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Analysis

Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: Theoretical framework

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ABSTRACT

This is the first part of a two-part paper providing an analytical model of the indirect rebound effect, given a direct rebound estimate, that integrates consumer demand theory with the embodied energy of household spending from environmentally-extended input–output analysis. The second part applies the model developed in part one to simulate the direct and indirect rebound for the average U.S. household in terms of primary energy, CO_2e, NO_x, and SO_2 emissions and for energy efficiency investments in electricity, natural gas, or gasoline services. Part one provides a critical review of the largely independent economic and industrial ecology literatures on the indirect rebound. By studying the two-goods case and the n-goods case, we demonstrate that the indirect rebound is bounded by the consumer budget constraint, and inversely related to the direct rebound. We also compare the common proportional spending and income elasticity spending assumptions with our model of cross-price elasticities including both substitution and income effects for the indirect rebound. By assuming zero incremental capital costs and the same embodied energy as conventional technologies for efficient appliances, we model an upper bound of the indirect rebound. Future work should also consider the increase in consumer welfare possible through the rebound effect.

1. Introduction

Many policymakers support energy efficiency policies as a cost-effective method to reduce energy consumption, criteria air pollutant emissions, and greenhouse gas emissions (GHG, measured in CO_2-equivalents) to mitigate climate change, while providing economical energy services (e.g., lighting, heating, transportation). For example, the International Energy Agency (IEA) projects that by 2030, one half of the lowest-cost GHG abatement options in Organization for Economic Cooperation and Development (OECD) countries will come from energy efficiency, largely in end use technologies (International Energy Agency, IEA, 2009). However, there is a well-established gap between the technical, economic, and feasible potential for energy efficiency because of market failures, market barriers, stock turnover issues, behavioral patterns (Azevedo, 2009; Gillingham et al., 2009; Greene, 2011; Howarth and Sanstad, 1995; Jaffe and Stavins, 1994; NAS, 2009; Sanstad et al., 1995; Sorrell, 2004), and the difference between laboratory and real-world conditions (Vine et al., 1994), which is called "shortfall" (Sorrell et al., 2009). In addition, there is a debate among scholars and policymakers about whether energy efficiency investments are able to lower energy consumption due to changes in consumer behavior in what is known as the rebound effect (R). The rebound effect accounts for a gap between engineering assessments of potential energy savings (PES) after accounting for shortfall, and actual energy savings (AES) (Guerra and Sancho, 2010; Sommerville, 2007), where

$$R = 1 - \frac{AES}{PES}. \tag{1}$$

Given the heavy reliance on energy efficiency in many countries to meet long-term GHG abatement and other energy policy goals, it is important to understand the extent of the rebound effect.

The rebound effect, decomposed into direct, indirect, and economy-wide components, describes the change in energy demand following an efficiency investment due to behavioral changes and economic effects. The *direct rebound effect* describes the increase in the demand for energy services due to the lower price of energy services with an efficiency investment (Berkhout et al., 2000; Greening et al., 2000; Khazzoom, 1980; Sorrell and Dimitropoulos, 2008), e.g. the owner of a fuel-efficient vehicle may increase his miles driven per year, relative to his behavior with a conventional vehicle, because the fuel cost per mile driven has decreased. The *indirect rebound effect* describes the re-spending of energy cost savings on other goods (Berkhout et al., 2000; Binswanger, 2001; Chalkley et al., 2001; Druckman et al., 2011; Greening et al., 2000; Schipper and Grubb, 2000), e.g. spending gasoline cost savings on an overseas vacation, which in turn requires additional energy and associate emissions for its provision. The *economy-wide rebound effect* includes both the direct and indirect effects as well as macroeconomic effects such as the energy consumption induced

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by a lower market price for energy, changes in economic structure, economic-competiveness (Allan et al., 2007; Brookes, 1990, 2000; Howarth, 1997; Saunders, 1992, 2000, 2008, 2010; Wei, 2010), investment and disinvestment, and labor market changes resulting from energy efficiency investments (Turner, 2009). In this analysis, we focus on direct and indirect rebound effects for a household whose energy efficiency investments would have marginal impacts on market energy prices, i.e. the household is a price-taker, and so economy-wide rebound effects do not apply. Although, direct and indirect rebound effects may also arise from efficiency investments in production processes, which influence firms' production factor choices, and may change the prices of intermediate and final goods faced by producers and consumers (Berkhout et al., 2000; Greening et al., 2000; Safarzynska, 2012), in this paper, we restrict our attention to the rebound effects from efficiency investments in residential energy end-uses such as electric air conditioning, natural gas heating, and gasoline-based transportation. Van den Bergh (2011) provides a comprehensive taxonomy of 14 mechanisms for the energy efficiency rebound effect. Rebound effects greater than 100%, a special case with greater energy consumption than before the energy efficiency investment was made, is called "backfire" (Khazzoom, 1980; Saunders, 2000; Sorrell, 2009).

The simple rebound definition in Eq. (1) requires a well-defined time period and boundary of analysis. The rebound effect can be measured in the short-run, including changes in energy service demand, and in the long-run, incorporating capital costs and increasing market saturation of appliances. Over decade- or century-long time frames, scholars suggest that the demand for lighting and personal transport has increased significantly and find evidence of large direct rebound effects, but price and income elasticities for energy services have been declining in recent decades (Fouquet, 2012; Fouquet and Pearson, 2012; Small and Van Dender, 2007; Tsao et al., 2010). Most studies of the rebound effect focus on changes in the marginal price of energy services, and disregard the income constraints imposed by the possibly higher investment costs of an energy efficient technology. Researchers who investigate how capital costs affect the rebound effect find, not surprisingly, that the higher capital cost of efficient technologies may lower the extent of the direct and indirect rebound effects (Chitnis et al., 2012; Henly et al., 1988; Mizobuchi, 2008; Nässén and Holmberg, 2009; Wirl, 1997) although methods for incorporation of capital costs in energy demand and energy service demand models are an open area of research. In this paper, we develop an analytical model of the direct and indirect rebound effects for consumers, excluding incremental capital costs for efficiency and household budget savings, from a static, fixed-price, general equilibrium perspective, by integrating methods from industrial ecology with microeconomics. By ignoring incremental capital costs for efficiency investments, our indirect rebound model develops an upper bound estimate (Chitnis et al., 2012; Henly et al., 1988; Mizobuchi, 2008).

This focus of this two-part paper is on the indirect, or re-spending, rebound effect and its relationship to the direct rebound effect. There are two different strategies used in the economic and industrial ecology literatures to interpret and measure the indirect rebound. In the economic literature, the indirect rebound effect is defined as the energy or emissions impacts from the *marginal* changes in spending under a fall in the price of energy (which is assumed to be equivalent to an increase in energy efficiency), and is jointly estimated with the direct rebound effect. In contrast, in the industrial ecology literature, the indirect rebound effect is attributed to the *supply-chain* or *embodied* energy or emissions from *average* spending patterns, independent of price changes and the direct rebound effect. In this two-part paper, we highlight the strengths and limitations of previous methods and integrate both the price effects from the economic literature with the embodied energy framework from the industrial ecology literature to model the indirect rebound effect.

In part one, we analyze consumer demand under a price change with the Slutsky decomposition of income and substitution effects in a static, general equilibrium framework to show that the direct and indirect rebound effects are linked, and that the indirect rebound effect is bounded by the consumer budget constraint and direct rebound effect. In part two, we apply the methods from part one in a numerical simulation of the indirect rebound effect using a U.S. economic input–output life-cycle assessment model for the year 2002 to estimate embodied energy and emissions from spending (Hendrickson et al., 2006; www.eiolca.net), the 2004 Consumer Expenditure survey (in 2002$) on average household spending patterns (BLS, 2004), and literature on direct rebound effects and the marginal spending patterns as incomes rise. We conduct sensitivity analyses to demonstrate when the indirect rebound will be negligible vs. when it will be comparable to or greater than the direct rebound effect.

In the remainder of part one of this two-part paper, we provide a critical review of direct rebound effect studies in Section 2, and direct and indirect rebound studies in the economic and industrial ecology literatures in Section 3. Then, we analyze the direct and indirect rebound effects in terms of income and substitution effects for the two-goods case in Section 4. Section 5 extends the analysis to the n-goods case, comparing different approximations of the indirect rebound effect, from the literature and our own approach, which vary in terms of the degree of substitution effects and Section 6 concludes.

2. Direct Rebound Effects

There has been considerable empirical research on the direct rebound effect, measured in terms of efficiency elasticities, energy service price elasticities, and energy price elasticities (Sorrell and Dimitropoulos, 2008) and using a variety of theoretical frameworks (Sorrell, 2007). Two issues important to evaluating this literature include (1) the definition of the direct rebound effect used in empirical measurement and (2) the treatment of self-selection in energy efficiency investments. Sorrell and Dimitropoulos (2008) argue that the appropriate measure of the direct rebound effect is an energy efficiency elasticity, which is equivalent to an energy service price elasticity (i.e. an operating cost elasticity) under exogenous market prices for energy. Henly et al. (1988) argue that energy price elasticities can also measure the direct rebound effect in econometric models that control for changes in efficiency. Self-selection describes the notion that rational consumers with higher energy prices and demand are more likely to invest in energy efficiency. Observational studies of energy demand that claim to measure the direct rebound effect must be careful to control for self-selection. The best studies make use of a field experiment in which energy efficient technologies were randomly assigned to consumers (Dubin et al., 1986) or compare the same households before and after an efficiency investment was made (Davis, 2008), to avoid the self-selection bias.

Scholars have found that the direct rebound effect varies by region, with generally higher rebound effects found in developing countries (Allan et al., 2007; Davis et al., 2012; Roy, 2000; Wang et al., 2012), and in low-income households in developed nations (Frondel et al., 2010; Gillingham, 2011; Greene, 2012; Hirst et al., 1985; Small and van Dender, 2005, 2007) where the demand for energy services is furthest from satiation. Direct rebound effects also depend on the energy service considered, with heating and cooling more prone to rebound effects than refrigeration, a baseline end-use, and clothes washing and drying, a time-intensive end-use (Davis, 2008; Davis et al., 2012; Greening et al., 2000; Schipper and Grubb, 2000; Sorrell, 2007). Rebound effects in terms of time use have also been studied (Jalas, 2002), but are outside the scope of this study.

"Consensus" estimates of the direct rebound effect depend on the method used. Scholars comparing household billing records before and after utility-sponsored energy efficiency program find that behavioral changes such as turning up the thermostat for increasing comfort lead to direct rebound estimates from as low as 1–3% (Dinan and Trumble, 1989) to a level of 10–15% (Hirst et al., 1985). Other scholars use simplified engineering models of building efficiency with econometric analysis of household billing data to measure direct rebound effects in terms of efficiency elasticities of 1–3% for electric space heating (Schwartz and Taylor, 1995). Dubin et al. (1986) exploit a field experiment with a control group in Florida to measure a direct rebound in terms of energy service price elasticities of 2–13% for electric cooling and 8–12% for electric heating. Davis (2008) exploits a field experiment in Kansas, which measured energy and water consumption before and after households received a high-efficiency clothes washer, to measure a 6% energy price elasticity, controlling for efficiency change, which can also serve as an unbiased measure of the direct rebound effect (Henly et al., 1988; Small and van Dender, 2007). By experimental design, both of these studies control for self-selection. In the transportation sector, with greater availability of data on energy service demand (vehicle-miles traveled) and vehicle efficiency (fuel economy), scholars have found direct rebound estimates in the 3–20% range, with differences stemming from short-run versus long-run effects, and the vintage of the data (Gillingham, 2011; Greene, 2012; Haughton and Sarkar, 1996; Small and van Dender, 2007; Schmiek, 1996). For example, in the 1997–2001 time frame, Small and van Dender (2007) find a direct rebound effect of 2–11%, and argue that direct rebound effects in personal transportation are declining due to rising real income and low fuel prices.

There is a larger body of economic literature that fails to account for self-selection when measuring energy price elasticities as proxy for the direct rebound effect, in the range of 4–87% (Greening et al., 2000; Hsueh and Gerner, 1993; Klein, 1987). However, energy price elasticities are an overestimate of the direct rebound effect because of the correlation between rising energy prices and investments in energy efficiency (Hanly et al., 2002; Henly et al., 1988). In particular, energy price elasticities measured without controlling for energy efficiency improvements over time will suffer from an omitted variable bias which will bias upward the energy price elasticity estimate (Small and van Dender, 2007). Our preferred measures of the direct rebound effect include efficiency elasticities, energy service price elasticities, and energy price elasticities in studies that control for self-selection of efficient appliance purchase. These approaches all require data and variation in appliance energy efficiency rather than merely variation in prices to identify the rebound effect. For a selected review of direct rebound estimates for electricity and transportation services using the preferred approaches, see Table 1.

3. Indirect Rebound Effects in Economics vs. Industrial Ecology

The indirect rebound effect has been studied through complementary but distinct methods in the energy economics and industrial ecology literatures, summarized in Table 2. Energy economists tend to jointly measure the direct and indirect rebound effects using a system of demand models for energy and other goods, such as the Almost Ideal Demand System (AIDS) model, pioneered by Deaton and Muellbauer (1980). Two main strengths of this approach are that it can measure the degree to which goods are complements and substitutes, and that it measures marginal changes in spending patterns as incomes rise and prices change, through the measurement of income and price elasticities. However, most prior studies applying the AIDS model to simulate direct and indirect rebound effects (Brannlund et al., 2007; Mizobuchi, 2008; Wang et al., 2012) also suffer from three weaknesses. First, they use energy price elasticities that overestimate the direct rebound effect. Kratena and Wuger (2010) is an exception, in that they develop indices of appliance efficiency to estimate direct and indirect rebound effects by energy service price elasticities within an AIDS model framework in the U.S. However, Kratena and Wuger's (2009) measure income elasticities are largely negative in some sectors, which is inconsistent with other studies of the U.S. consumer demand (Taylor and Houthakker, 2010). Second, these prior AIDS model studies of direct and indirect rebound effects have not included time trends or other corrections for non-stationary technology change or other changes over time, and without doing so, their elasticity estimates may violate the properties of elasticities from microeconomic consumer demand theory, as Deaton and Muellbauer (1980) noted in their seminal paper introducing the model. Hunt and Ryan (2011, 2012) argue that incorporation of time trends, lagged price variables, or other measures of technological change is important to estimate direct and indirect rebound effects with the AIDS model in an energy services framework. Third, these studies from the energy economics literature tend to include only the combustion emissions, called scope 1 emissions, and/or purchased electricity emissions, called scope 2 emissions, in their indirect rebound estimates.

Other sources of emissions are upstream or supply-chain emissions required to extract materials, and manufacture, distribute, and sell goods and services, called scope 3 emissions. These scope 3 emissions

Table 1
Selected review of U.S. direct rebound studies using energy services model.

Author (year)	Method	Sample size	Sample years	Region	Direct rebound estimate	Notes
Space heating/electric end-uses						
Hirst et al. (1985)	Pre vs. post measurements	79	1981–1983	Pacific Northwest U.S.	10–15%	Control group, low income groups have higher take-back
Dubin et al. (1986)	Energy service price elasticity	214–396 (cool), 252 (heat)	1982–1983	Florida	8–12%	Electric space heating and cooling
Dinan and Trumble (1989)	Pre vs. post thermostat settings	254	1984–1986	Oregon	3%	Only 5% of gap between engineering estimates and actual savings is due to behavior change (thermostat changes)
Schwartz and Taylor (1995)	Energy service price elasticity	~270	1984–1985	9 census divisions	1–3%	Electric space heating
Davis (2008)	Energy price elasticity, controlling for self-selection in field trial		1997	Bern, Kansas	6%	Compared electricity and water use from residential clothes washers in field trial; controlling for unobserved factors
Transport						
Haughton and Sarkar (1996)	VMT elasticity of fuel intensity (inverse of fuel economy)		1970–1991		16% (SR) and 22% (LR)	CAFE standard variable is correlated with historical high price variable
Small and van Dender (2007)	VMT elasticity of fuel economy	1734	1966–2001	US states panel	5% (SR) 22% (LR)	Declining with income and over time
Gillingham (2011)	VMT elasticity of fuel economy	>1 million	2000–2006	California households/vehicles	9%	Structural model for vehicle choice and utilization and quantile regression by income
	VMT elasticity of gas prices				15%	
Greene (2012)	VMT elasticity of fuel cost per mile	51	1970s–2007	US states aggregate time series	3% (SR) 13% (LR)	Time series regression, fuel economy variation is small

Table 2
Literature review of direct and indirect rebound studies.

Author	Sample period	Sector number	Country	Action	Respending scenario	Direct rebound parameter	Embodied energy	Direct rebound	Indirect rebound, energy/GHG
Lenzen and Dey (2002)	1995	150	Australia	Efficiency, behavior change	Proportional spending	No direct effect	Scopes 1–3	NA	45–50% for GHGs, 112–123% energy consumption
Alfredsson (2004)	1996	300	Sweden	Behavior change (food, travel, utilities)	Income elasticity	Energy service/ price elasticity	Scopes 1–3	10–30%	14–300%
Brannlund et al. (2007)	1980–1997	13	Sweden	Efficiency in Heating, Transport, Both	Linear AIDS	Energy price elasticity	Scopes 1–2	15%	106%
Mizobuchi (2008)	1990–1998	13	Japan	Efficiency in Heating, Transport, Both	Linear AIDS	Energy price elasticity	Scopes 1–2	111% electricity, 5% transport	84% (electricity), 22% (gasoline)
Thiesen et al. (2008)	2001–2003	34	Denmark	Behavior change & price change (food, i.e. cheese)	Slopes in spending, by income	No direct effect	Scopes 1–3	NA	NA
Nässén and Holmberg (2009)	2003	42	Sweden	Efficiency in space heating, appliances, and transport	Income elasticity	Energy service price elasticity	Scopes 1–3	9 to 22%	−1 to 26%
Kratena and Wuger (2010)	1972-2005	6	US	Efficiency	Quadratic AIDS	Energy service price elasticity	Scopes 1–2	14% (gas) to 19% (elec)	−57% (elec) to 71% (gasoline)
Girod and de Haan (2010)	2002–2005	450	Switzerland	Behavior change (food)	Income elasticity	No direct effect	Scopes 1–3	NA	53%
Freire-Gonzalez (2011)	2000–2008, 2005 IO Tables	31	Catalonia	Efficiency	Income elasticity & proportional spending	Energy price elasticity	Scopes 1–3	36% (SR) 49% (LR)	20% (SR) 16% (LR)
Murray (2011)	2003–2004	36	Australia	Efficiency	Income elasticity	No direct effect	Scopes 1–3	NA	5–40%
Druckman et al. (2011)	1992–2004, 2008 elasticities	16	UK	Behavior change/ conservation	Income elasticity	No direct effect	Scopes 1–3	NA	7–51%
Chitnis et al. (2012)	2004	16	UK	Efficiency, Investments, and behavior change	Income elasticity	No direct effect	Scopes 1–3	NA	3–11% with capital costs, 15–20% without capital costs
Wang et al. (2012)	1994–2009	7	China	Personal transport efficiency	Linear AIDS	Energy price elasticity	None	2–246%	NA

Notes: Adapted and expanded from Chitnis et al. (2012).

are extensively studies in the industrial ecology literature on household and national carbon footprints (CF) or environmental footprints. These studies use environmentally extended input–output (EEIO) analysis (Leontief, 1970) and show that over half of household CF can be attributed to non-energy goods and services for the case of the Netherlands (Biesiot and Noorman, 1999), Sweden (Carlsson-Kanyama et al., 2005), the U.S. (Weber and Matthews, 2008), the U.K. (Druckman and Jackson, 2009), and 73 other nations, based on evidence from a multi-regional trade-linked analysis (Hertwich and Peters, 2009). Industrial ecology studies tend to focus on aspects of the indirect rebound effect related to various measures of household spending patterns and the change in scope 1 (combustion), scope 2 (purchased electricity), and scope 3 (supply chain) emissions, as measured from an EEIO model.

A weakness of industrial ecology studies is the assumption that household budget savings will be re-spent in proportion to current spending patterns, for broadly defined sustainability measures, such as “greener” diets or conservation activities, including energy efficiency (Lenzen and Dey, 2002; Takase et al., 2008), or reducing office work by teleworking (Kitou and Horvath, 2003). However, the importance of the difference between average and marginal spending is empirically unclear. Goedkoop et al. (1999) argue that marginal spending patterns are more important than proportional or average spending patterns, and Thiesen et al. (2008) attempt to quantify these using slopes of spending patterns between one income group to the next higher income group. Thiesen et al. (2008) find that for global warming impacts, the differences between average and marginal spending patterns are minimal. Other studies directly measure marginal spending patterns using income elasticities from consumption data and couple them with an EEIO model to measure indirect rebound effects from conservation or efficiency activities (Alfredsson, 2004; Chitnis et al., 2012; Druckman et al., 2011; Girod and de Haan, 2010; Murray, 2011). However, these studies do not include a direct rebound effect, which is not applicable for non-efficiency activities, and so cannot be compared with energy economics studies of the indirect rebound effect. Freire-Gonzalez (2011) does include the direct rebound effect in a Catalonian study, and compares indirect rebound effects measured by proportional spending patterns and income elasticities with an EEIO model, and finds limited differences in indirect rebound effects. However, he overestimates the direct rebound effect by using energy price elasticities. Nässén and Holmberg (2009) is the study most similar to our approach, which uses energy service price elasticities with income elasticities and scope 1–3 emissions from an EEIO model for Sweden, but they use a different functional form for energy demand and do not compare the difference between average and marginal spending patterns and their influence on indirect rebound estimates.

4. Slutsky Model of Price Elasticities and Rebound Effects: Two-goods Case

We begin by defining a few conceptual terms related to the direct and indirect rebound effects for consumers to show the relationship between the two effects and to bound the indirect rebound effect using the properties of elasticities for the two-goods case. A glossary of key symbols for Section 4 and 5 is shown in Table 3.

Suppose a household starts with a baseline demand for a fuel, E (e.g. electricity, gasoline), consumed by an appliance of efficiency ε (e.g. lumen-h/Wh, miles/gal), providing a single energy service S (e.g. lumen-h of lighting, miles driven), and holding constant all non-energy attributes (e.g. safety, comfort, quality, etc.), then Eq. (2) holds.

$$E = \frac{S(P_{S,}\varepsilon)}{\varepsilon} \tag{2}$$

Table 3
Summary of key symbols.

Symbol	Description
E	Demand for fuel or energy carrier (e.g. electricity)
S	Demand for an energy service provided by E
O	Demand for other good or service
P_s	Price (or operating cost) of energy service S
ε	Efficiency metric of providing energy service S with fuel E, i.e. a fuel economy or light bulb efficacy
P_e	Market price for fuel E
$\eta_{E,\varepsilon}$	Efficiency elasticity for fuel, i.e. percent change in demand for fuel E with respect to percent change in efficiency ε
$\eta_{S,\varepsilon}$	Efficiency elasticity for energy service, i.e. percent change in demand for energy service S with respect to percent change in efficiency ε
η_{S,P_S}	Price elasticity of energy service, i.e. percent change in demand for energy service S with respect to percent change in the price of energy service (or operating cost) P_S
η_{O,P_S}	Price elasticity of energy service, i.e. percent change in demand for energy service S with respect to percent change in the price of energy service (or operating cost) P_S
$\eta_{S,I}$	Income elasticity for energy service S
$\eta_{O,I}$	Income elasticity for other good O
w_S	Budget share for energy service S
w_O	Budget share for other good O
$\eta_{S,P_S}\vert_U$	Constant Utility, U, or compensated price elasticity of energy service P_S
$\eta_{O,P_S}\vert_U$	Constant Utility, U, or compensated cross-price elasticity of demand for other good O with respect to the price of energy service, P_S
τ	Percentage change in the price of energy service, $\Delta P_S/P_S=\delta/(1+\delta)$
δ	Percentage change in the efficiency metric of an energy service, $\Delta\varepsilon/\varepsilon$
Y_B	Annual household expenditures in the base case
Y_E	Annual household expenditures in the efficient case
Y_R	Annual household expenditures in the efficient case with rebound
I	Annual household income
Z	A vector of embodied primary energy or emissions for each expenditure category
V	A vector or direct primary energy or emissions for each expenditure category
V^c	A vector of combustion emissions or primary energy for natural gas and gasoline; 0 for everything else
A	An input–output table representing a closed economy with Linear/Leontief production functions
E_B	Embodied primary energy or emissions in the base case
E_E	Embodied primary energy or emissions in the efficient case
E_R	Embodied primary energy or emissions in the rebound case
R_{D+I}	Direct plus indirect rebound effect
R_{I_PS}	Indirect rebound effect under the assumption of spending in proportion to current spending
R_{I_IE}	Indirect rebound effect under the assumption of no substitution effect for other goods and marginal spending patterns from income elasticities
R_{I_CP}	Indirect rebound effect under the constant cross-price elasticity for non-energy services assumption and marginal spending patterns from income elasticities

where P_s (e.g. \$/lumen-h, \$/mile), is the price of energy services. Eq. (2) reflects that households do not derive utility from energy per se, but from the useful energy services that a fuel or energy carrier provides when used with an appliance, i.e. the demand for energy is derived from the demand for energy services. Eq. (3) demonstrates the relationship between the price of energy, P_e (e.g. \$/kWh or \$/gallon), the price of energy services, P_s, and appliance efficiency, ε.

$$P_e = P_S\varepsilon \tag{3}$$

The direct rebound effect can be defined as an efficiency elasticity of energy services, $\eta_{S,\varepsilon}$ or the negative of the price elasticity of energy services, $-\eta_{S,P_S}$ (since $\eta_{S,P_S}<0$) as seen in Eqs. (4) and (5), respectively, which are defined in terms of the efficiency elasticity of energy demand, $\eta_{E,\varepsilon}$ (Berkhout et al., 2000; defs. 1 and 3 in Sorrell and Dimitropoulos, 2008).

$$\eta_{E,\varepsilon}\equiv\frac{\partial E}{\partial\varepsilon}\frac{\varepsilon}{E}=\frac{\varepsilon}{E}\left(\frac{1}{\varepsilon}\frac{\partial S(\varepsilon)}{\partial\varepsilon}-\frac{1}{\varepsilon^2}S\right)=\frac{\Delta S}{\Delta\varepsilon}\frac{\varepsilon}{S}-1\equiv\eta_{S,\varepsilon}-1 \tag{4}$$

$$\eta_{E,\varepsilon}=\frac{\partial E}{\partial\varepsilon}\frac{\varepsilon}{E}=\frac{\varepsilon}{E}\left(\frac{1}{\varepsilon}\frac{\partial S}{\partial P}\frac{\partial P}{\partial\varepsilon}-\frac{1}{\varepsilon^2}S\right)=\frac{\varepsilon}{E}\left(\frac{\Delta S}{\Delta P}\frac{P_e}{\varepsilon^3}-\frac{1}{\varepsilon^2}S\right)$$
$$=-\frac{\Delta S}{\Delta P_S}\frac{P_S}{S}-1\equiv\eta_{S,P_S}-1 \tag{5}$$

The representation of the direct rebound effect as an energy service price elasticity assumes that energy prices are exogenous, which may not generally be the case, as Hanly et al. (2002) demonstrate with U.K. travel statistics. However, the upward-bias on energy service price elasticities that endogeneity introduces is still less than for energy price elasticities, given Hanly et al.'s (2002) bounding analyses on travel demand elasticities. The study of the endogeneity between energy prices and efficiency investments requires a simultaneous equations econometric model with panel data, which is outside the scope of this paper.

The indirect rebound effect is related to the re-spending of energy cost savings on other goods, O, with prices P_o, and the energy or emissions associated with this induced consumption (Berkhout et al., 2000; Schipper and Grubb, 2000; Sorrell and Dimitropoulos, 2008). The pattern of household re-spending that occurs in response to the change in the price of energy services is measured by cross-price elasticities of the demand for other goods with respect to the price of energy services, η_{O,P_S}, where

$$\eta_{O,P_S}\equiv\frac{\Delta O}{\Delta P_S}\frac{P_S}{O}. \tag{6}$$

The relationship between price elasticities, income elasticities, $\eta_{S,I}$, and budget shares, w_S, for good S, such as an energy service, can be illustrated by the Slutsky decomposition for consumer demand in response to price changes (Nicholson, 2005), as seen in Eq. (7), where $\eta_{S,P_S}|_U$ is the compensated, or constant-utility, price elasticity for energy services.

$$\eta_{S,P_S}=\eta_{S,P_S}\Big|_U-w_S\eta_{S,I} \tag{7}$$

We can use similar reasoning to examine the change in "other goods" demand, O, with respect to a change in energy service prices, to obtain a similar decomposition of cross-price elasticities of the demand for other goods with respect to the price of energy services, shown in Eq. (8).

$$\eta_{O,P_S}=\eta_{O,P_S}\Big|_U-w_S\eta_{O,I} \tag{8}$$

The cross-price elasticity of the demand for other goods with respect to energy services together with the energy intensity of other goods spending models the indirect rebound effect (Berkhout et al., 2000; Sorrell and Dimitropoulos, 2008). The linkage between the demand for energy services, S, and other goods, O, implied by the two Slutsky relations in Eqs. (7) and (8) is illustrated in Fig. 1.

In Fig. 1, the household's original budget constraint, $B(\varepsilon_B)$, which is a function of appliance efficiency, moves outward to $B(\varepsilon_E)$ with a decrease in the price of energy services implied by investment in an appliance with higher efficiency, $\varepsilon_E>\varepsilon_B$. This implies that the household's utility maximizing consumption bundle changes from $Q_0(S_B,O_B)$ at utility U_0, to $Q_2(S_{RD},O_{RI})$ so that the household is able to achieve a higher level of utility, U_1. The change in demand for energy services and other goods can be decomposed into the substitution and income effects, where the substitution effect leads to a change in demand for energy services and other goods, holding utility constant, and the income effect leads to an increase in demand for all (non-inferior) goods and services to achieve a higher utility level. The net change in the demand for energy services is the direct rebound effect, while the net change in the demand for other goods is related to the indirect rebound effect. Thus, the direct and indirect rebound effects are both

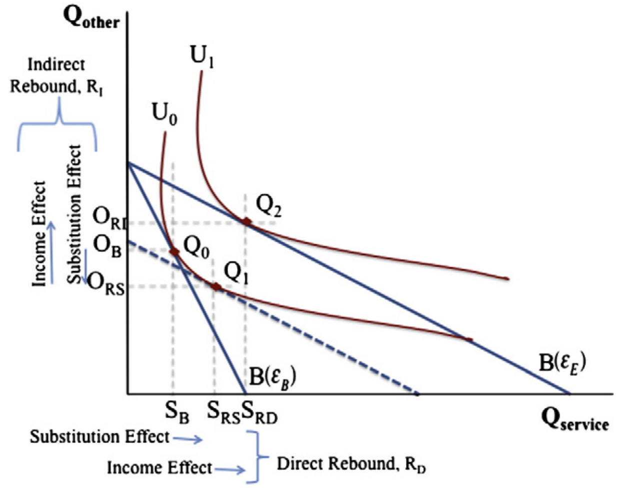

Fig. 1. Slutsky decomposition analysis of the rebound effect for consumers. The direct and indirect rebound effects can both be decomposed into substitution and income effects in response to a change in the price of energy services with an efficiency investment.

due to the substitution and income effects arising from the change in the price of energy services with an efficiency investment. Fig. 2 shows how a decline in the price of energy services can still lead to a reduction in energy consumption, if the energy efficiency intervention does not lead to a change in the market price for energy, and if the rebound effect is less than 100%.

In Figs. 1 and 2, the larger the direct rebound effect or the further the distance from S_{RD} to S_B, while the indifference curve, U_1, is still tangent to the budget constraint, the smaller the distance between O_{RI} and O_B, the cross-price elasticity or re-spending of energy cost savings from the efficiency investment. In fact, if the direct rebound is 100%, or $E_R = E_B$, then the cross-price elasticity would be zero, or $O_{RI} = O_B$. If the direct rebound effect was 0%, or $S_B = S_{RD}$, this would correspond to a case in which all energy cost savings from an efficiency investment are re-spent or the maximum possible cross-price elasticity. This simple graphical analysis demonstrates that the cross-price elasticity of the indirect rebound effect is bounded by the budget constraint and the direct rebound effect in the two-goods case.

The bounds on the indirect rebound effect can be shown analytically as well using the Slutsky decomposition for energy services and other

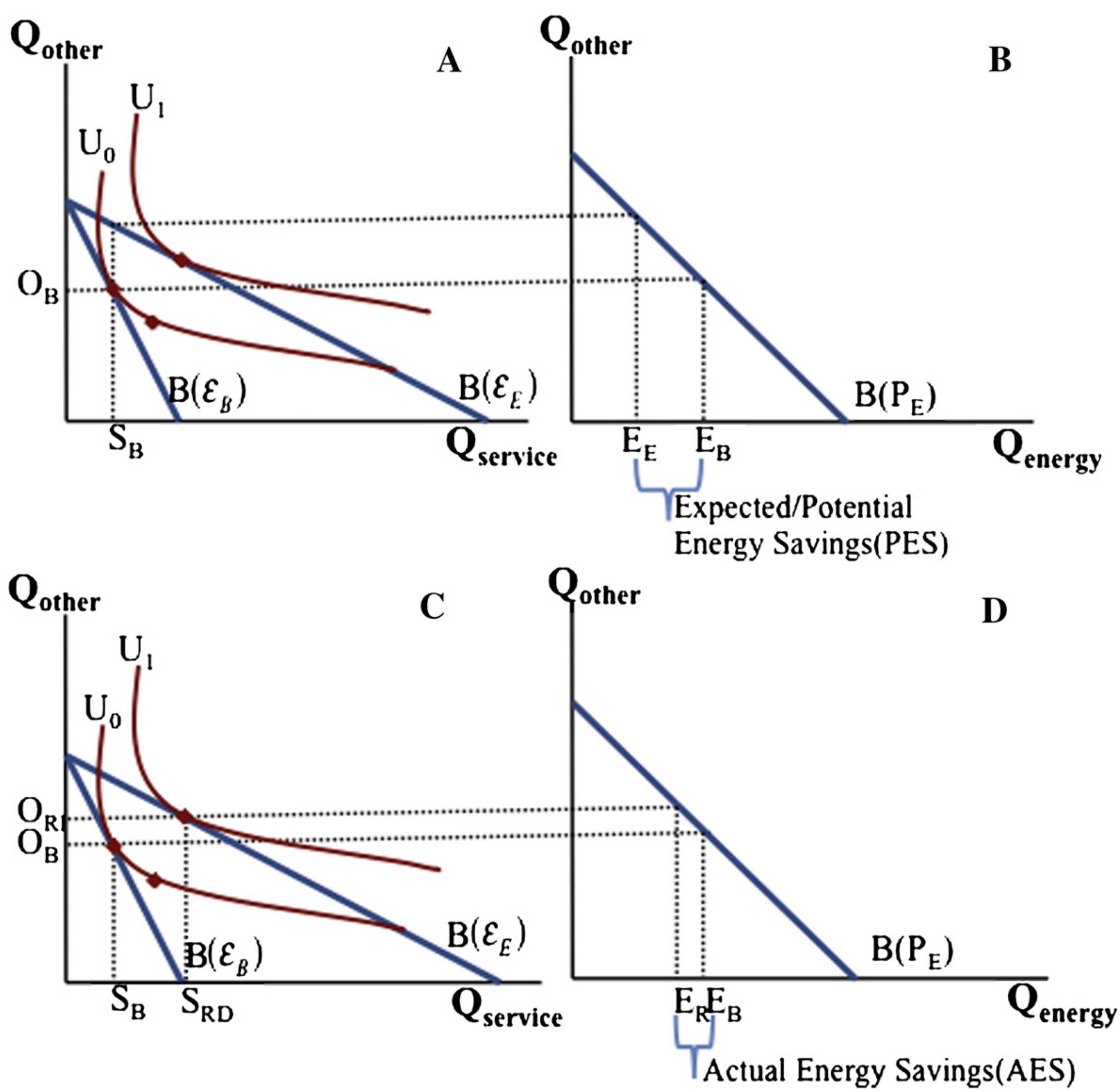

Fig. 2. Rebound in energy services vs. energy consumption. Graphs A and C show how an increase in demand for energy services due to the lower price of energy services can still lead to a net reduction of energy consumption in Graphs B and D with a rebound effect less than 100% and exogenous energy prices.

goods and another fundamental property of elasticities, Cournot aggregation, shown in Eq. (9).

$$w_S\eta_{S,P_S} + w_O\eta_{O,P_S} = -w_S \tag{9}$$

We then substitute the Slutsky decomposition for the energy price elasticity and cross-price elasticities, Eqs. (7) and (8), into Eq. (9), to obtain Eq. (10).

$$w_S\left[\eta_{S,P}\Big|_U - w_S\eta_{S,I}\right] + w_O\left[\eta_{O,P_S}\Big|_U - w_S\eta_{O,I}\right] = -w_S \tag{10}$$

Gathering the income and energy service-price elasticity terms together, we use the Engel aggregation property that $\sum_{a=1}^{2} w_a\eta_{a,I} = 1$, in the second bracketed term in Eq. (11), to obtain Eq. (12).

$$\left[w_S\eta_{S,P_S}\Big|_U + w_O\eta_{O,P_S}\Big|_U\right] - w_S\left[w_S\eta_{S,I}\Big|_U + w_O\eta_{O,I}\Big|_U\right] = -w_S \tag{11}$$

$$\left[w_S\eta_{S,P_S}\Big|_U + w_O\eta_{O,P_S}\Big|_U\right] = 0 \tag{12}$$

We then solve for the compensated cross-price elasticity:

$$\eta_{O,P_S}\Big|_U = \frac{-w_S\eta_{S,P_S}\Big|_U}{w_O} = \frac{-w_S\left(\eta_{S,P_S} + w_S\eta_{S,I}\right)}{1-w_S}. \tag{13}$$

By substituting the above expression for compensated cross-price elasticity for other goods into Eq. (8), we construct uncompensated cross-price elasticities for other goods in terms of Eq. (13) and income elasticities, in Eq. (14).

$$\eta_{O,P_S} = \frac{-w_S\left(\eta_{S,P_S} + w_S\eta_{S,I}\right)}{1-w_S} - w_S\eta_{O,I} \tag{14}$$

Eq. (14) demonstrates that the higher the direct rebound effect, the lower the cross-price elasticity of the indirect rebound effect, which is also constrained by the fact that $0<w_S<1$. Incorporating this cross-price elasticity with embodied energy or emissions to define the indirect rebound effect is the same for the 2-goods case and the n-goods case, and will be shown in the next section.

5. Slutsky Model of Price Elasticities and Rebound Effects: n-Goods Case

In the n-goods case, we define the indirect rebound effect in terms of a cross-price elasticity and embodied or supply chain emissions for other goods, using a four-step algorithm. First, we define the annual energy service and other expenditures of the household, *Y*. Second, we define the energy or emissions from those expenditures, *E*, from a static general equilibrium perspective using input–output analysis, where market prices for energy and other goods are constant, but efficiency and energy service prices have changed. We will also consider the differences in rebound estimates using direct combustion and supply chain emissions data, assuming that all of the goods consumed by the household were produced in the U.S. Third, we derive a model for the direct and indirect rebound effects from their basic definitions. Fourth, we consider various approaches to approximate a parameter in the rebound model, the cross-price elasticity, using proportional or average spending shares, income elasticity re-spending, or by constructing a cross-price elasticity for the n-goods case which is similar to the two-goods case, includes both substitution and income effects, and is consistent with consumer demand theory.

5.1. Household Expenditures

There are three expenditure cases to consider: the base case, Y_B, the efficiency case (an engineering or input–output estimate) in which an efficiency investment has been made but assumes no change in energy service or other goods demand, Y_E, and a rebound case in which the demand for energy services is responsive to the price of energy services, Y_R. We represent these expenditures in terms of annual household disposable income, I (excluding savings), and expenditure shares on energy services, w_s, and other goods, w_o.

Starting with the base case expenditures, decomposed in spending a single energy service (i.e. heating), Y_s and spending on other goods, Y_o.

$$Y_B = Y_S + \sum_{o=1;\neq s}^{n} Y_O = P_S S + \sum_{o=1;\neq s}^{n} P_O O = I\left(w_s + \sum_{o=1;\neq s}^{n} w_o\right) \tag{15}$$

Suppose a household makes an efficiency investment which increases efficiency by $\delta = \Delta\varepsilon/\varepsilon$ and decreases the price of energy services (or operating cost) by $\tau = \Delta P_s/P_s = \delta/(1+\delta)$. The percent increase in efficiency does not equal the percent decrease in the price of energy services; e.g. a 100% increase in vehicle fuel efficiency would decrease gasoline consumption by 50%. The engineering efficiency case then assumes no change in Y_o, i.e. no spending on other goods.

$$Y_E = Y_B - P_S S\frac{\Delta P_S}{P_S} = I\left(w_s(1-\tau) + \sum_{o=1;\neq}^{n} w_o\right) \tag{16}$$

In the rebound case, energy service demand would increase by $\Delta S/S$ due to the direct rebound effect, or a decrease in the price of energy services, and other goods demand would change by $\Delta O/O$ due to the cross-price elasticity, η_{O,P_S}. Writing $\Delta S/S$ and $\Delta O/O$ in terms of elasticities, using Eqs. (5) and (6), we obtain:

$$\begin{aligned} Y_R &= Y_B - Y_S\frac{\Delta P_S}{P_S} + Y_S\frac{\Delta S}{S} + \sum_{o=1;\neq s}^{n} Y_o\frac{\Delta O}{O} \\ Y_R &= Y_B - Y_S\frac{\Delta P_S}{P_S} - Y_S\eta_{S,P_S}\frac{\Delta P_S}{P_S} - \sum_{o=1;\neq s}^{n} Y_o\eta_{O,P_S}\frac{\Delta P_S}{P_S} \\ Y_R &= I\left(w_S\left(1-\tau-\eta_{S,P_S}\tau\right) - \sum_{o=1;\neq}^{n} w_o\left(1-\eta_{O,P_S}\tau\right)\right). \end{aligned} \tag{17}$$

Our expressions for household expenditure are a linear approximation of Nässén and Holmberg's (2009) approach. For simplicity, we assume that the efficiency investment has the same embodied energy and capital cost as the less efficient technology it replaces, and has been financed from savings, or alternatively, that there is no incremental capital cost for the efficiency investment. We do not consider capital or financing costs in our re-spending scenarios, as these are likely to depend on the specific equipment investment undertaken and could also represent delayed consumption with a different embodied energy or emissions intensity than the economy at the time frame of the analysis. In our view, indirect rebound effects with capital costs should be studied in a dynamic framework to account for any changes in the embodied energy or emissions of savings over time. Studies (using a static framework) have shown that the incorporation of capital costs reduces the direct and indirect rebound effects (Chitnis et al., 2012; Henly et al., 1988; Mizobuchi, 2008; Nässén and Holmberg, 2009). Thus, our model represents an upper bound of the indirect rebound effect, given an estimate of the direct rebound.

5.2. Energy and Emissions from Expenditures

We next consider the energy or emissions implications of the three expenditure patterns above, using environmentally-extended input–

output analysis (EEIO), which represents a static general equilibrium framework for evaluating the environmental implications of production and consumption activities. For the simulations of the indirect rebound effect in part two of this paper, we use the publicly available purchaser price, environmentally-extended economic input–output lifecycle assessment (EIO-LCA) model for the 2002 U.S. economy, the latest year for which the data are available (Hendrickson et al., 2006; www.eiolca.net). EIO-LCA contains a 428-sector industry by commodity structure, to which household expenditure data and elasticities can be matched. In the EEIO framework, the supply chain energy or environmental emissions, E, associated with the household's expenditures, which are obtained from EPA and EIA data sources (see documentation at www.eiolca.net), and can be represented as in Eq. (18).

$$E = ZY = \left(V(I-A)^{-1} + V^C\right)IY \tag{18}$$

where Y is a $[428\times 1]$ vector of household expenditures, I is the identity matrix, and A is a $[428\times 428]$ unitless matrix representation of production functions for all sectors of the economy. V is the $[1\times 428]$ vector of direct energy (J) or emissions (e.g. kg CO_2e) per dollar of expenditure for final goods, also known as the direct energy or emissions intensity. The direct energy or emissions in EIO-LCA are both a function of the level of "activity" or expenditures in a sector, which are a function of 2002 U.S. prices, and the energy intensity of that sector (Schipper and Grubb, 2000). The matrix $(I-A)^{-1}$ represents the Leontief inverse (Leontief, 1970), which transforms direct emissions intensities, V, into supply chain emissions intensities, Z $[1\times 428]$, assuming constant, national average prices, constant returns to scale, and linear production functions, which assume zero fixed costs (Lenzen and Dey, 2002). For natural gas and gasoline fuels, we add combustion emissions, V^C, from the use of these fuels to the supply chain emissions vector, Z. Electricity has no combustion emissions in the end-use phase.

5.3. Direct and Indirect Rebound Model

By using Eq. (18) with the three expenditure cases in Eqs. (15) to (17), following the basic definition of the rebound effect in Eq. (1), and replacing Y_o by the product of income and budget shares, w_oI, we can derive a model of the direct and indirect rebound effects, similar to Nässén and Holmberg (2009) and Freire-Gonzalez (2011), who draw from Druckman et al. (2011) to model re-spending with savings. Our model differs from Nässén and Holmberg (2009) in that we take a linear approximation of household spending under increased energy service prices. We differ from Freire-Gonzalez (2011) in that we use energy service price elasticities as a measure of the direct rebound effect, we explore substitution effects of the cross-price elasticity, and we provide an analytical expression of direct and indirect rebound effects in terms of elasticities and embodied emissions, as follows:

$$\begin{aligned}
R[\%] &= 1-\frac{AES}{PES} = 1-\frac{E_B-E_R}{E_B-E_R} = \frac{E_R-E_E}{E_B-E_E} \\
E_B &= z_S y_S + \sum_{O=1;\neq S}^{n} z_O y_O \\
E_E &= z_S y_S(1-\tau) + \sum_{O=1;\neq S}^{n} z_O y_O \\
E_R &= z_S y_S\left(1-\tau-\eta_{S,P_S}\tau\right) + \sum_{O=1;\neq S}^{n} z_O y_O \eta_{O,P_S}\tau \\
R_{D+I}[\%] &= \frac{-z_S y_S \eta_{S,P_S}\tau - \sum_{O=1;\neq S}^{n} z_O y_O \eta_{O,P_S}\tau}{z_S y_S \tau} \\
R_{D+I}[\%] &= -\eta_{S,P_S} - \frac{\sum_{O=1;\neq S}^{n} z_O w_O \eta_{O,P_S}}{z_S w_S}
\end{aligned} \tag{19}$$

where the direct rebound, R_D is

$$R_D = -\eta_{S,P_S}$$

and the indirect rebound R_I is

$$R_1 = -\frac{\sum_{O=1;\neq S}^{n} z_O w_O \eta_{O,P_S}}{z_S w_S}.$$

Note that in our measure of the direct and indirect rebound in Eq. (19), potential energy/emissions savings (PES) is equal to $E_B-E_E=z_s y_s\tau=z_s w_s I\tau$. which is a general equilibrium estimate of the supply-chain impacts of reducing household consumption of a particular fuel, and similar to the approach taken by Guerra and Sancho (2010) in their study of the economy-wide rebound effect in Spain. Guerra and Sancho (2010) argue that partial equilibrium (engineering) measures of PES, as traditionally used by 'rebound economists', lead to upward- or downward-biased measures of the economy-wide rebound effect, depending on elasticities of substitution for energy. Alternatively, if utilities and policymakers do not use input–output models in their energy efficiency program evaluations, one could argue that partial equilibrium engineering estimates should be used for PES. In this case, there would be a downward pressure on the indirect rebound as reduced household energy expenditures also lead to greater supply-chain reductions in energy consumption, in addition to upward pressures from embodied energy/emissions when the household re-spends energy expenditure savings from efficiency on other goods. We leave consideration of the impacts of partial equilibrium measures of PES on estimates of the indirect rebound for future work.

5.4. Approximating Cross-price Elasticities

We compare several approximations for the cross-price elasticity for other goods to study the bounds on η_{O,P_S} and the indirect rebound effect, given an estimate of the direct rebound effect, η_{S,P_S}, that is consistent with the literature described in Section 3. We assume that all electric-end uses have the same price elasticity, that all natural gas end-uses have the same price elasticity, and all gasoline end-uses have the same price elasticity; in other words, each fuel provides a single energy service. This implies that the share of expenditures spent in the fuel is equal to the share of expenditures spent in the energy service, $w_e=w_s$. This assumption is fairly accurate for gasoline and natural gas, but restrictive for electricity. For example, if space cooling represents only a portion of electricity expenditures (along with refrigeration, lighting, etc.), this would decrease the space cooling budget share and increase the emissions from non-space cooling spending, which now includes other electric end-uses. We investigate the sensitivity of the indirect rebound effect to budget share, emissions intensities, and other factors in part two of this paper. Using the single service per fuel assumption, Engel aggregation, obtained by differentiating the budget constraint by income, also implies that the income elasticity of the demand for an energy service is equal to the income elasticity of the demand for energy, $\eta_{S,I}=\eta_{E,I}$. In addition, using the single service per fuel assumption still allows P_E and P_S to differ from each other according to Eq. (3), which is the driver for the direct and indirect rebound effects.

Our approximations for the cross-price elasticity of the demand for other goods with respect to the price of energy services are based on the Slutsky decomposition shown in Eq. (8) and reproduced below.

$$\eta_{O,P_S} = \eta_{O,P_S}|_U - w_s\eta_{O,I}$$

There are many possible approximations for η_{O,P_S} which could be used in principle. We examine three possible approximations for η_{O,P_s}, the first two of which, proportional spending and income elasticity spending, were explored numerically by Freire-Gonzalez (2011) but not presented in an analytical expression for the direct and indirect rebound effects. Our contribution, the third approximation for η_{O,P_s}, explores the extent of the substitution effect of the indirect rebound effect, which to our knowledge has not yet been analyzed in the literature. The three approximations for η_{O,P_s} include:

(1) the proportional spending (R_{I_PS}) case, which assumes $\eta_{O,I}=1$, $\eta_{O,P_s}|_U=0$ for all non-energy service goods, O, and $\eta_{O,P_s}=-w_S$. By assumption, this approximation assumes no substitution effects for other goods spending with a change in the price of energy services. In addition, this approximation requires a calibration factor. Since $-\eta_{S,P_S}$ percent of energy cost savings were re-spent on energy services, only the remaining $\left(1+\eta_{S,P_S}\right)$ percent of energy cost savings can be re-spent on other goods, if the budget constraint is to be met. However, because of this calibration factor, this approximation is not flexible enough to allow for the possibility of rebound effects greater than 100% or "backfire." In addition, if all re-spending in the energy service, S, is absorbed in the direct rebound effect, a factor of $1/(1-w_S)$ must be included to ensure that all extra energy cost-savings are re-spent. Without adding the $\left(1+\eta_{S,P_S}\right)/(1-w_S)$ factor, the proportional spending approximation of the cross-price elasticity would either break the budget constraint or restrict η_{S,P_S} to be $-w_S$.

$$R_{I_{PS}}=\frac{\sum_{O=1;\neq S}^{n} z_O w_O w_S\left(1+\eta_{S,P_S}\right)}{z_S w_S(1-w_S)}$$
$$R_{I_{PS}}=\frac{\sum_{O=1;\neq S}^{n} z_O w_O\left(1+\eta_{S,P_S}\right)}{z_S w_S(1-w_S)} \tag{20}$$

(2) the income elasticity (R_{I_IE}) case, which assumes $\eta_{O,P_s}|_U=0$ for all non-energy goods, and $\eta_{O,P_s}=-w_s\eta_{O,I}$. As in the proportional spending case, this approximation implies that there are no substitution effects and only income effects with a change in energy service prices. A calibration factor of $\left(1+\eta_{S,P_S}\right)/\left(1-w_s\eta_{S,P_S}\right)$ is needed to meet the budget constraint at the expense of flexibility to depict backfire, for similar reasons as discussed above for the proportional spending approximation. Without this calibration factor, this approximation of household re-spending would have to restrict η_{S,P_S} to be $-w_s\eta_{S,I}$, in order to meet the budget constraint.

$$R_{I_{IE}}=\frac{\sum_{O=1;\neq S}^{n} z_O w_O \eta_{O,I}\left(1+\eta_{S,P_S}\right)}{z_S\left(1-w_S\eta_{S,P_S}\right)} \tag{21}$$

(3) the constant cross-price elasticity (R_{I_CP}) for non-energy services case, which is analogous to the two-goods case, and which assumes $\eta_{O,P_s}\Big|_U=C=\frac{-w_s\left(\eta_{S,P_s}+w_s\eta_{S,I}\right)}{\sum_{o=1;\neq s}^{n}w_o}$, and $\eta_{O,P_s}=\frac{-w_s\left(\eta_{S,P_s}+w_s\eta_{S,I}\right)}{\sum_{o=1;\neq s}^{n}w_o}-w_s\eta_{O,I}$ and is derived in Appendix A. This assumption places restrictions on the curvature of the household's utility function, and may underestimate the degree of substitution between energy services and other goods, but is useful to examine how substitution effects compare to income effects. The cross-price elasticity derivation relies on the Cournot aggregation property of elasticities, which is obtained by differentiating the budget constraint by the price of energy services, and so maintains the budget constraint without the need for additional calibration factors (see Appendix A). This approximation does bound the substitution effects for other goods spending and is flexible enough to allow for backfire, as will be shown in part two of this two-part paper.

$$R_{I_{CP}}=\frac{\sum_{O=1;\neq S}^{n} z_O w_O\left(\eta_{S,P_S}+w_S\eta_{S,I}\right)}{z_S\sum_{O=1;\neq S}^{n} w_O}+\frac{\sum_{O=1;\neq S}^{n} z_O w_O \eta_{O,I}}{z_S} \tag{22}$$

In summary, the three direct and indirect rebound effect models are:

$$R_{D+I_{PS}}=-\eta_{S,P_S}+\frac{\sum_{O=1;\neq S}^{n}\left(v_O(I-A)^{-1}+v_O^C\right)w_O\left(1+\eta_{S,P_S}\right)}{\left(v_S(I-A)^{-1}+v_S^C\right)(1-w_S)}$$
$$R_{D+I_{IE}}=-\eta_{S,P_S}+\frac{\sum_{O=1;\neq S}^{n}\left(v_O(I-A)^{-1}+v_O^C\right)w_O\eta_{O,I}\left(1+\eta_{S,P_S}\right)}{\left(v_S(I-A)^{-1}+v_S^C\right)\left(1-w_S\eta_{S,P_S}\right)}$$
$$R_{D+I_{CP}}=-\eta_{S,I}+\frac{\sum_{O=1;\neq S}^{n}\left(v_O(I-A)^{-1}+v_O^C\right)w_O\left(\eta_{S,P_S}+w_S\eta_{S,I}\right)}{\left(v_S(I-A)^{-1}+v_S^C\right)\sum_{O=1;\neq S}^{n}w_O}+\frac{\sum_{O=1;\neq S}^{n}\left(v_O(I-A)^{-1}+v_O^C\right)w_O\eta_{O,I}}{v_S(I-A)^{-1}+v_S^C}.$$

Note that in all three approximations, Eqs. (20) to (22), since $\eta_{S,P_s}<0$, the higher the direct rebound effect, the lower the indirect rebound effect, because fewer energy cost savings will be available for re-spending. Also note that these direct and indirect rebound effects in percent do not depend on the percent reduction in energy expenditures, τ. However, the consequence of the rebound effect in emissions (e.g. J, kg CO_2e), or the difference between potential and actual energy or emissions savings (PES-AES) after accounting for direct and indirect rebound effects, obtained by multiplying the rebound in percent by PES, or $z_s y_s\tau=z_s w_s I\tau$, does depend on τ. In Part two of this paper we will show simulations of the direct and indirect rebound in primary energy, CO_2e, NO_x, and SO_2 emissions in percent terms (Eqs. (20) to (22)), as well as the consequences of the rebound effect in energy/emissions, obtained by multiplying the percent rebound against a common PES baseline across energy efficiency interventions in electricity, natural gas, or gasoline services.

An alternative method to the cross-price elasticity approximations described above would be an econometric study with cross-sectional, time-series, or panel expenditure data, appliance/vehicle efficiency collected at the household level, geographically delineated commodity prices, and other variables needed to account for self-selection of efficient technologies (Gillingham, 2011). Due to data limitations, we focus on constructing cross-price elasticities given an estimate of the direct rebound effect to provide a bounding analysis on the substitution effect of the indirect rebound in part two of this two-part paper.

6. Conclusion

While the utility-maximizing model underlying the Slutsky decomposition and other price elasticity properties describes the behavior of an individual household, the own-price and cross-price elasticity estimates are typically measured by exploiting price, income, and demand variations in time-series or cross-sectional survey data and represent the behavior of the average household in the survey sample. This disconnect between the individual utility model and average household elasticity estimates reveals an important caveat for interpretation: rebound models should not be used to predict a particular household's response to changes in energy service prices, since individual elasticities are not measured. Instead, rebound models provide a guide to policymakers and utilities on the average household's rebound effect relative to engineering models of baseline energy savings due to price responses for the population, in the geographic area and time frame in which the price elasticities are measured. In this context, the percentage reduction of energy expenditures, τ could be large (>25%) for an individual household but τ could be small (<10%) for a given population, since not all households will be willing or able to make efficiency improvements due to capital constraints and other barriers to efficiency, and some households may already be in possession of efficient appliances. With large reductions in energy service expenditures, τ for a population, it is conceivable that energy prices would change, leading to economy-wide rebound effects, which are not captured by Eqs. (19) to (22). In the long-term, such changes in energy prices could lead to shifts in economic structure and disinvestment effects (Greening et al., 2000; Turner, 2009). Due to barriers to energy efficiency investments and the possibility of economy-wide rebound effects, Eqs. (19) to (22) are only valid to study direct and indirect rebound effects for a moderate τ averaged over a population.

Past studies of the indirect rebound effect suffer from three deficiencies. The economics literature tends to ignore the distinction between energy and energy services, which recent work has emphasized (Sorrell and Dimitropoulos, 2008), and exclude embodied energy or emissions, while the industrial ecology literature largely ignores the distinction between average and marginal spending patterns. This study balances the two approaches by starting with an energy services framework for the direct rebound effect and including marginal spending patterns and embodied energy for the indirect rebound effect, relying on fundamental properties of elasticities from consumer demand theory. By assuming zero incremental capital costs and the same embodied energy for an efficient appliance, our model would provide an upper bound on the indirect rebound effect, given a direct rebound estimate. All of the models of the direct and indirect rebound effects analyzed in this paper show that the direct and indirect rebound effects are inversely related.

While rebound effects lead to an increase in equipment usage and re-spending and associated energy consumption and emissions, they also lead to an increase in social welfare. The social welfare gains from rebound effects are not accounted for in our model and are an important area for future study. In part two of this paper, we will provide simulations of the indirect rebound effect for the U.S. primarily using the constant cross-price elasticity approximation and comparing with the proportional spending and income elasticity approximations to show the empirical importance of income and substitution effects.

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Appendix A. Construction of Cross-price Elasticities for the n-goods Case

Our model of the indirect rebound effect relies on the assumption that each fuel provides a single energy service, i.e. all electric-end uses have a price elasticity similar to that of space-cooling; all natural gas end-uses have a price elasticity similar to that of space heating; all gasoline end-uses have a price elasticity similar to that of driving. The single service per fuel assumption implies that the share of expenditures spent in a fuel is equal to the share of expenditures spent in the energy service, $w_e = w_s$. Using the single service per fuel assumption, Engel aggregation also implies that the income elasticity of the demand for an energy service is equal to the income elasticity of the demand for energy, $\eta_{S,I} = \eta_{E,I}$.

To drive cross-price elasticities of the demand for non-energy services with respect to the price of energy services, we start with the Cournot Aggregation property in elasticity form, which assumes that the price of energy is uncorrelated with other prices.

$$w_S \eta_{S,P_S} + \sum_{O=1;\neq S}^{n} w_O \eta_{O,P_S} = -w_S \tag{A.1}$$

We then substitute the Slutsky decomposition for the energy price elasticity and cross-price elasticities, Eqs. (7) and (8), into Eq. (A.1), using the single service per fuel assumption to obtain Eq. (A.2).

$$w_S \left[\eta_{S,P_S}\Big|_U - w_S \eta_{S,I} \right] + \sum_{O=1;\neq}^{n} w_O \left[\eta_{O,P_S}\Big|_U - w_S \eta_{O,I} \right] = -w_S \tag{A.2}$$

Gathering the income and energy service-price elasticity terms together, we use the Engel aggregation property that $\sum_{a=1}^{n} w_a \eta_{a,I} = 1$, in the second bracketed term in Eq. (A.3), to obtain Eq. (A.4).

$$\left[w_S \eta_{S,P_S}\Big|_U + \sum_{O=1;\neq S}^{n} w_O \eta_{O,P_S}\Big|_U \right] - w_S \left[w_S \eta_{S,I}\Big|_U + \sum_{O=1;\neq S}^{n} w_O \eta_{O,I}\Big|_U \right] = -w_S \tag{A.3}$$

$$\left[w_S \eta_{S,P_S}\Big|_U + \sum_{O=1;\neq S}^{n} w_O \eta_{O,P_S}\Big|_U \right] = 0 \tag{A.4}$$

We assume that all compensated (constant utility) cross-price elasticities with respect to the price of energy are equal, which is generally not the case; see for example, Blundell (1988), for the U.K. context. However, this assumption is useful to illustrate the dependency between the indirect and direct rebound effects. See Tarr (1990) for alternative methods of constructing cross-price elasticities for closely related substitutes, such as natural gas and fuel oil. We then solve for the compensated cross-price elasticity:

$$\eta_{O,P_S}\Big|_U = \frac{-w_S \eta_{S,P_S}\Big|_U}{\sum_{O=1;\neq S}^{n} w_O} = \frac{-w_S \left(\eta_{S,P_S} + w_S \eta_{S,I} \right)}{1 - w_S}. \tag{A.5}$$

By substituting the above expression for compensated cross-price elasticity for other goods into Eq. (8), we construct uncompensated cross-price elasticities for other goods in terms of Eq. (A.5) and income elasticities, in Eq. (A.6).

$$\eta_{O,P_S} = \frac{-w_S \left(\eta_{S,P_S} + w_S \eta_{S,I} \right)}{1 - w_S} - w_S \eta_{O,I} \tag{A.6}$$

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