline efficiency.

Within a plausible 5–25% range for the direct rebound effect, highlighted in Fig. 5, the IE method is very similar to our CP method, implying that with our assumption of constant cross-price elasticities for non-energy services, substitution effects are small and income effects dominate. Future work could empirically test this assumption or develop alternate methods for constructing cross-price elasticities. In cases where the direct rebound effect is higher than the 5–25% range, such as for low-income households or in developing countries, substitution effects may be more important, but then direct rebound effects are more important than indirect effects. Scholars have found evidence of large but declining direct rebound effects from historical price and income elasticity studies of lighting and transport service demand (Fouquet, 2012; Fouquet and Pearson, 2012; Tsao et al., 2010).

Only the cross-price elasticity model is flexible enough to allow for the possibility of backfire, or rebound greater than 100% (Saunders, 2000) with a direct rebound near 100%. The only cases in which backfire could occur is with efficiency in electricity services or natural gas services, and using the Linear Expenditure System (LES) income elasticities measured by Taylor and Houthakker (2010) in our constructed cross-price elasticity re-spending scenario, since the LES predicts highly elastic gasoline demand as incomes rise.

The rebound results in this study are for the average U.S. household. Of course, an individual household may experience a higher or lower indirect rebound effect depending on their spending patterns. Re-spending electricity cost savings from an efficiency investment entirely on natural gas for home heating or gasoline for personal travel, would lead to indirect rebound effects in GHG emissions as high as $Z_{ng}/Z_{elec} = 94\%$ and $Z_{gas}/Z_{elec} = 87\%$, respectively, where Z_{ng} , Z_{gas} , and Z_{elec} represent the embodied emissions per dollar of expenditure, E_s , for each efficiency type (see Appendix A).

4.3. Sensitivity Analyses for the Indirect Rebound Effect

The results in Figs. 3 and 4a–d were obtained with the 2002 EIO-LCA model estimates of embodied energy and emissions for the U.S. economy, assuming 2002 prices, household spending patterns in 2004 (in 2002\$), and the 2002 U.S. economic structure. In Fig. 6a–c, we exogenously vary direct production emissions from electricity, v_s , i.e. the grid emission factor in kg CO₂e/kWh divided by 2002 electricity prices, in the EIO-LCA model to estimate the embodied emissions per dollar of expenditure, z_s and z_o , for all other goods for a scenario in which the U.S. uniformly reduces its CO₂e emissions from electricity across states.

As Fig. 6a–c shows, the indirect rebound effect in CO₂e emissions for each of the three fuels is sensitive to grid emission factor (GEF), fuel/energy carrier prices, and gasoline budget shares and income

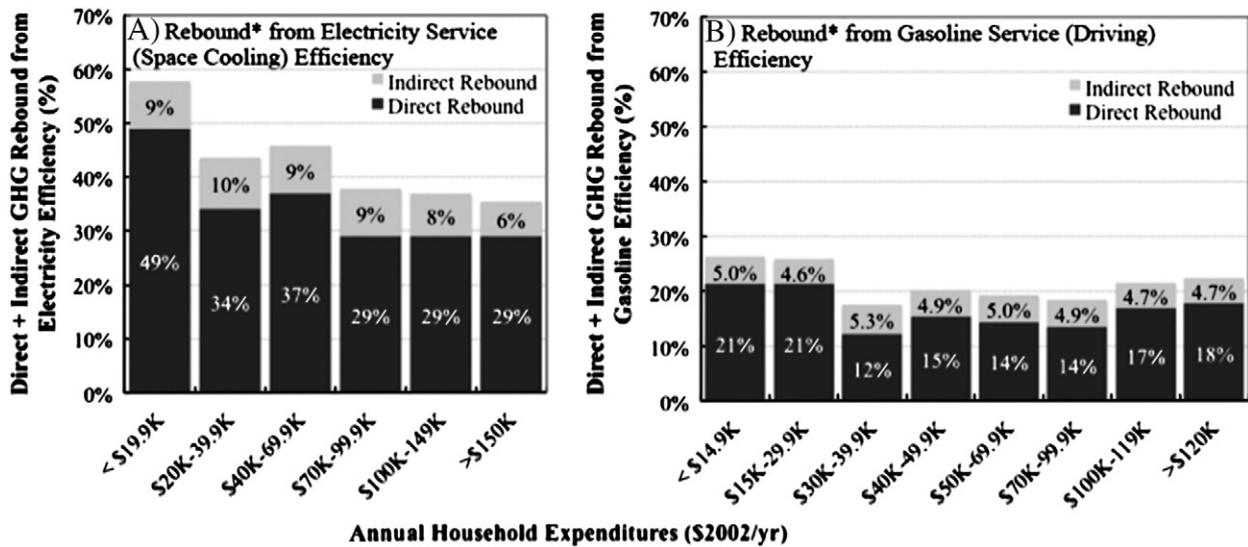


Fig. 7. A–B: Direct and indirect rebound effects in (A) electricity efficiency and (B) gasoline efficiency decline with income. Sources/Notes: *Direct rebound is likely overestimated due to use of own-price elasticity of electricity and gasoline from Reiss and White (2005) and Gillingham (2011). Income elasticities are from Taylor and Houthakker (2010), and budget shares are from 2004 Consumer Expenditure Survey (BLS, 2004).

elasticities, with GEFs and prices being the strongest upward drivers of CO₂e indirect rebound effects in percent. CO₂e indirect rebound effects are fairly robust to differences in electricity and natural gas budget shares and income elasticities. It is not surprising that indirect rebound effects from electricity service efficiency vary considerably with GEF, as this is another dimension of the diminishing marginal (emission abatement) returns to energy efficiency, as the electric grid becomes less GHG-intensive.

The GEF varies considerably among U.S. states and between countries, and gasoline budget shares will vary greatly across regions and individuals, so these sensitivity analyses support the need for further regional and microsimulation studies of the indirect rebound effect, as our study is limited to considering domestically produced goods and the spending patterns of the average U.S. household. As the U.S. electric grid mix becomes less GHG-intensive (and perhaps more expensive), a new equilibrium will be reached, perhaps with a lower level of household expenditure on energy, and less-energy intensive industrial processes used to make other goods. However, these sensitivity analyses do not consider changes in household budget shares and firm production functions as fuel or electricity prices change, due to the static, fixed price structure of EIO-LCA.

The indirect rebound effect also depends on the price of energy commodities relative to other fuels, as higher prices lead to greater energy expenditure savings that can be re-spent on other goods. For example, Fig. 6c suggests that at the 2011 retail gasoline price of \$3.6/gal (EIA, 2012), which is double the 2002 gasoline price in real terms, the indirect rebound effect from gasoline efficiency would increase to 17%, compared to 5% with 2002 prices. As gasoline prices increase, this may lead to greater efficiency and conservation in household gasoline use, and changes in the price of transportation-intensive goods, which may lead to second order offsetting effects not captured in the sensitivity analysis.

4.4. Direct and Indirect Rebound Effects Vary by Household Income

Fig. 7a–b demonstrates the variation in the direct and indirect rebound effects by household income, using the 2004 CES summary tables by income (BLS, 2004). Lower-income groups have a slightly higher CO₂e rebound in percentage terms, as expected, since they are furthest away from satiation of energy services (Khazzoom, 1980; Wörsdorfer, 2010). The direct and indirect rebound effect for electricity efficiency varies between 35 and 60% for various income brackets. However, by using electricity price elasticities rather than price elasticities for electricity

services, such as heating or lighting, we overestimate the direct rebound (Hanly et al., 2002) and understate the indirect rebound effects for electricity efficiency. The direct and indirect rebound effect for gasoline efficiency, using a price elasticity of driving (Gillingham, 2011) is relatively insensitive to income, and varies between 15 and 25%.

The income variation of the rebound effect is largely driven by the heterogeneous own-price elasticity estimates for electricity (Reiss and White, 2005) and driving (Gillingham, 2011) by income bracket. Reiss and White's (2005) own-price elasticity estimates for electricity show greater than the variation by income than Gillingham's (2011) estimates for driving, thus there is a smaller variation in the rebound effect for gasoline efficiency by income. When constant own-price elasticities are used to estimate rebound effects, the variation by income group is limited, since the differences in GHG emissions per dollar of expenditure by income brackets are minimal.

While lower income groups may have higher direct and indirect rebound effects in the percent, the consequences of these rebound effects, i.e. the difference between potential and actual supply chain CO₂e emission savings, reveal the importance of the scale of baseline emissions. Fig. 8 demonstrates that for a 10% reduction in household electricity

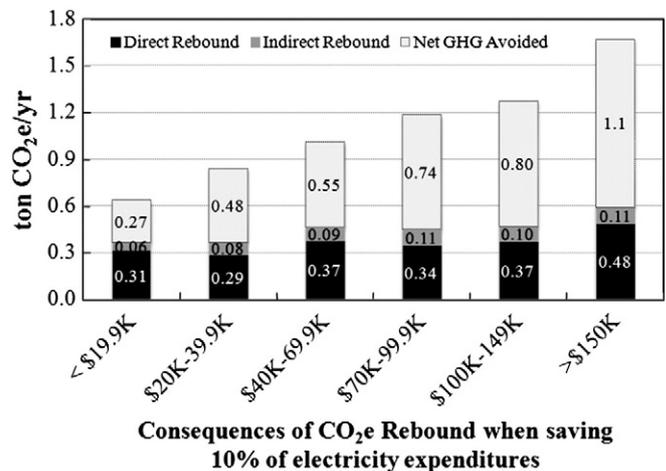


Fig. 8. Consequences in CO₂e emissions of direct and indirect rebound effects from reducing 10% of annual electricity bills with efficiency for the average household in each income bracket. Sources: 2004 Consumer Expenditure Survey; www.eiolca.net; Reiss and White (2005).

bills, the direct and indirect rebound in CO₂e emissions are 0.45–0.59 ton CO₂e/yr for households with incomes greater than \$70,000/yr (in 2002 \$), compared to a direct and indirect rebound of 0.37 ton CO₂e/year for the households that would be eligible for energy assistance programs, with incomes less than \$40,000/year. While efficiency investments in low-income households may not reduce electricity demand as much or as cost-effectively as in high-income households, the consequences of higher percent CO₂e rebound effects in low-income households for the climate change problem are relatively small. Instead, efficiency investments in low-income households help to alleviate energy poverty in households that spend over 10% of their budget on energy bills.

Of course a 10% reduction in electricity bills in mid to high income households also yield higher net CO₂e emission savings of 0.74–1.1 kg CO₂e/yr after accounting for direct and indirect rebound effects, compared to net savings of just 0.27–0.48 kg CO₂e/yr for a comparable efficiency investment made in a low-income household. This highlights the need to target energy efficiency programs for the greatest electricity users in a utility service area. Weatherization programs may be more useful for helping low-income households escape energy poverty than for reducing energy consumption and CO₂e emissions.

5. Discussion and Conclusion

5.1. Reliability of the Results

There are several sources of uncertainty that limit the reliability of our results. Among the first are the uncertainties inherent in an EEIO model, reviewed by Lenzen (2000) and Weber and Matthews (2008), which stem from aggregation of sectors, vintage lags between emission data and IO tables, the linear production function assumption, and changes in structure and production functions of the economy as technology progresses and prices change. The assumption of domestic production of goods (or similar production functions for imports and domestic goods) is particularly problematic since Weber and Matthews (2008) have shown that up to 30% of U.S. household carbon footprints can be attributed to imports, using the same 2004 CES data as in this study. If imports are produced in a more carbon-intensive production process than domestically produced goods, this could increase the indirect rebound effect from the estimates provided in this paper.

In addition, using aggregate CES data masks the considerable variation in spending patterns across households. The income elasticities, direct rebound parameter, and the cross-price elasticities that they imply may not adequately represent the behavior of households in the 2004 CES or future spending patterns. Since the CES data does not contain price information for the various commodities purchased by households, income elasticity estimates obtained from the CES micro data without controlling for price may be biased if incomes and prices for goods and correlated. Econometric studies similar to the AIDS model which augment the CES data with price indices, and appliance efficiency trends may obtain better direct rebound parameters and cross-price and income elasticity estimates from microdata, but at the expense of further aggregating sectors according to the availability of price data.

Thirdly, we make a strong assumption of constant cross-price elasticity for other goods to model the indirect rebound effect. This approach could be complemented with (AIDS-type) econometric studies and other approaches to constructing cross price elasticities (Tarr, 1990) in order to understand the cases in which substitution effects are important for empirical estimates of the indirect rebound effect. Sensitivity analyses in this study indicate that the relationship between home energy demand and vehicle and other travel is of particular importance as gasoline price elasticities and budget shares strongly influence our indirect rebound effect estimates, as does the generation mix of the U.S. electric grid. Our indirect rebound estimates are likely to be lower than those of prior indirect rebound studies (Alfredsson, 2004; Chitnis et al., 2012; Druckman et al., 2011; Freire-Gonzalez, 2011; Girod and de Haan, 2010; Murray, 2011; Nässén

and Holmberg, 2009) because of our focus on the U.S., which generally has lower energy prices and a more carbon-intensive electric grid, so that energy efficiency interventions reduce more energy and emissions for a given reduction in energy expenditures.

5.2. Relevance of Results

Contrary to Brannlund et al. (2007), this study shows that residential energy efficiency investments do lead to a reduction in primary energy consumption or CO₂e, NO_x, or SO₂ emissions – there is no evidence of backfire or rebound greater than 100% – while direct rebound effects are on the order of 10%, as found in prior studies in the U.S. Backfire only occurs when direct rebound effects are close to 100% and U.S. households exhibit high (>2) income elasticities for driving, at 2002 prices, electric grid mix, and U.S. economic structure. Thus, current energy efficiency incentives in the U.S. residential sector should be able to reduce supply chain energy and emissions after accounting for rebound effects, unless all those who participate in such programs are free-riders, i.e. households that capture incentives for efficiency investments that they would have made anyway. We find relatively modest direct and indirect rebound effects of 15–25%, although indirect rebound effects in NO_x or SO₂ emissions as large as 30–40% are possible for efficiency in natural gas services. Since our analysis ignores the effect of higher capital costs for efficient appliances or vehicles, and, our results tend to overestimate the extent the direct and indirect rebound effects (Chitnis et al., 2012; Henly et al., 1988; Mizobuchi, 2008).

We also show that the proportional re-spending case, typically used in industrial ecology studies of the rebound effect, is fairly accurate for natural gas efficiency, may underestimate the indirect rebound effect for electricity efficiency, and overestimate the indirect rebound effect for gasoline efficiency, due to the differences in patterns of spending implied by income elasticities. Income elasticity spending appears to be a good representation of re-spending effects, in situations in which the direct rebound effect is small (<25%). The substitution effects implied by the cross-price elasticity model developed in part one of this two-part paper are small, except at high direct rebound effects that may apply for low-income households or in developing countries.

Furthermore, we have shown that direct and indirect rebound effects are inversely proportional, so that the larger the direct rebound, the smaller the indirect rebound. As household incomes rise, the direct rebound effect is expected to decline as households reach satiation of existing energy services (Small and van Dender, 2007). As energy prices increase or the U.S. electric grid mix switches to less carbon-intensive resources, our results show that the indirect rebound effect will increase. It remains to be seen which effect dominates over time for electricity, natural gas, and gasoline efficiency. We also find that a focus on the rebound effect in percentage terms is highly misleading in regions with different energy prices and different baseline levels of energy consumption and income, and should be augmented with estimates of the consequences of the rebound effect in primary energy consumption or emissions.

Households experience a rebound effect because they can achieve greater economic utility from increased demand for energy services and other goods. If the rebound effect lowers social welfare, this is due to the externalities imposed by energy consumption in general and could be addressed with carbon or emission taxes, cap-and-trade policies, or other mechanisms to price the externality at the social cost. Van den bergh (2011) argues that emission trading schemes, which cap energy consumption and emissions, are better than carbon taxes given the possibility of rebound effects. However, policies explicitly designed to counter rebound effects may not be necessary if externalities, such as carbon dioxide and criteria air pollutants, were priced at the social cost, so that any rebound effects that occur would unambiguously increase households' welfare.

An important consideration from the policymaker or utility manager's perspective is the cost-effectiveness of energy efficiency relative to

investments in new energy supply or pollution control equipment in meeting reliable energy supply, reduced air pollution, and climate change mitigation goals. Further research on the cost-effectiveness of energy efficiency relative to low-carbon energy supply can guide decisions about the optimal level of investment in these technologies to meet climate change mitigation, energy security, and air pollution reduction goals.

Several energy efficiency options will have net economic savings over the course of their useful lifetime, and our work shows that these will lead to low rebound effects. Thus such energy efficiency strategies should be pursued as a means to reduce carbon emissions. However, even the wide deployment of those cost-saving efficiency options won't be sufficient to lead to the large emission reductions necessary to curb greenhouse emissions to a level that would avoid potentially dangerous climate change consequences. In order to do so, a portfolio of climate change mitigation strategies is needed.

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Appendix A

Table A.1

Primary energy-, CO₂e-, NO_x-, and SO₂-intensities, E_s and E_o, per dollar of household expenditure for 13 categories.

2004 annual expenditures						
Expenditure category	(02\$)	w _o	MJ/\$	kg CO ₂ e/\$	g NO _x /\$	g SO ₂ /\$
Food, Bev	3227	8%	11	1.3	2.6	1.8
Shelter, furniture, maint	6381	15%	3	0.2	0.6	0.7
Appliances	1036	3%	7	0.4	1.3	1.1
Electricity	1014	2%	111	9.4	18.1	36.8
Natural gas, fuel oil	519	1%	144	8.2	8.2	3.4
Other utilities	1704	4%	6	0.6	0.9	1.0
Gasoline	1575	4%	110	7.7	24.6	7.5
Transportation equip & fees	4696	11%	7	0.5	1.5	1.2
Public transit	80	0%	32	1.9	18.9	2.0
Air, water transportation	312	1%	31	2.1	8.0	3.2
Health care	1625	4%	4	0.3	0.8	0.7
Financial services	8370	20%	2	0.1	0.3	0.3
Miscellaneous	10,792	26%	7	0.5	1.2	1.2
<i>Mean expenditures</i>						
Non-electricity			12	0.8	2.2	1.2
Non-natural gas			12	1.0	2.5	2.1
Non-gasoline			10	0.8	1.7	1.9
<i>Marginal (weighted by $\epsilon_{i,0}$) expenditures</i>						
Non-electricity			16	1.1	3.3	1.6
Non-natural Gas			16	1.1	3.4	1.7
Non-gasoline			6	0.5	1.3	1.1

Sources: Emissions/\$ from EIO-LCA02 (Hendrickson et al., 2006; www.eiolca.net) and combustion emissions; U.S. household expenditure 11 shares (w_o) from the U.S. Consumer Expenditure Survey (BLS, 2004) in (2002\$); $\epsilon_{i,0}$ from Linear Expenditure System results from Taylor and Houthakker, 2010.

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