Energy, expenditure, and consumption aspects of rebound, Part II: Applications of the framework

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Abstract

Widespread implementation of energy efficiency is a key greenhouse gas emissions mitigation measure, but rebound can "take back" energy savings. However, the absence of solid analytical foundations hinders empirical determination of the size of rebound. In Part I, we developed a rigorous analytical framework that is approachable for both energy analysts and economists. In this paper (Part II of two), we develop energy, expenditure, and consumption planes, a novel, mutually consistent, and numerically precise way to visualize and illustrate rebound. Further, we ~~perform the first calibration of the~~ operationalize the macro factor for macroeconomic rebound~~, finding $k \approx 3$~~. Using the framework and rebound planes, we calculate and show total rebound for two examples: energy efficiency upgrades of a car (~~47~~56.2%) and an electric lamp (~~67~~67.0%). Comparison of our rebound values to previous values is provided. Finally, we provide information about new open source software tools for calculating magnitudes and visualizing rebound effects using the framework.

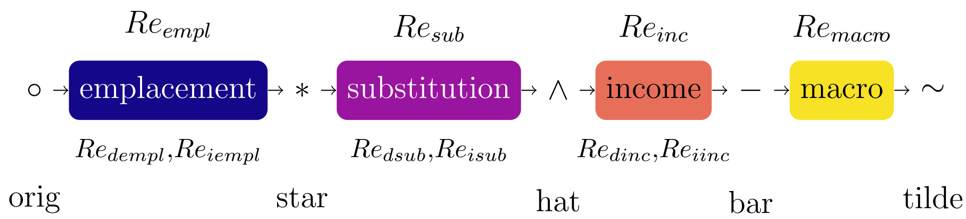

Fig. 1: Flowchart of rebound effects and decorations.

Keywords: Energy efficiency, Energy rebound, Energy services, Microeconomic rebound, Substitution and income effects, Macroeconomic rebound

JEL codes: O13, Q40, Q43

1 Introduction

In Part I of this two-part paper, we argued that improved clarity is needed about energy rebound. We said that

> [a] description of rebound [is needed] that is (i) consistent across energy, expenditure, and consumption aspects, (ii) technically rigorous and (iii) approachable from both sides (economics and energy analysis). ... In other words, the finance and human behavior aspects of rebound need to be presented in ways energy analysts can understand. And the energy aspects of rebound need to be presented in ways economists can understand.

To ~~move~~ help improve clarity in the rebound field, we developed in Part I a rigorous analytical framework for energy rebound, one that is tractable for both energy analysts and economists. Three aspects of rebound are analyzed in the framework: energy, expenditure, and consumption. The framework contains both direct and indirect rebound and four rebound effects (emplacement, substitution, income, and macro) between five stages ($\circ$, $*$, $\wedge$, $-$, and $\sim$). Rebound terms and symbol decorations are shown in Fig. 1. (See Table 1 in Part I for details. See Appendix A for nomenclature.)

In this paper (Part II), we make further progress toward the goal of clarity in four ways. First, we develop a new way to visualize components and mechanisms of rebound (rebound planes). Second, we make a first attempt at ~~calibrating~~ calculating the macro rebound effect via a macro factor (k).

Third, we apply the framework to two energy efficiency upgrades (EEUs) (a car and an electric lamp) with detailed explication of the examples. Finally, we show calculations of rebound magnitudes for both examples.

The key contributions of this paper are (i) development of ~~the first (to our knowledge)~~ mutually consistent and numerically precise visualizations of rebound effects in energy, expenditure, and consumption planes, (ii) ~~calibration~~ operationalization of the macro factor (k) to link microeconomic and macroeconomic rebound levels, (iii) presentation of new rebound values for car and electric lamp upgrades based on ~~a calibrated version of our~~ the framework from Part I, and (iv) documentation of new open source software tools to calculate and visualize rebound for any EEU.

The remainder of this paper is structured as follows. Section 2 describes data for the examples, our method of visualizing rebound, and open source software tools for calculating and visualizing rebound. Section 3 provides results for two examples: energy efficiency upgrades to a car and an electric lamp. Section 4 ~~calibrates~~ operationalizes the macro factor (k) and discusses results, and Section 5 concludes.

2 Data and methods

This section contains data for the examples (Section 2.1), an explication of our new method for visualizing rebound effects and magnitudes (Section 2.2), and a description of new open source software tools for rebound calculations and visualization (Section 2.3).

2.1 Data

To demonstrate application of the rebound analysis framework developed in Part I, we analyze two examples: energy efficiency upgrades to a car and an electric lamp. The examples are presented with much detail to support our goal of ~~bringing clarity to~~ helping to advance clarity for the process of calculating the magnitude of rebound effects. Here, we collect parameter values for the equations to calculate ~~eight~~ nine rebound components: Re_{dempl}, Re_{emb}, ~~Re_{md},~~ Re_{OM}, Re_{d}, Re_{dsub}, Re_{isub}, Re_{dinc}, Re_{iinc}, and Re_{macro}. Total rebound (Re_{tot}) is given by the sum of the above components or equivalently by Eq. (35) of Part I.

2.1.1 Data for car example

For the first example, we consider the purchase of a more fuel efficient car, namely a gasoline-electric Ford Fusion Hybrid car, to replace a conventional gasoline Ford Fusion car. The cars are matched as closely as possible, except for the inclusion of an electric battery in the hybrid car. The car case study features a larger initial capital investment ($C^{\circ}_{cap} < \tilde{C}_{cap}$) for the long-term benefit of decreased energy service costs ($\dot{C}^{\circ}_{s} > \tilde{\dot{C}}_{s}$).

We require three sets of data. First, basic car parameters are summarized in Table 1. Second, we require several general economic parameters, mainly relating to the U.S. economy and personal finances of a representative U.S.-based user shown in Table 2. Third, we require elasticity parameters, as given in Table 3.

Table 1: Car example: Vehicle parameters.

Description Parameters [units]	Ford Fusion (gasoline)	Ford Fusion (hybrid EV)	Data sources and notes
Fuel economy η°, $\tilde{\eta}$ [mpg]	25	42	Combined cycle mpg value taken from Thecarconnection.com (2020), for Titanium FWD 2020 model with Intercooled I-4, 2.0 L engine. Combined cycle mpg value taken from Thecarconnection.com (2020), for Titanium FWD 2020 model with Gas/Electric I-4, 2.0 L engine.
~~Capital~~ Undiscounted capital expenditure rate $\dot{C}^\circ_{cap}$, $\dot{C}^*_{cap}$ [\$/yr]	~~4,778~~ 2,533	~~4,720~~ 2,518	Seven year annual, averaged capital costs = purchase + finance costs – resale value (purchase – depreciation). Ford Fusion gasoline costs from Edmunds.com (2020a). Ford Fusion Hybrid car costs from Edmunds.com (2020b).
Lifespan t°_{life}, t^*_{life} [yr]	14	14	Lifetime taken as 14 years, based on 13–17 years for U.S. cars from Berla.com (2016) and 14 years for UK cars from Society of Motor Manufacturers and Traders (2020).
Embodied energy E°_{emb}, E^*_{emb} [MJ]	34,000	40,000	34,000 MJ for conventional Ford Fusion gasoline car taken from Argonne National Laboratory, Energy Systems Division (2010). We assume an additional 6,000 MJ added for Ford Fusion Hybrid Electric Vehicle (HEV) battery, as HEV typically adds 10–25% to total LCA energy of vehicle manufacture (Onat et al., 2015). Battery lifetime assumed same as car lifetime, based on Nordelöf et al. (2014) and Onat et al. (2015).
Operations and maintenance expenditure rate $\cancel{\dot{C}^\circ_{OM}, \dot{C}^*_{OM}}$ ~~[\$/yr]~~	~~2,731~~ 5,050	~~2,710~~ 4,779	Lifetime (14 year) annual, averaged operation and maintenance (O+M) costs = sum of insurance, maintenance, repairs, taxes, and fees (excluding financing, depreciation, fuel). 5-year Ford Fusion O&M costs from Edmunds.com (2020a). 5-year Ford Fusion Hybrid O&M costs from Edmunds.com (2020b). Extrapolation of O&M costs for years 6–14 based on Djokic et al. (2015).
Disposal cost C°_d, C^*_d [\$]	−300	−300	Salvage value (negative cost) taken from Junk Car Medics (2024)
Ops., maint., and disposal expenditure rate, discounted $\dot{C}^\circ_{OMd}$, $\dot{C}^*_{OMd}$ [\$/yr]	5,033	4,762	Sum of annualized operations, maintenance, and disposal costs.

Table 2: Car example: Economic parameters (2020).

Description Parameter [units]	Value	Data sources and notes
Distance driven prior to upgrade $\dot{q}_s^{\circ}$ [miles/yr]	12,416	Average U.S. vehicle miles/yr, calculated from Carinsurance.com (2019). This is slightly lower than the average driver miles/yr (13,476) (US Department of Transportation, 2018), as there are more registered U.S. vehicles than drivers.
Real median personal income U.S., in 2018 [$/yr]	34,317	Taken from Federal Reserve Bank of St Louis (2019).
U.S. 2018 disposable income / real income (minus current taxes) [–]	0.88319	Taken from U.S. Bureau of Economic Analysis (BEA) National and Products Accounts (NIPA) Table 2.1. Personal Income and Its Disposition (US Bureau of Economic Analysis, 2020).
Share of savings from 2018 disposable income [–]	0.07848	Taken from U.S. Bureau of Economic Analysis (BEA) National and Products Accounts (NIPA) Table 2.1. Personal Income and Its Disposition (US Bureau of Economic Analysis, 2020).
Personal consumption in 2018 $\dot{M}$ [$/yr]	27,~~929.83~~ 930	Calculation: $(\$34,317/\text{yr})(0.88319)(1-0.07848)$
Price of gasoline p_E [$/gallon]	2.63	Source: US Energy Information Administration (2020b)
Fractional spend on original energy service $f^{\circ}_{\dot{C}_s}$ [–]	~~0.064~~ 0.066	Calculation: $1,306 (spend on energy service) / [$19,115 (other goods) + $1,306 (energy service)] = 0.064, where spend on energy service = 12,416 miles / 25 mpg × $2.63/gallon = $1,306.
Real discount rate r [1/yr]	0.03	**** Info here from GS justifying the value. ****
Macro factor k [–]	1.0	An initial value. See Section 4.2 for additional details.

Table 3: Car example: Elasticity parameters.

Description Parameter [units]	Value	Data sources and notes
Uncompensated own price elasticity of car use demand $\varepsilon^{\circ}_{\dot{q}_s,p_s}$ [–]	-0.2	We adopt -0.2 as our baseline value, based on U.S. studies including Gillingham (2020) who estimated a value of -0.1, Goetzke & Vance (2018) who estimated values between -0.05 and -0.23, and Parry & Small (2005) who estimated values between -0.1 and -0.3. For comparison, Borenstein (2015) uses values of -0.1 to -0.4 based on Parry & Small (2005).
Compensated price elasticity of car use demand $\varepsilon^{\circ}_{\dot{q}_s,p_s,c}$ [–]	~~-0.136~~ -0.134	Calculated via the Slutsky Equation (Eq. (175) in Part I).
Compensated cross price elasticity of demand for other goods $\varepsilon^{\circ}_{\dot{q}_o,p_s,c}$ [–]	0.009	Calculated via Eq. (181) in Part I.
Income elasticity of demand for car use $\varepsilon_{\dot{q}_s,\dot{M}}$ [–]	1.0	Follows from CES utility function.
Income elasticity of demand for other goods $\varepsilon_{\dot{q}_o,\dot{M}}$ [–]	1.0	Follows from CES utility function.

2.1.2 Data for lamp example

For the second example, we consider purchasing a Light Emitting Diode (LED) electric lamp to replace a baseline incandescent electric lamp. Both lamps are matched as closely as possible in terms of energy service delivery (measured in lumen output per lamp), the key difference being the energy required to provide that service. The LED lamp has a low initial capital investment rate when spread out over the lifetime of the lamp (less than the incumbent incandescent lamp, actually) and a long-term benefit of decreased direct energy expenditures at approximately the same energy service delivery rate (lm·hr/yr).

Again, three sets of data are required. First, basic lamp parameters are summarized in Table 4. Second, several general economic parameters, mainly relating to the U.S. economy and personal finances of a representative U.S.-based user are given in Table 5. Third, we require the elasticity parameters, as shown in Table 6.

Table 4: Lamp example: Electric lamp parameters.

Description Parameters [units]	Incandescent lamp	LED lamp	Data sources and notes
Lamp efficiency η°, $\tilde{\eta}$ [lm·hr/W·hr]	8.83	81.8	Incandescent: 530 lm output / 60 W energy input. LED: 450 lm output / 5.5 W energy input.
~~Capital~~ Undiscounted capital expenditure rate $\dot{C}^{\circ}_{cap}$, $\dot{C}^{*}_{cap}$ [$/yr]	1.044	0.121	Purchase costs: $1.88 for incandescent lamp from HomeDepot.com (2020b), and $1.21 for LED lamp from HomeDepot.com (2020a).
Lifespan t°_{life}, t^{*}_{life} [yr]	1.8	10	Based on assumed 3 hr/day from HomeDepot.com (2020b) and HomeDepot.com (2020a).
Life cycle analysis (LCA) embodied energy E°_{emb}, E^{*}_{emb} [MJ]	2.20	6.50	Base document: Table 4.5 Manufacturing Phase Primary Energy (MJ/20 million lm·hr), contained in U.S. DoE Life-cycle assessment of energy and environmental impacts of LED lighting products (US Department of Energy, 2012). Incandescent lamp: LCA energy = 42.2 MJ/20 million lm·hr. Lifetime output = 530 lm × 3 hr/day × 365 days/yr × 1.8 yr = 1,044,630 lm·hr. Thus LCA energy / lamp = 42.2 × 1.0446/20 = 2.21 MJ. LED lamp: LCA energy = 132 MJ/20 Million lm·hr for pack of 5 LED lamps. Lifetime output = 450 lm × 3 hr/day × 365 days/yr × 10 yr = 4,926,405 lm·hr. Thus LCA energy / lamp = 132 MJ/5 × 4.9264/20 = 6.5 MJ.
Operations and maintenance expenditure rate $\dot{C}^{\circ}_{OM}$, $\dot{C}^{*}_{OM}$ [$/yr]	0	0	Lifetime annual, averaged operations and maintenance (O&M) costs. Once installed assumed 0. Note: O&M costs exclude fuel (i.e., electricity) costs.
Disposal cost C°_{d}, C^{*}_{d} [$]	~~0~~ 0	~~0~~ 0	Disposal cost assumed negligible (local/doorstep recycling facility).
Ops., maint., and disposal expenditure rate, discounted $\dot{C}^{\circ}_{OMd}$, $\dot{C}^{*}_{OMd}$ [$/yr]	0	0	Sum of annualized operations, maintenance, and disposal costs.

Table 5: Lamp example: Economic parameters (2020).

Description Parameter [units]	Value	Data sources and notes
Lighting consumption prior to upgrade $\dot{q}_s^{\circ}$ [lm·hr/yr]	580,350	Calculation: (530 lm) (3 hrs/day) (365 days/yr).
Real median personal income U.S. in 2018 [$/yr]	34,317	Refer to Table 2.
U.S. 2018 disposable income / real income (minus current taxes) [–]	0.88319	Refer to Table 2.
Share of savings from 2018 disposable income [–]	0.07848	Refer to Table 2.
Personal consumption in 2018 $\dot{M}$ [$/yr]	27,~~929.83~~930	Calculation: $(\$34,317/\text{yr})(0.88319)(1-0.07848)$.
Price of electricity p_E [$/kW·hr]	0.1287	U.S. 2018 average U.S. household electricity price (US Energy Information Administration, 2020a).
Fractional spend on original energy service $f^{\circ}_{\dot{C}_s}$ [–]	0.0003028	Calculation: $8.5/yr (spend on energy service) / [$27,920/yr (other goods) + $8.5/yr (energy service)] = 0.00030, where spend on energy service = 580,350 lm·hr/yr / 8.83 lm/W / 1000 W/kW × $0.1287/kW·hr= $8.5/yr. Note: this is energy service from a single lamp.
Real discount rate r [1/yr]	0.03	**** Info here from GS justifying the value. ****
Macro factor k [–]	1.0	An initial value. See Section 4.2 for additional details.

Table 6: Lamp example: Elasticity parameters.

Description Parameter [units]	Value	Data sources and notes
Uncompensated own price elasticity of lighting demand $\varepsilon^{\circ}_{\dot{q}_s,p_s}$ [–]	-0.4	We adopt -0.4 as our baseline value, as the average of last 50 years from Fouquet (2014, Fig. 4). For comparison, Borenstein (2015) uses a range of -0.4 to -0.8, based on Fouquet & Pearson (2011).
Compensated own price elasticity of lighting demand $\varepsilon^{\circ}_{\dot{q}_s,p_s,c}$ [–]	-0.3997	Calculated via the Slutsky Equation (Eq. (175) in Part I).
Compensated cross price elasticity of demand for other goods $\varepsilon^{\circ}_{\dot{q}_o,p_s,c}$ [–]	0.00012	Calculated via Eq. (181) in Part I.
Income elasticity of lighting demand $\varepsilon_{\dot{q}_s,\dot{M}}$ [–]	1.0	Follows from CES utility function.
Income elasticity of demand for other goods $\varepsilon_{\dot{q}_o,\dot{M}}$ [–]	1.0	Follows from CES utility function.

2.2 Visualization

A rigorous rebound analysis should track energy, expenditure, and consumption aspects of rebound at the device (direct rebound) and elsewhere in the economy (indirect rebound) across adjustments for all rebound effects (emplacement, substitution, income, and macro). Doing so involves many terms and much complexity.

To date, visualizing the energy, expenditure, and consumption aspects of rebound phenomena has not been done in a numerically precise manner with a set of mutually consistent graphs.

~~We introduce rebound planes to bring clarity to~~ So we introduce *rebound planes* to help advance clarity of (direct and indirect) rebound and adjustments (via emplacement, substitution, income, and macro effects) across all aspects (energy, expenditure, and consumption). Each aspect is represented by a path in its own plane, showing adjustments in response to the EEU. The order of presentation below is energy first, followed by expenditure, ending with consumption, because the EEU triggers rebound (the topic of this article and visible in the energy plane), but is caused by expenditures on the EEU and further monetary adjustments (visible in the expenditure plane), which are calculated via details about substitution (visible in the consumption plane).

Axes of the rebound planes represent direct and indirect effects, with direct effects shown on the x-~~axis~~-axes, and indirect effects shown on the y-~~axis~~-axes. Specifically, (i) direct and indirect energy consumption rates ($\dot{E}_{dir}$, $\dot{E}_{indir}$) are placed on the x- and y-axes of the energy plane, respectively; (ii) direct and indirect expenditure rates ($\dot{C}_{dir}$ and $\dot{C}_{indir}$, discounted when appropriate) are placed on the x- and y-axes of the expenditure plane, respectively; and (iii) the indexed consumption rate of the energy service ($\dot{q}_s$) and the indexed expenditure rate of other consumption goods ($\dot{C}_o$) are placed on the x- and y-axes of the consumption plane, respectively. Paths through energy, expenditure, and consumption planes consist of segments that represent changes due to the various rebound effects. Table 7 provides the key for rebound path segments. Effects that include both direct and indirect rebound will show displacement along both axes and create a path in the x-y plane. ~~(~~See Appendix B for detailed mathematical descriptions for constructing paths on the rebound planes~~.)~~

~~Figs. ??–?? show notional energy, expenditure, and consumption planes, respectively. The notional planes are not quantified, i.e., there are no scales on the axes. Later (~~, and see Section 3 ~~),~~

Table 7: Segments in rebound planes.

Segment	Rebound effect
$\circ\,a$	Direct emplacement
$a \cdots b$	Embodied energy
$b\,*$	~~Maintenance and disposal~~ Ops. maint. and disp.
$*\,c$	Indirect substitution
$c\,\wedge$	Direct substitution
$\wedge\,d$	Direct income
$d\,-$	Indirect income
$-\,\sim$	Macro

~~rebound planes with numerical scales illustrate the car and lamp examples~~for rebound path graphs for EEU examples of a car and an electric lamp.

Each rebound plane is described in the subsections below. Reference to the rebound planes in Figs. 2–7 below will be beneficial.

2.2.1 The energy plane

~~Fig. ?? shows a notional energy plane, with~~ The energy plane (see Figs. 2 and 5 below) shows the direct energy consumption rate ($\dot{E}_{dir}$) on the x-axis and the indirect energy consumption rate ($\dot{E}_{indir}$) on the y-axis.[1] Points $\circ$, $*$, $\wedge$, $-$, and $\sim$ represent ~~the rebound~~ stages between the rebound effects ~~.~~ of Fig. 1. Points a, b, c, and d represent intermediate stages. Lines with negative slope through points $\circ$, a, $*$, $\wedge$, $-$, and $\sim$ indicate energy consumption isoquants at key points. ~~Table 7 shows segments and rebound effects for all rebound planes.~~ Note that segment $-$ $\sim$ appears only in the energy plane, because the framework tracks energy consumption but not expenditures or consumption for the macro effect.

~~Notional energy plane. See Table 7 for meanings of path segments.~~

~~In the notional energy planeof Fig. ??~~In the energy plane, point a lies on the $Re_{tot} = 0\%$ line indicating that point a (and the $Re_{tot} = 0\%$ line) is the point from which all rebound effects (Re_{empl}, Re_{sub}, Re_{inc}, and Re_{macro}) are measured. If rebound effects cause total energy demand to return to the original energy consumption level (negative sloping line through the $\circ$ point), all expected energy savings are taken back by rebound effects. Thus, the line of constant energy consumption

[1] A related, notional-only (not quantified as in Section 3), one-dimensional visualization of direct and indirect energy rebound (but not on expenditure or consumption planes) can be found in Fig. 1 of Exadaktylos & van den Bergh (2021).

through the $\circ$ point is labeled $Re_{tot} = 100\%$. The contribution of each rebound effect to total rebound is represented by the distance that each component's segment moves across the rebound isoquants. Total rebound (Re_{tot}) is measured linearly between and beyond the $Re_{tot} = 0\%$ and $Re_{tot} = 100\%$ lines, with direct rebound in the x direction and indirect rebound in the y direction. The region below and to the left of the $Re_{tot} = 0\%$ line ~~in Fig. ??~~ exhibits negative rebound, indicating hyperconservation. The region above and to the right of the $Re_{tot} = 100\%$ line shows backfire, i.e., greater total energy consumption after the EEU than before it.

~~In the notional energy plane (Fig. ??), emplacement rebound is negative ($Re_{empl} < 0$), because the upgraded device has a lesser embodied energy rate ($\dot{E}^{\circ}_{emb} > \dot{E}^{*}_{emb}$, as shown by point b being below point a) and has a lesser energy consumption rate for maintenance and disposal ($\dot{E}^{\circ}_{md} > \dot{E}^{*}_{md}$, as shown by point $*$ being below point b) due to lower expenditure rates on these two categories compared to the original device.~~

~~In Fig. ?? segments and move in the negative y direction, consistent with the description above.~~ Segment $*$—c moves in the negative y direction by definition of the indirect substitution effect, and segment c—$\wedge$ moves in the positive x direction by the definition of the direct substitution effect. Both income effect segments ($\wedge$—d and d—$-$) show more energy consumption, because net savings are spent on goods and services that rely on at least some energy consumption.[2] Segment $-$—$\sim$ always moves in the positive y direction, because macro effects lead to additional indirect energy consumption.

2.2.2 The expenditure plane

~~A notional expenditure plane is shown in Fig. ??, with~~ The expenditure plane (see Figs. 3 and 6 below) shows the direct expenditure rate on the energy service ($\dot{C}_{dir}$) on the x-axis and the indirect expenditure rate ($\dot{C}_{indir}$, discounted when appropriate) on the y-axis. Lines with negative slope through points $\circ$, a, $*$, and $\wedge$ indicate expenditure isoquants. The line through the $\circ$ point is an isoquant for the cost of purchasing the original consumption bundle at the original prices. The line through the $*$ point is an isoquant for the cost of purchasing the original consumption bundle at the

[2] We exclude the case of an inferior good, whose consumption decreases as real income increases, but we note here the possibility of such behavior. This behavior would however require a different utility model besides the CES utility model, which we use throughout this analysis.

new prices.

~~Notional expenditure plane. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments.~~

~~In the notional planes of Figs. ?? and ??, embodied energy rates and capital cost rates (represented by segments~~ Segments a⋯b and b—$*$ ~~)~~ could both move in the ~~same direction (both in the negative~~ positive y direction~~). However, segments and~~ , they could both move in the ~~positive~~ negative y direction, or they could move in opposite directions, depending on the results of the independent analyses for embodied energy and capital cost rates. The substitution effect along segments $*$—c and c—$\wedge$ will together, by definition, lead to lower expenditure due to the energy service price decline and the ~~budget reducing~~ budget-reducing compensating variation (CV). The income effect (segments $\wedge$—d and d—$-$) must bring expenditure back to the original expenditure line (equal to the budget constraint set by income in dollar or nominal terms) by assumptions about non-satiation and utility maximization in the device user's decision function.

2.2.3 The consumption plane

~~A notional consumption plane is shown in Fig. ??. The~~ The consumption plane (Figs. 4 and 7 below) shows the indexed rate of energy service consumption ($\dot{q}_s/\dot{q}_s^\circ$) ~~is shown~~ on the x-axis ~~,~~ and the indexed rate of other goods consumption ($\dot{C}_o/\dot{C}_o^\circ$) ~~is shown~~ on the y-axis. Iso-expenditure loci of indexed energy service and other goods demand, i.e. budget constraints, are shown as lines with negative slope (lines $\circ$—$\circ$, $*$—$*$, $\wedge$—$\wedge$, and $-$—$-$). Note that budget constraints $\circ$—$\circ$ and $-$—$-$ intersect at the y-axis, because the prices of other goods and services don't change as a result of the EEU. ~~(The x-axis of Fig. ?? does not extend to 0 at the left, so the intersection is not visible.)~~ Emplacement (by itself) does not alter consumption patterns, so the rate of energy service consumption and the rate of other goods consumption are unchanged across the emplacement effect ($\dot{q}_s^\circ = \dot{q}_s^*$ and $\dot{C}_o^\circ = \dot{C}_o^*$, respectively). Thus, only movements after the $*$ point are visible as a path in the consumption plane, and points $\circ$, a, b, and $*$ collapse to the same location in the consumption plane.

Indifference curves for the CES untility model are denoted by i°—i° and $\bar{\mathrm{i}}$—$\bar{\mathrm{i}}$ and represent lines of constant utility through the $\circ$ and $-$ points. Prior to the EEU, the consumption basket (of the energy service and other goods) is represented by the $\circ$ point. The budget constraint, here in real terms, i.e., the capacity to purchase either the energy service or other goods and services, is shown as isoquant $\circ$—$\circ$. The original budget constraint line ($\circ$—$\circ$) is tangent to the original indifference curve (i°—i°) at point $\circ$, the optimal consumption bundle prior to the EEU. The real budget line $*$—$*$ indicates the (higher) capacity to purchase combinations of energy services and other goods and services using the same money needed to purchase the old consumption bundle but at the new, lower price for the energy service, thanks to the EEU.

The substitution effect leads to the cheaper, optimal ~~utility-preserving~~ CES-utility-preserving consumption bundle at the $\wedge$ point. The substitution effect is shown by segments $*$—c (the indirect component, which represents the decrease in other goods consumption) and c—$\wedge$ (the direct component, which represents the increase in energy service consumption). Although the substitution effect is calculated ~~on~~ in the consumption plane, its impact can be seen in the energy and ~~expenditures planes(Figs. ?? and ??, respectively).~~ expenditure planes.

~~The~~ In the consumption plane, the income expansion path under the CES utility model is a ray (r—r) from the origin through the $\wedge$ point in the consumption plane. ~~In the consumption plane, the~~ The pre- and post-income-effect points ($\wedge$ and $-$, respectively) lie along the r—r ray, due to homotheticity. The increased consumption rate of the energy service is represented by segment $\wedge$—d~~in Figs. ??–??. The~~ , and the increased consumption rate of other goods and services is represented by segments d—$-$~~in Figs. ??–??~~.

Under non-homothetic utility models, the income expansion path will be closer to vertical in the consumption plane, as the device owner spends more net income ($\dot{\hat{N}}$) on other goods and less on the energy service. In the limit, consumption of the energy service is already satiated, so net income is spent completely on other goods, resulting in a vertical income expansion path.

~~Notional consumption plane. See Table 7 for meanings of path segments.~~

2.3 Software tools

We developed an open source `R` package called `ReboundTools` to standardize and distribute the methods for calculating rebound magnitudes in our framework. `ReboundTools` can be found at `https://github.com/MatthewHeun/ReboundTools`. (See Heun (2023).) `ReboundTools` provides functions for (i) reading input data from a spreadsheet, (ii) performing rebound calculations, and (iii) generating rebound tables and rebound planes. `ReboundTools` was used for all calculations and all rebound planes in this paper.

To find the path ~~in storage~~ to an example spreadsheet bundled with the package, users of `ReboundTools` can call the function `ReboundTools::sample_eeu_data_path()`. After filling the example spreadsheet with parameters for an EEU, users can call two functions (`ReboundTools::load_eeu_data()` and `ReboundTools::rebound_analysis()`) to perform all rebound calculations described in this paper. The function `ReboundTools::path_graphs()` creates rebound paths in the energy, expenditure, and consumption planes. Extensive documentation for `ReboundTools` can be found at `https://matthewheun.github.io/ReboundTools/`.

In addition, an Excel workbook that performs identical rebound calculations using the framework of this paper **** will be stored at the Research Data Leeds Repository if this submission is accepted. The spreadsheet file is included with the submission of this paper. **** (See Brockway et al. (2023).)

3 Results

In this section we present rebound calculation results for two examples: energy efficiency upgrades of a car (Section 3.1) and an electric lamp (Section 3.2). Univariate sensitivity studies for both examples (car and lamp) can be found in Appendix C.

3.1 Example 1: Purchase of a new car

Armed with the ~~parameter values from~~ data in Tables 1–3, and the equations in Section 2 of Part I, we calculate important values at each rebound stage, as shown in Table 8. Note that Table 8 applies to the car user. Across the macro effect (segment $-$—$\sim$ in Fig. 2), changes occur only in the macroeconomy. For the car user, no changes are recorded across the macro effect. Thus, the $-$ (bar) and $\sim$ (tilde) columns of Table 8 are identical. Rebound components for the car upgrade are shown in Table 9. Figs 2–4 show energy, expenditure, and consumption planes for the car example.

Table 8: Results for car example with macro factor (k) assumed to be 1.

	~~$\circ$ (orig~~Original ($\circ$)	~~$*$ (star~~After empl ($*$)	~~$\wedge$ (hat~~After sub ($\wedge$)	~~$-$ (bar~~After inc ($-$)	~~$\sim$ (tilde~~After macro
t_{life} [yr]	14	14	14	14	
R_α [–]	1.2	1.2	1.2	1.2	
R_ω [–]	0.8	0.8	0.8	0.8	
η [mile/gal]	25.0	42.0	42.0	42.0	
η [mile/MJ]	0.197	0.332	0.332	0.332	0
p_s [$/mile]	0.105	0.063	0.063	0.063	0
$\dot{q}_s$ [mile/yr]	12,416	12,416	13,~~336~~ 323	13,~~756~~ 899	13,~~756~~
p_E [$/MJ]	0.0208	0.0208	0.0208	0.0208	0.0
$\dot{E}_s$ [MJ/yr]	62,885	37,432	40,~~204~~ 167	41,~~470~~ 903	41,~~470~~
$\dot{E}_{emb}$ [MJ/yr]	2,429	2,857	2,857	2,857	2
$\dot{C}_s$ [$/yr]	1,306	777	~~835~~ 834	~~861~~ 870	~~861~~
$\dot{C}_{cap}$ [$/yr]	~~4,778~~ 2,533	2,518	2,518	2,518	2,
$\dot{C}_{OM}$ [$/yr]	5,050.0	4,~~720~~ 779.0	4,~~720~~ 779.0	4,~~720~~ 779.0	4,~~720~~ 7
~~$\dot{C}_{md}$~~ C_d [$]	−300	−300	−300	−300	−
$\dot{C}_d$ [$/yr]	~~2,731~~ −21	~~2,710~~ −21	~~2,710~~ −21	~~2,710~~ −21	~~2,710~~
$\dot{C}_{OMd}$ [$/yr]	5,033.0	4,762.0	4,762.0	4,762.0	4,7
$\dot{C}_o$ [$/yr]	~~19,115~~ 18,543	~~19,115~~ 18,543	~~19,040~~ 18,469	19,~~639~~ 267	19,~~639~~
$\dot{N}$ [$/yr]	0	~~608~~ 817	~~626~~ 835	0	
$\dot{M}$ [$/yr]	27,930	27,930	27,930	27,930	27

~~Results are represented graphically on energy, expenditure, and consumption planes in Figs. 2–4. The energy plane (Fig. 2) shows the size of each rebound effect for the car example. Rebound components for the car upgrade are shown in Table 9.~~

~~The energy plane for the car example. Macro factor (k) is assumed to be 1. See Table 7 for meanings of path segments.~~

~~The expenditure plane for the car example. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments.~~

~~The consumption plane for the car example. See Table 7 for meanings of path segments.~~

The emplacement effect has three components: the direct emplacement effect, the embodied energy effect, and the ~~maintenance and disposal effect~~combined operations, maintenance, and disposal effects. Rebound from the direct emplacement effect (Re_{dempl}) is 0.0% always, because energy takeback (and, therefore, rebound) occurs after the upgraded device is emplaced. Indirect

Table 9: Car example: rebound results with macro factor (k) assumed to be 1.

Rebound term	Value [%]
Re_{dempl}	0.0
Re_{emb}	1.7
~~Re_{md}~~ Re_{OMd}	−~~0.3~~ 3.4
Re_{dsub}	~~10.9~~ 10.7
Re_{isub}	−~~1.0~~ 0.9
Re_{dinc}	~~5.0~~ 6.8
Re_{iinc}	~~7.6~~ 10.2
Re_{macro}	~~7.7~~ 10.4
Re_{tot}	~~31.7~~ 35.4

rebound due to the embodied energy effect (Re_{emb}) is 1.7%, due to the higher embodied energy rate ($\Delta \dot{E}^{*}_{emb} = 429$ MJ/yr) stemming from the electric battery in the hybrid EV car. Rebound due to the ~~maintenance and disposal effect (~~~~Re_{md}~~operations, maintenance, and disposal effects (Re_{OMd}) is small and negative (~~-0.3~~-3.4%), because of the slightly lower ~~maintenance~~ operations, maintenance, and disposal costs for the hybrid EV car.

The substitution effect has two components: direct and indirect substitution effect rebound. Rebound from direct substitution (Re_{dsub}) is positive, as expected (~~10.9~~10.7%). The car user will, on average, prefer more driving purely from the change in relative prices because of the fuel economy enhancements (42 mpg > 25 mpg). In other words, due the relative price change, the more fuel-efficient car is driven ~~7.4~~7.3% further each year. Conversely, the indirect substitution effect (Re_{isub}) is slightly negative (~~-1.0~~-0.9%) to achieve the same level of utility after increased driving. Indeed, across the substitution effect, less money is spent on other goods (~~$\Delta\hat{\dot{C}}_o = -75.18$~~$\Delta\hat{\dot{C}}_o = -74.15$ \$/yr). In Appendix C.7 we show how the displacement along an indifference curve alters the price elasticities, and in particular, that the uncompensated own price elasticity declines in magnitude. The decline slows the rate of additional consumption of ~~energy intensive~~ energy-intensive driving, and attenuates the microeconomic rebound relative to assuming constant price elasticities.

The income effect also has two components: direct and indirect income effect rebound. The direct income effect (Re_{dinc}) is positive (~~5.0~~6.8%), because the car user allocates some net savings to additional driving. Rebound from the indirect income effect (Re_{iinc}) is positive (~~7.6~~10.2%) due to higher spending on other goods. Thus, the net savings after the substitution effect (~~$\hat{\dot{N}} = 625.79$~~$\hat{\dot{N}} = 834.65$ \$/yr) translates into positive direct and indirect income rebound at the microeconomic level. Total microeconomic rebound (emplacement, substitution, and income effects)

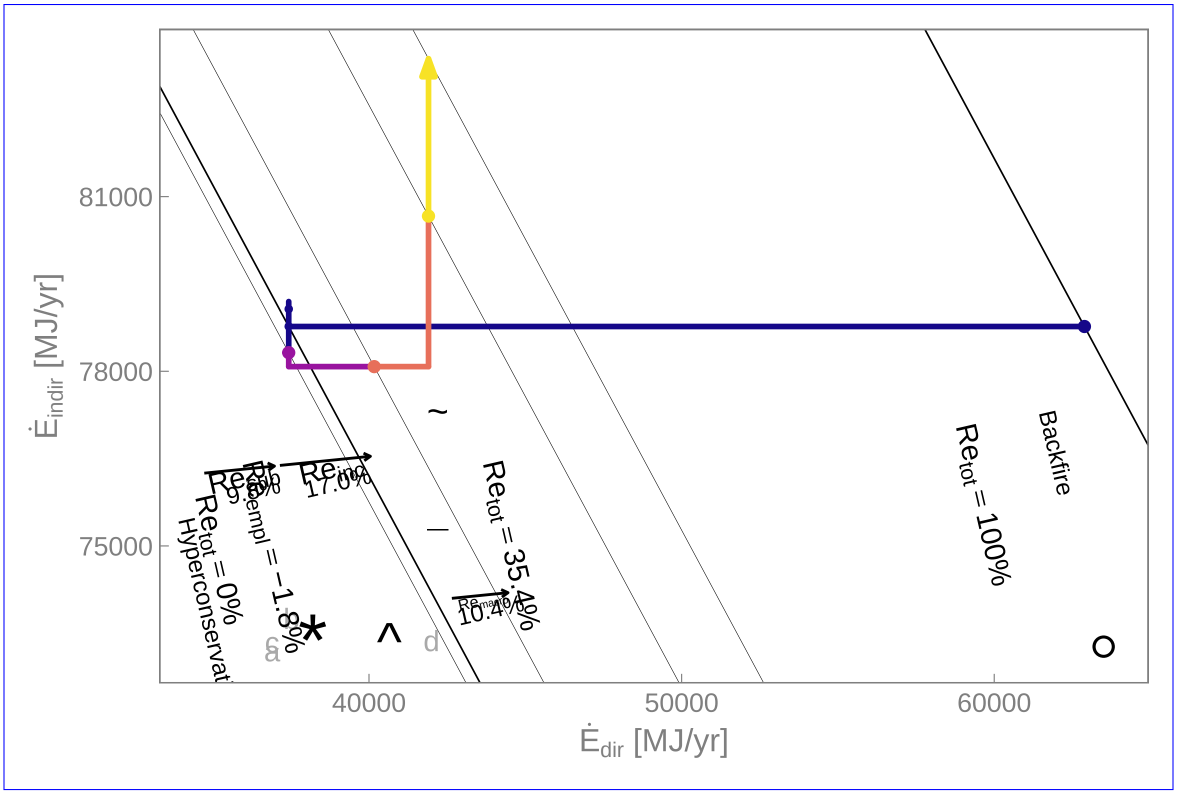

Fig. 2: The energy plane for the car example. Macro factor (k) is assumed to be 1. See Table 7 for meanings of path segments. **** MKH to fix label positions. ****

sums to ~~$Re_{micro} = 24.0$~~$Re_{micro} = 25.0$%.

Finally, in Part I we noted that the link between macroeconomic and microeconomic rebound is largely unexplored, so we assume a value of $k = 1$ for both examples, initially. We return to the ~~matter of calibrating~~ value for k in the Discussion (Section 4.2). With k assumed to be 1, the macro effect leads to macroeconomic rebound (Re_{macro}) of ~~7.7~~10.4% for the car example, due to economic expansion caused by productivity enhancements arising from the more-efficient provision of the energy service (transportation).

3.2 Example 2: Purchase of a new electric lamp

With the ~~parameter values from~~ data in Tables 4–6 and the equations in Section 2 of Part I in hand, we calculate important values at each rebound stage, as shown in Table 10. Similar to Table 8, Table 10 applies to the lamp user, so no changes are recorded across the macro effect, and the $-$ (bar) and $\sim$ (tilde) columns of Table 10 are identical. Rebound components for the lamp upgrade are shown in Table 11. Figs. 5–7 show energy, expenditure, and consumption planes for the lamp

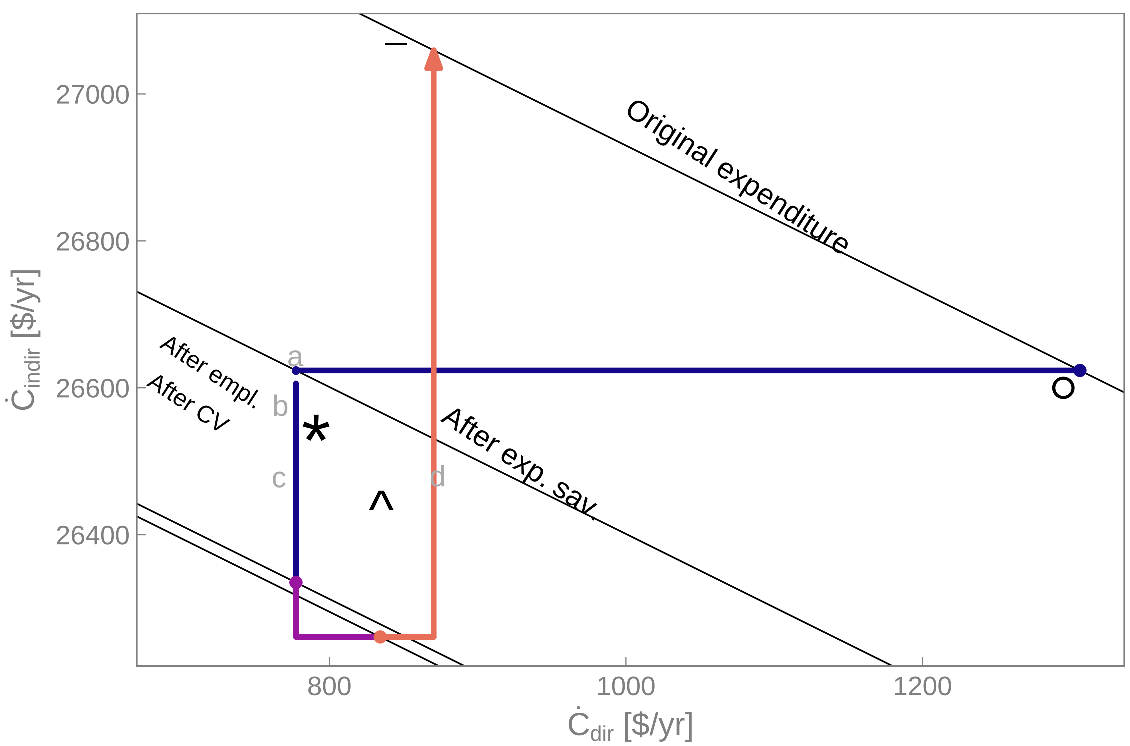

Fig. 3: The expenditure plane for the car example. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments. **** MKH to fix label positions. ****

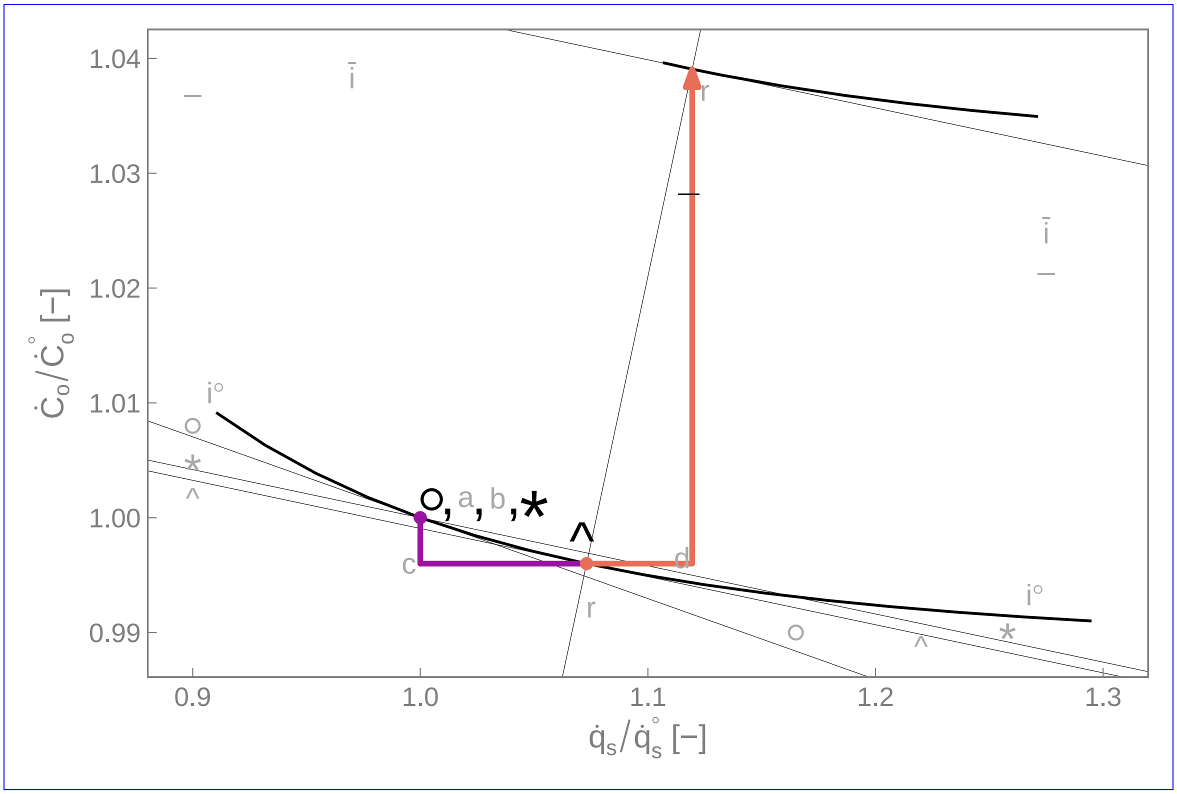

Fig. 4: The consumption plane for the car example. See Table 7 for meanings of path segments. **** MKH to fix label positions. ****

example.

~~Results are represented graphically on energy, expenditure, and consumption planes in Figs. 5–7. The energy plane (Fig. 5) shows the size of each rebound effect for the lamp example. Rebound components for the lamp upgrade are shown in Table 11.~~

The emplacement effect rebound components start with the direct emplacement effect (Re_{dempl}), which is always 0.0%. Indirect rebound due to the embodied energy effect (Re_{emb}) is -0.3%. Although the LED lamp has higher embodied energy ($E^*_{emb} = 6.50$ MJ) than the incandescent lamp ($E^\circ_{emb} = 2.20$ MJ), the LED lamp has a much longer lifetime, meaning that the LED embodied energy *rate* ($\dot{E}^*_{emb} = 0.65$ MJ/yr) is less than the incandescent embodied energy rate ($\dot{E}^\circ_{emb} = 1.22$ MJ/yr). Thus, the change in embodied energy rate ($\Delta\dot{E}^*_{emb}$) is -0.57 MJ/yr, and embodied energy rebound is negative ($Re_{emb} = -0.3\%$). Rebound due to the ~~maintenance and disposal effect (Re_{md}~~combined operations, maintenance, and disposal effects (Re_{OMd}) is 0.0%, because we assume no difference in ~~maintenance and~~ operations, maintenance, or disposal costs between the incandescent lamp and the

Table 10: Results for lamp example with macro factor (k) assumed to be 1.

	~~$\circ$ (orig~~Original ($\circ$)	~~$*$ (star~~After empl ($*$)	~~$\wedge$ (hat~~After sub ($\wedge$)	~~$-$ (bar~~After inc ($-$)	~~$\sim$ (tilde~~After mac
t_{life} [yr]	2	10	10	10	
R_α [–]	1.0	1.1	1.1	1.1	
R_ω [–]	1.0	0.8	0.8	0.8	
η [lm·hr/kW·hr]	8,833	81,800	81,800	81,800	
η [lm·hr/MJ]	2,454	22,722	22,722	22,722	
p_s [\$/lm·hr]	0.00001457	0.00000157	0.00000157	0.00000157	0.00
$\dot{q}_s$ [lm·hr/yr]	580,350	580,350	1,412,867	1,413,439	1,4
p_E [\$/MJ]	0.0358	0.0358	0.0358	0.0358	
$\dot{E}_s$ [MJ/yr]	236.5	25.5	62.2	62.2	
$\dot{E}_{emb}$ [MJ/yr]	1.222	0.650	0.650	0.650	
$\dot{C}_s$ [\$/yr]	8.46	0.91	2.22	2.22	
$\dot{C}_{cap}$ [\$/yr]	1.04	0.12	0.12	0.12	
~~$\dot{C}_{md}$~~ $\dot{C}_{OM}$ [\$/yr]	0.00	0.00	0.00	0.00	
C_d [\$]	0.00	0.00	0.00	0.00	
$\dot{C}_d$ [\$/yr]	0.00	0.00	0.00	0.00	
$\dot{C}_{OMd}$ [\$/yr]	0.00	0.00	0.00	0.00	
$\dot{C}_o$ [\$/yr]	27,920	27,920	27,916	27,927	
$\dot{N}$ [\$/yr]	0.00	~~8.47~~ 8.46	~~11.31~~ 11.30	0.00	
$\dot{M}$ [\$/yr]	27,930	27,930	27,930	27,930	

Table 11: Lamp example: rebound results with macro factor (k) assumed to be 1.

Rebound term	Value [%]
Re_{dempl}	0.0
Re_{emb}	−0.3
Re_{OMd}	0.0
Re_{dsub}	17.4
Re_{isub}	−6.4
Re_{dinc}	0.0
Re_{iinc}	17.3
Re_{macro}	13.0
Re_{tot}	41.1

LED lamp.[3]

Direct substitution effect rebound (Re_{dsub}) is 17.4% due to the much higher LED lamp efficiency ($\tilde{\eta} = 81.8$ lm/W) compared to the incandescent lamp ($\eta^\circ = 8.83$ lm/W), leading to increased demand for lighting (from $\dot{q}_s^* = 580,350$ lm·hr/yr to $\hat{\dot{q}}_s = 1,412,867$ lm·hr/yr) as shown by segment c—$\wedge$ in Fig. 7. To maintain constant utility, consumption of other goods is reduced ($\Delta\hat{\dot{C}}_o = -4.15$ \$/yr), as shown by segment $*$—c in Fig. 7, yielding indirect substitution effect rebound (Re_{isub}) of −6.4%.

Income effect rebound arises from spending net energy cost savings associated with converting from the incandescent lamp to the LED lamp (~~$\hat{\dot{N}} = 11.31$~~ $\hat{\dot{N}} = 11.30$ \$/yr). Direct income effect re-

[3]Maintenance cost rates for both incandescent and LED lamps are likely to be equal and negligible; lamps are usually installed and forgotten. Real-world disposal cost differences between the incandescent and LED technologies are also likely to be negligible. However, if "disposal" includes recycling processes, cost rates may be different between the two technologies due to the wide variety of materials in LED lamps compared to incandescent lamps.

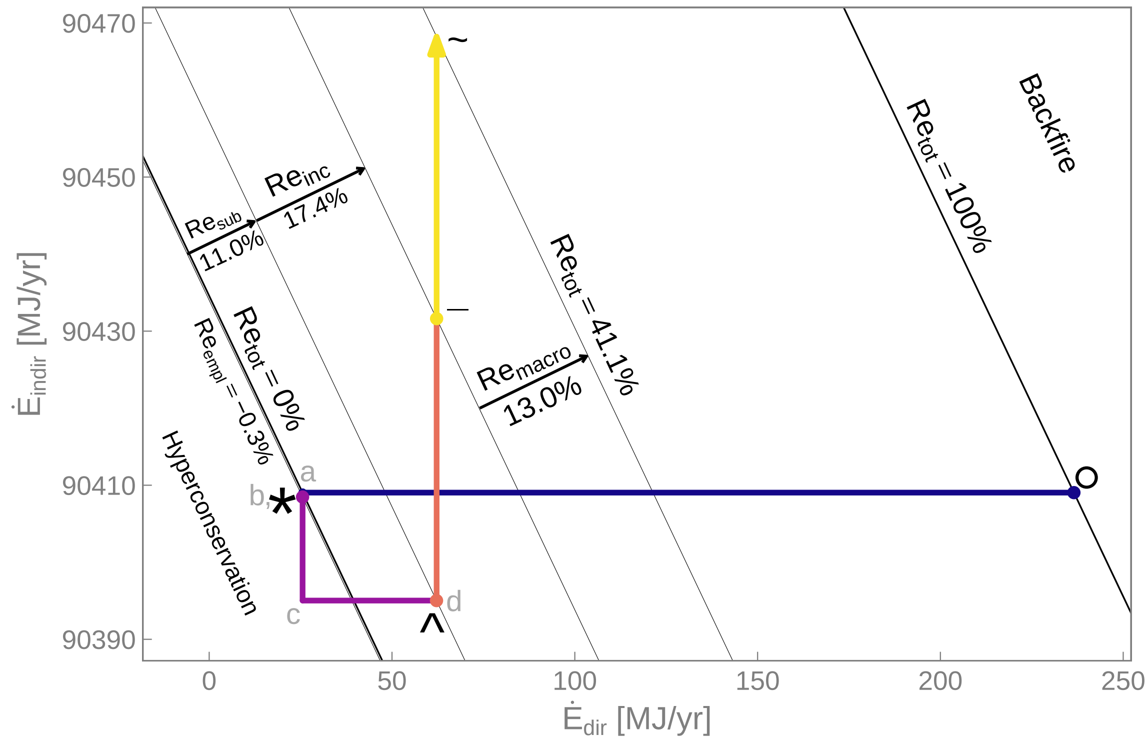

Fig. 5: The energy plane for the lamp example. Macro factor (k) is assumed to be 1. See Table 7 for meanings of path segments. **** MKH to fix label positions. ****

bound (Re_{dinc}) is 0.01%, positive but small, as the lamp user allocates some of the net savings to additional demand for lighting. The indirect income effect rebound is large (~~$Re_{iinc} = 17.4$~~$Re_{iinc} = 17.3$%), due to the energy implications of increased spending on other goods. Total microeconomic level rebound (emplacement, substitution, and income effects) sums to $Re_{micro} = 28.1\%$.

Finally, macro effect rebound (Re_{macro}) is 13.0% with k assumed to be 1, due to economic expansion caused by productivity enhancements arising from the more-efficient provision of the energy service (lighting).

~~Lamp example: rebound results with macro factor (k) assumed to be 1. Rebound term Value %Re_{dempl} 0.0 Re_{emb} −0.3 Re_{md} 0.0 Re_{dsub} 17.4 Re_{isub} −6.4 Re_{dinc} 0.0 Re_{iinc} 17.4 Re_{macro} 13.0 Re_{tot} 41.1~~

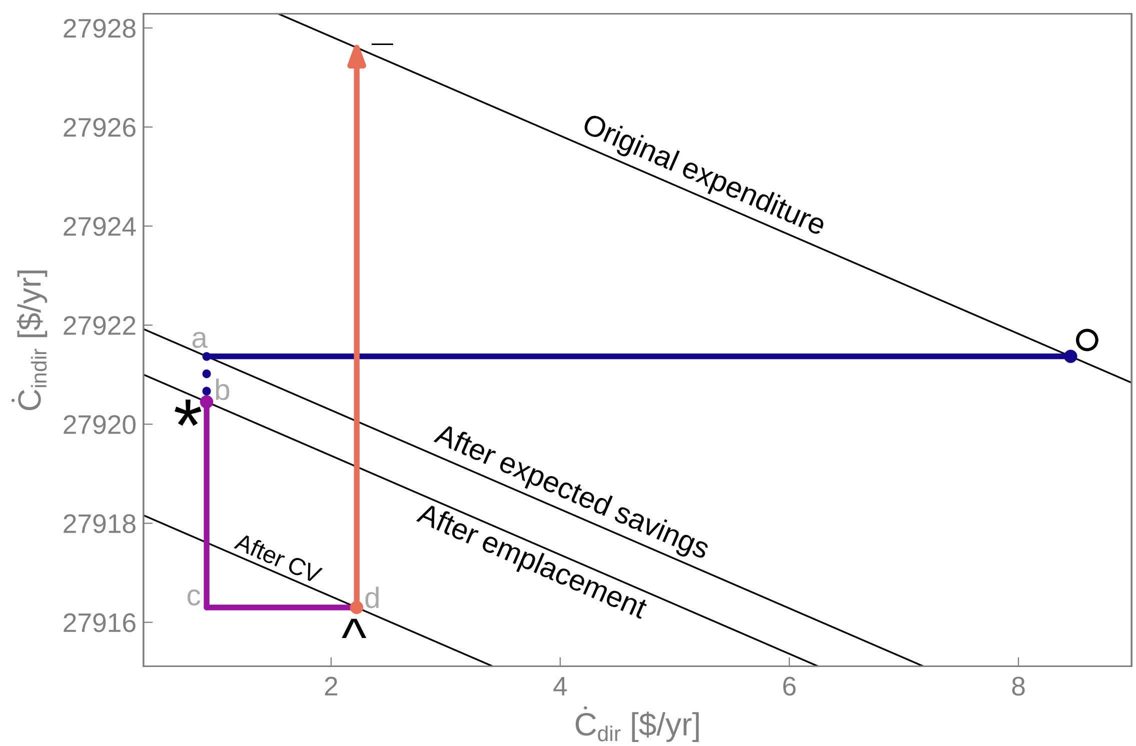

Fig. 6: Expenditure plane for the lamp example. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments. **** MKH to fix label positions. ****

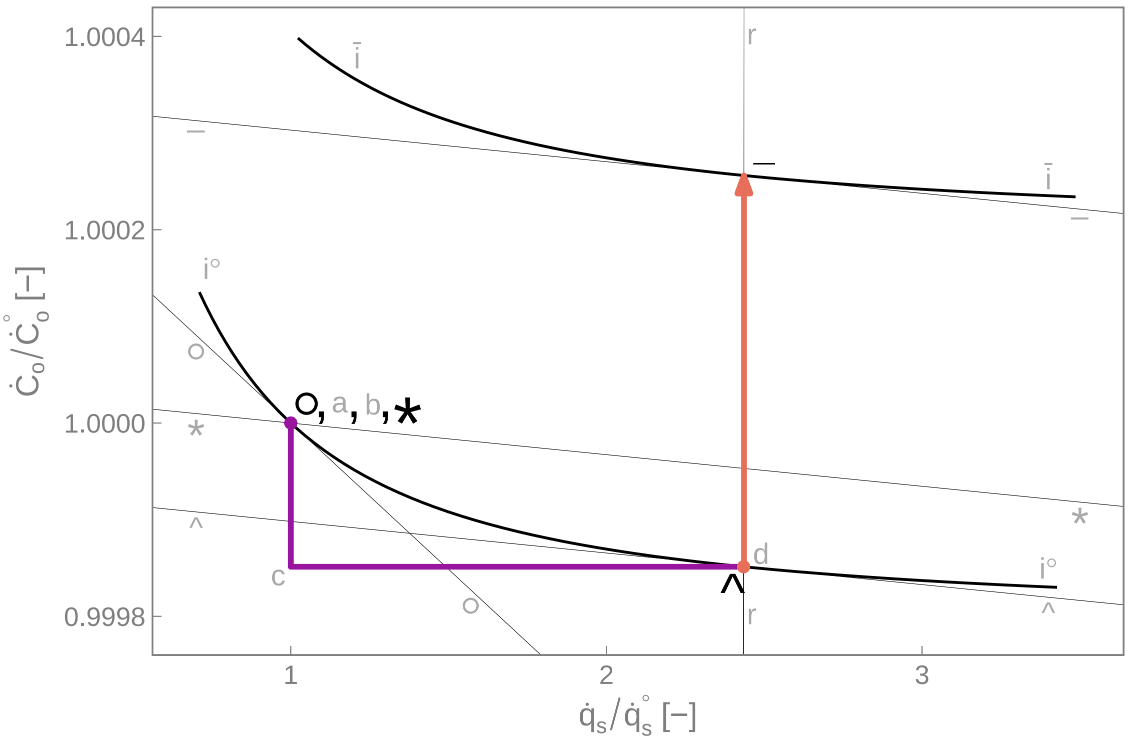

Fig. 7: Consumption plane for the lamp example. See Table 7 for meanings of path segments. **** MKH to fix label positions. ****

4 Discussion

4.1 Comparison of CES with satiated and constant price elasticity utility models

In Section 2.5.3 of Part I, we showed income-effect rebound expressions under the limiting condition of already-satiated consumption of the energy service such that the income expansion path is a vertical line in the consumption plane of Figs. 4 and 7. Here, we discuss the numerical impact of the different utility models.

Table 12 compares income-effect rebound under the CES utility model and the bounding condition of satiated consumption of the energy service. In the car example, income effect rebound (Re_{inc}) reduces from 17.0% to 10.6% when moving from the CES utility model to the bounding condition of already-satiated consumption of the energy service. Total rebound (Re_{tot}) goes from 56.2% to 49.8%. On the other hand, the lamp example shows very little change in total rebound (Re_{tot}), moving from 67.04% (CES utility model) to 67.03% (already-satiated consumption of the energy

Table 12: Comparison of substitution effects (Re_{dsub}, Re_{isub}, Re_{sub}), income effects, (Re_{dinc}, Re_{iinc}, and Re_{inc}) and total (Re_{tot}) rebound between the CES utility model and satiated consumption of the energy service for the car and lamp examples. **** MKH to fill rows and columns as suggested by GS. ****

	Car example			Lamp example		
Rebound term	CES	Satiated	CPE	CES	Satiated	CPE
Re_{dsub} [%]						
Re_{isub} [%]						
Re_{sub} [%]						
Re_{dinc} [%]	6.8	0.0		0.01	0.00	
Re_{iinc} [%]	10.2	10.6		17.35	17.35	
Re_{inc} [%]	17.0	10.6		17.36	17.35	
Re_{tot} [%]	56.2	49.8		67.04	67.03	

service).

The reason for the nearly unchanged value for total rebound (Re_{tot}) in the lamp example is evident in the consumption plane of Fig. 7. In the CES (homothetic) utility model shown in Fig. 7, there is almost no income-effect spending on more of the energy service. Almost all spending of net income ($\hat{\dot{N}}$) is on other goods. The path between the $\wedge$ and $-$ points is nearly vertical already. In contrast, the path from $\wedge$ to $-$ in the car example (Fig. 4) is decidedly *not* vertical and a reduction in income-effect rebound (Re_{inc}) is observed when moving from the CES utility model to the bounding condition of already satiated energy service consumption. Reality is probably somewhere in between.

The results shown in Table 12 indicate that each rebound situation should be analyzed independently. One should never assume that the rebound characteristics of one device will apply to another.

Calculation of substitution rebound under the constant price elasticity utility model, which approximates the sum of substitution and income effects by holding the uncompensated price elasticities constant, leads to a similar conclusion that the specific case determines the deviation of rebound from an exact model. The lower part of Table 12 shows that the sum of deviation of direct and indirect substition effect is only 0.3% in the car example but 5.5% in the lamp example. **** Change numbers in previous sentence to calculations. —MKH **** This is intuitive. The lamp example has a larger increase in energy conversion efficiency, so the change in the energy service price is farther away from the "marginal" change for which holding the price elasticity constant leads to the same rebound as the exact model. We note that whether the deviation of the approximation results in lower or higher rebound depends on the exact model comparison. For instance, in comparison with the satiated model, or a CES model with an elasticity of substition greater than one, the CPE model would overstate the substitution rebound. Appendix C.7 quantifies the change in price elasticity for both case studies.

4.2 A first attempt at ~~calibrating k~~calculating a macro rebound

Few previous studies explored the link between microeconomic and macroeconomic rebound. Inspired by Borenstein (2015) and others, the framework developed in Section 2 of Part I links macroeconomic rebound to microeconomic rebound via the macro factor (k) that scales magnitudes in the microeconomic portion of the framework. (See Section 2.5.4 of Part I.)

For the results presented in Section 3 above, we assumed a placeholder value of $k = 1$, meaning that every \$1 of spending by the device user in the income effect generates only \$1 of additional economic activity in the broader economy. ~~In combination, the framework presented in Section 2 of Part I, the results obtained in Section 3 of this paper, and recent calculations of total rebound in general equilibrium frameworks allow, for the first time, a discussion about calibrating k. After calibrating~~ There are no estimates of k, ~~macro rebound and total rebound can be calculated.~~

~~To calibrate the macro factor (~~which ultimately traces the aggregate growth effects of a single, device-specific technical progress and is likely to differ between EEUs. However, using recent empirical estimates of sectoral multipliers we can ascertain ourselves that k ~~), we treat macro rebound (Re_{macro}) as a residual. The macro factor (k) becomes an unknown parameter whose value is to be chosen such that Re_{macro} is sufficient to achieve an expected value for total rebound (Re_{tot}).~~ [4] ~~We take the expected value for Re_{tot} from Brockway et al. (2021). Four of 33 studies reviewed by Brockway et al. (2021) examined total rebound from only consumer EEUs in a computable general equilibrium (CGE) framework. The average total rebound (Re_{tot}) for the four consumer studies is 54%.~~[4] ~~The calibrated values of k that give identical $Re_{tot} = 54\%$ for both examples are $k = 3.9$ for the car example and $k = 2.0$ for the lamp example.~~

[4] ~~This approach means that the calibrated value of k incorporates all macroeconomic rebound sub-effects included in the studies whose total rebound value we calibrate against.~~

[4] ~~The average total rebound among all 33 studies stood at 63%, supporting the claim by Turner (2013) that consumer and producer rebounds vary.~~

~~Qualitative differences in benefits from EEUs as well as the considerable variance in Re_{tot} in 33 surveyed studies (Brockway et al., 2021) indicates that total rebound from one EEU is likely to be different from total rebound from another EEU. For a first approximation of a calibration for k, we take $k \approx 3$, being between the values of k calculated from the car and lamp examples. Note that $k \approx 3$ implies that every \$~~should be different from 1 ~~of net savings spent by the device user ($\dot{N}^*$) generates \$3 of additional economic activity in the broader economy. We multiply $k\dot{N}^*$ by the energy intensity of the economy (I_E) to find the energy implications of macro-effect respending throughout the economy.~~ and choose a different value in line with those estimates.

~~There are three ways to interpret $k \approx 3$. First , $k \approx 3$ can be considered the average long-run economic growth generated by the productivity increase implied by the EEU and subsequent productivity increases benefitting from the EEU.Efficiency increases in equipment drive a significant part of long-run productivity growth (Greenwood et al., 1997), therefore a large long-run effect is plausible, even if the initial productivity change occurred in household production which is not accounted in GDP. (See Section 2.5.4 of Part I for further discussion of this point.) Second, it could be that growth is less than \$~~Sectoral multipliers capture the impact of sectoral revenue increases into aggregate demand or GDP growth. While the idea of scale economies from larger markets for particular products have a long history in economic thought dating back at least to Smith (1776) , data from input-output tables and recent advances in network theory allowed formalization of the spill-overs from sectoral to aggregate growth. First results show that U.S. aggregate output growth may have been up to 3 ~~for every \$1 of respending, but that the macroeconomic "energy price effect" (a decline in energy prices due to the fallen demand) induces consumption at a higher energy intensity than that of the pre-EEU economy. Third, from the demand-side perspective entertained by Borenstein (2015), $k \approx 3$ could be interpreted as growth induced by the device user's spending of net savings with a marginal propensity to consume (MPC) of approximately 0.75 that translates into a multiplier of~~ times as large as the growth of the sector in which growth originated (Foerster et al., 2022). And industrial policy to encourage technology adoption in certain sectors was found to pay back up to 5 times its cost in India, but with wide variation across sectors (Buera & Trachter, 2024). Since our problem also concerns technology adoption, one that features energy augmenting technical change, we take the value from the Buera & Trachter (2024) study, where the majority of multipliers cluster around 3. ~~(See Fig. ?? in Appendix ?? of Part I.)~~ ~~$MPC \approx 0.75$ is a reasonable value, being in the upper half of recent estimates from Carroll et al. (2017). Although the cause of the growth in economic activity and energy consumption from an EEU is a supply-side productivity shock, the subsequent demand-side effects may well be interpreted as a multiplier effect, caused by higher real income instead of by higher monetary income~~Thus, we adopt the value of $k = 3$, fully aware that this can only be a first approximation.

After ~~calibrating $k \approx 3$~~setting $k = 3$, we can recalculate all rebound components in our framework. Emplacement (Re_{empl}), substitution (Re_{sub}), and income (Re_{inc}) rebound magnitudes are unchanged after ~~calibrating $k \approx 3$~~setting $k = 3$. However, we see that choosing a placeholder value of $k = 1$ resulted in a low value for Re_{macro} and, therefore, Re_{tot} in Section 3. In Figs. 2 and 5, the macro effect segments (−—∼) should be three times longer than they appear. In Tables 9 and 11, the values of macro rebound (Re_{macro}) should triple to ~~23.2~~31.2% and 39.0%, and the values of total rebound (Re_{tot}) should increase to ~~47.2% and 67.1~~56.2% and 67.0% for the car and lamp examples, respectively. For the remainder of this paper, we use ~~the calibrated value of $k \approx 3$~~$k = 3$.

4.3 Comparison between the car and lamp case studies

Tables 9 and 11 and ~~our calibration of $k \approx 3$~~ selection of $k = 3$ in Section 4.2 enable fuller comparisons between the car and lamp examples. Several points can be made.

First, the magnitude of every rebound effect is different between the two examples, the exception being direct emplacement rebound (Re_{dempl}) which is always 0.0% by definition. The implication is that every EEU needs to be analyzed separately. Values for rebound effects for one EEU should never be assumed to apply to a different EEU.

Second, one cannot know *a-priori* which rebound effects will be large and which will be small for a given EEU. Furthermore, some rebound effects are dependent upon economic parameters, such as energy intensity (I_E). Thus, it is important to calculate the magnitude of all rebound effects for each EEU in each economy.

Third, the two examples illustrate the fact that embodied energy rebound (Re_{emb}) can be positive or negative, as discussed in Section 2.5.1 of Part I. The car's embodied energy rebound is positive (1.7%) because of the high embodied energy of the ~~EV~~hybrid's battery relative to the internal combustion engine vehicle. Although the LED lamp's embodied energy is larger than the incandescent lamp's embodied energy, the LED lamp's embodied energy rebound is small but negative (−0.3%), due to the longer life of the LED lamp compared to the incandescent lamp. Thus, each EEU should be analyzed independently for its embodied energy rebound.

Fourth, macro effect rebound is different between the two examples, owing to differences in net income ($\dot{N}^*$) relative to expected savings ($\dot{S}_{dev}$). (For the car, Re_{macro} is ~~23.2~~31.2%. For the lamp, Re_{macro} is 39.0%.) The efficiency gain for the lamp is far greater than the efficiency gain for the car, leading to much different rates of net income ($\dot{N}^*$) and different macro rebound values.

4.4 Comparison to previous rebound estimates

Tables 13 and 14 compare car and lamp results (with ~~$k \approx 3$~~$k = 3$) to results from previous studies. The ~~comparison studies are~~ suite of comparison studies is neither comprehensive nor definitive of car and lamp EEUs; rather, they are examples that show the sort of calculations and estimations carried out in the general literature using a variety of methods. That said, many of the studies are highly cited, thereby carrying sufficient academic weight for our purposes. Tables 13 and 14 and their associated references enable two types of observations, comparing (i) coverage of rebound components and (ii) magnitudes and associated calculation or estimation methods.

Table 13: Rebound magnitude comparisons for the car example. All numbers in %. Note that $Re_{tot} = Re_{empl} + Re_{sub} + Re_{inc} + Re_{macro}$, $Re_{tot} = Re_{micro} + Re_{macro}$, and $Re_{tot} = Re_{dir} + Re_{indir}$.

	Rebound study	Coverage	Analysis method	Re_{empl}	Re_{micro} Re_{sub}	Re_{inc}	Re_{macro}	Re_{dir}	Re_{indir}	Re_{tot}
	This paper (~~2023~~2024)	U.S., 2020	Energy, expenditure, and consumption planes	~~1.4~~ −1.8	~~9.9~~ 9.8	~~12.6~~ 17.0	~~23.2~~ 31.2	~~15.9~~ 17.6	~~31.3~~ 38.6	~~47.2~~ 56.
1	Small & Van Dender (2007)	U.S., 1967–2001	Elasticity of VMT w.r.t. fuel cost per mile					4.5 (short run, 1967–2001) 22.2 (long run, 1967–2001) 2.2 (short run, 1997–2001) 10.7 (long run, 1997–2001)		
2	Greene (2012)	U.S., 1966–2007	Elasticities of transport fuel w.r.t. price & efficiency					4 (short run) 16 (long run)		
3	Koesler (2013)	Germany, 2009	Static CGE model, 10% efficiency shock					≤ 64	≤ 16	56
4	Thomas & Azevedo (2013)	U.S., 2004	Expenditure/cross price elasticities of personal transport fuels, using household spending survey data					10	6	
5	Borenstein (2015)	U.S., 2012	Microeconomic framework		13 (6–28)	11				
6	Chitnis & Sorrell (2015)	UK, 1964–2014	Estimated own/cross price elasticities of transport fuels, uses household spending survey data		72	5		55	23	86
7	Gillingham et al. (2015)	Pennsylvania, 2000–2010	Estimation of gasoline price elasticity of driving demand, from dataset of 75 million vehicle inspection records, including odometer data					10 (short run)		
8	Stapleton et al. (2016)	UK 1970–2011	Elasticity of VMT w.r.t. fuel cost/prices					9–36		
9	Moshiri & Aliyev (2017)	Canada, 1997–2009	Price elasticity of transport fuel, using household spending survey data					82–88		
10	Duarte et al. (2018)	Spain, 2010–2030	Dynamic CGE model, efficiency shock							26 (short ru 52 (long ru

Table 14: Rebound magnitude comparisons for the lamp example. All numbers in %. Note that $Re_{tot} = Re_{empl} + Re_{sub} + Re_{inc} + Re_{macro}$, $Re_{tot} = Re_{micro} + Re_{macro}$, and $Re_{tot} = Re_{dir} + Re_{indir}$.

	Rebound study	Coverage	Analysis method	Re_{empl}	Re_{micro} Re_{sub}	Re_{inc}	Re_{macro}	Re_{dir}	Re_{indir}	Re_{tot}
	This paper (~~2023~~2024)	U.S., 2020	Energy, expenditure, and consumption planes	−0.3	11.0	17.4	39.0	17.4	49.7	~~67.1~~ 67.0
1	Guertin et al. (2003)	Canada, 1993	Econometric residential energy demand model based on Canadian household data					32–49		
2	Freire-González (2011)	Catalonia, Spain, 2000–2008	Input-output based energy model, utilising expenditure/cross price elasticities					49	16	
3	Thomas & Azevedo (2013)	U.S., 2004	Expenditure/cross price elasticities of home electricity use, using household spending survey data					10	10	
4	Schleich et al. (2014)	Germany, 2012	Survey of electricity consumption in 6409 German households					6		
5	Borenstein (2015)	U.S., 2012	Microeconomic framework		14 (6–37)	6				
6	Chitnis & Sorrell (2015)	UK, 1964–2014	Estimated own/cross price elasticities of transport fuels, uses household spending survey data		14	35		41	8	49
7	Duarte et al. (2018)	Spain, 2010–2030	Dynamic CGE model, efficiency shock							12 (short run) 51 (long run)
8	Barkhordar (2019)	Iran, 2018–2040	Dynamic CGE model					28 (average)		43 (average)
9	Chitnis et al. (2020)	UK, 1964–2015	Household demand analysis via Linear approximation to the Almost Ideal Demand System (LAIDS)					95	−41	54
10	Shojaeddini & Gilbert (2022)	U.S., 2009	Price elasticity of lighting from cross sectional data from the 2009 Residential Energy Consumption Survey (RECS)					18–29		

First, we see that none of the comparison studies report all rebound effects ~~, as we have done in Sections 3.1, 3.2, and 4.2~~considered in this paper. Also, no previous studies report either emplacement rebound ($\cancel{Re_{empl} = Re_{emb} + Re_{md}}$$Re_{empl} = Re_{emb} + Re_{OMd}$) or include all of direct and indirect, substitution and income microeconomic rebound effect combinations. In addition, none of the other studies report macro rebound (Re_{macro}) by itself. In fact, only 4 ~~or~~ and 5 of the 10 studies in each category (car and lamp, respectively) report total rebound (Re_{tot}). Therefore, by carefully including all rebound components in the framework and elucidating all rebound components in Part II, we are (i) ~~adding conceptual clarity to~~ helping to advance conceptual clarity in the field of energy rebound, which (ii) may enable future studies to estimate a broader range of rebound components.

We also observe that studies which provide total rebound are based on a top-down calculation of overall, economy-wide rebound, rather than the bottom-up "sum-of-components" approach that we employ. That finding is instructive. It supports the view that a rigorous analysis framework that sets out individual rebound components has been missing, which informed the objective for Part I of this paper. Further, the finding means that comparisons between top-down estimations or calculations of total, economy-wide rebound may also be of limited value, because the rebound effects included or excluded may not be clear, giving an appearance of a "black box" calculation approach.[4]

Second, helpful insights can be gained from comparison of rebound magnitudes and calculation methods. Greatest alignment between our values and earlier values appears within the direct (microeconomic) rebound (Re_{dir}) column in Tables 13 and 14. Our car (~~15.9~~17.6%) and lamp (17.4%) values are in the lower half of the comparison studies for both cases (10% to 49% for the car and 10% to 55% for the lamp). This alignment may be due to the easier determination of direct rebound, from either empirical data (e.g., Small & Van Dender (2007)) or via own price elasticities (e.g., Chitnis & Sorrell (2015)).[5]

For indirect rebound (Re_{indir}), there is little agreement on the magnitude of rebound effects.

[4]That said, without the top-down approaches, we would not have the information needed to calibrate the macro factor (k) in Section 4.2.

[5]Also worthy of note is that direct (microeconomic) rebound of personal transport may be the most-studied subfield in the rebound literature and likely the only topic with enough studies to enable meta-reviews such as Sorrell et al. (2009), Dimitropoulos et al. (2018), and Gillingham (2020).

Our values for car (~~31.3~~38.6%) and lamp (49.7%) indirect rebound magnitudes are higher than those found in the comparison studies for either the car (6% to 23%) or the lamp (8% to 16%) cases. The most likely cause of our larger indirect rebound values is that we include both micro and macro rebound levels, whereas the comparison studies focus mainly on microeconomic rebound only (commonly via cross price elasticities). In other words, comparisons of our indirect rebound values with the studies in Tables 13 and 14 may be too simple and not very meaningful, as we (alone) include macro-level effects in indirect rebound. If we exclude Re_{macro} from Re_{indir}, our indirect microeconomic rebound values become ~~8.1~~7.5% (car) and 10.7% (lamp), which fit within the ranges reported by the car (6% to 23%) and lamp (−41% to 16%) comparison studies.

For total rebound (Re_{tot}), our values of ~~47.2~~56.2% (car) and ~~67.1~~67.0% (lamp) are very close to those in the comparison studies for both the car (49% to 51%) and lamp (43% to 51%) examples. Beyond that, comparisons (as noted earlier) are inhibited by methodological differences between previous studies (top-down methods) and our bottom-up approach for calculating total rebound.

4.5 Price effect

Section 3.2, Eq. (36), and Appendix F of Part I provide an extension to the framework involving energy price effect rebound (Re_{p_E}). This section quantifies price-effect rebound for the car and lamp examples.

To quantify price-effect rebound, data are needed for personal consumption ($\dot{E}^\circ$) of the type of energy used by the device, including energy for the upgraded device and all other devices. For the car example, there is typically little other gasoline consumption besides for cars, so we assume $\dot{E}^\circ$ equal to $\dot{E}_s^\circ/0.95$. For the lamp example, a median U.S. household consumes about 10,000 kW·hr/yr of electricity (U.S. Energy Information Agency, 2023). Given that there are 2.5 persons per household (Statista, 2024), the consumer consumes electricity at a rate of $\dot{E}^\circ = 4000$ kW·hr/yr.

We also need data for the price elasticity of energy supply ($\varepsilon_{\dot{Q}_E, p_E}$). For the car case, we take the price elasticity of gasoline supply to be 0.29 from Coyle et al. (2012). For the lamp case, we adopt the value of 0.33 from Ghoddusia & Roy (2017, Table 3).

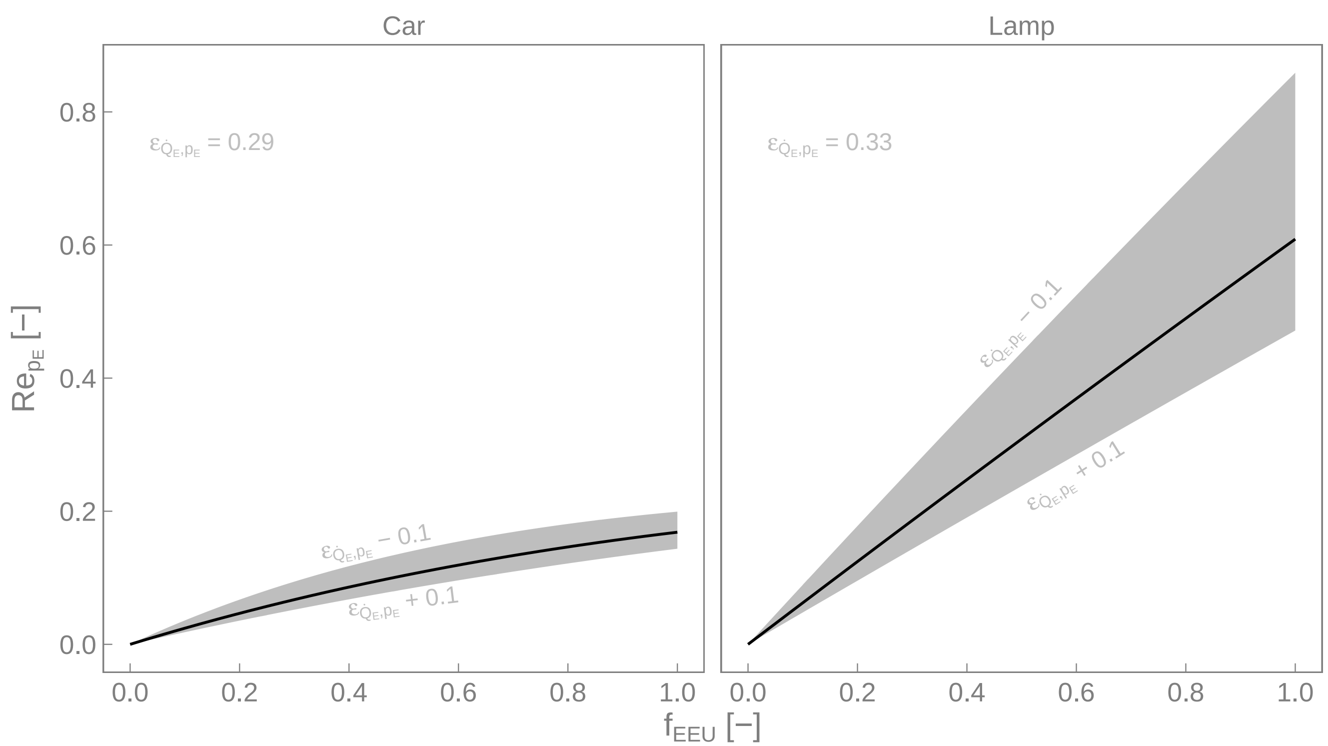

Fig. 8: Energy price effect rebound (Re_{p_E}) as a function of the fraction of all devices replaced by higher-efficiency versions (f_{EEU}). Black lines represent the nominal energy price elasticity of energy supply ($\varepsilon_{\dot{Q}_E,p_E}$). Gray bands provide ± 0.1 range in $\varepsilon_{\dot{Q}_E,p_E}$.

Parameterizing on the fraction of all devices in the economy that are upgraded (f_{EEU}) and the energy price elasticity of energy supply ($\varepsilon_{\dot{Q}_E,p_E}$) yields Figure 8. As expected, price-effect rebound (Re_{p_E}) grows as more devices are upgraded, i.e., as f_{EEU} increases. Furthermore, inelastic energy supply (smaller $\varepsilon_{\dot{Q}_E,p_E}$) leads to higher price-effect rebound.

In these examples, the car upgrade yields little additional freed cash beyond the (slightly) cheaper fuel for the car, so there is limited spending on other goods and services and little additional indirect energy demand. In contrast, the upgrade of the electric lamp is much more likely to provide energy price effect rebound, because electricity for the upgraded lamp is a small fraction of total electricity consumption by the consumer. *All* electricity purchased by the consumer becomes cheaper when the price of electricity falls due to widespread lamp upgrades throughout the economy, leading to freed cash spent on other goods and services which, themselves, demand energy at the energy intensity of the economy.

At 100% penetration of LED lamps ($f_{EEU} = 1$) and at the nominal energy price elasticity of supply ($\varepsilon_{\dot{Q}_E,p_E} = 0.33$), price effect rebound is $Re_{p_E} = 60.9\%$. Combined with consumer sided rebound of 67.0% from Section 4.2, the sum of consumer-sided and supply-side rebound is 127.9%, demonstrating that backfire could occur under conditions of full penetration of the lamp EEU.

5 Conclusions

In this paper (Part II), we ~~advance clarity to~~ help to advance clarity in the field of energy rebound by (i) developing ~~of the first (to our knowledge)~~ mutually consistent and numerically precise visualizations of rebound effects in energy, expenditure, and consumption planes, (ii) ~~calibrating~~ operationalizing the macro factor ~~($k \approx 3$)~~ and selecting $k = 3$, (iii) documenting in detail new calculations of rebound for car and lighting upgrades, (iv) showing the extensibility of our framework by applying it to estimate price effect rebound, and (v) providing information about new open source software tools for calculating and visualizing rebound for any energy efficiency upgrade. We encourage energy analysts and economists to use visualizations like the energy, expenditure, and consumption planes to document rebound calculations going forward. Our hope is that additional clarity will (i) narrow the gap between economists and energy analysts, (ii) lead to deeper interdisciplinary understanding of rebound phenomena, and (iii) enable energy and climate policy that takes full account of rebound.

From the development and application of the framework in Part II, we draw two important conclusions. First, the car and lamp examples (Section 3) show that the framework enables quantification of rebound magnitudes at microeconomic and macroeconomic levels, including energy, expenditure, and consumption aspects of direct and indirect rebound for emplacement, substitution, income, and macro effects. Second, the examples show that magnitudes of all rebound effects vary with the type of EEU performed. Thus, values for rebound effects for one EEU should never be assumed to apply to a different EEU, and it is important to calculate the magnitude of all rebound effects for each EEU in each economy.

Further work could be pursued in several areas. (i) Additional empirical studies could be performed to calculate the magnitude of different rebound effects for a variety of real-life EEUs. (ii) Deeper study of macro rebound is needed, including improved determination of the value of the macro factor (k)~~and its relation to the MPC~~. (iii) The ~~rebound implications of~~ framework could be used to study the distribution of ~~*MPC*~~ rebound values across socioeconomic and demographic groups (Carroll et al., 2017)~~could be explored~~. (iv) The rebound effects of fossil-energy taxes could be studied, especially for the web of interconnected dynamic effects among rebound components that are functions of the energy intensity of the economy (I_E). (v) Sensitivities of rebound components to model parameters could be investigated more fully than in Appendix C, although this will be challenging work because many rebound parameters are covariant. For example, post-EEU efficiency ($\tilde{\eta}$) is unlikely to be independent of post-EEU capital cost ($\tilde{C}_{cap}$). (vi) The framework could be extended to encompass fuel-switching EEUs, such as the move from a gasoline car to an all-electric car. (vii) This framework could be embedded in energy-economy models to better include rebound effects in discussions of macro energy modeling, energy policy, and CO_2 emissions mitigation.

Competing interests

Declarations of interest: none.

Author contributions

Author contributions for this paper (Part II of the two-part paper) are shown in Table 15.

Table 15: Author contributions.

	MKH	GS	PEB
Conceptualization	●	●	
Methodology	●	●	●
Software	●		●
Validation	●		●
Formal analysis	●	●	
Investigation	●	●	●
Resources	●	●	●
Data curation			●
Writing–original draft	●	●	
Writing–review & editing	●	●	●
Visualization	●	●	
Supervision	●		
Project administration	●		
Funding acquisition			●

Data repository

**** Data and example calculations in spreadsheet format will be stored at the Research Data Leeds Repository if this submission is accepted. The spreadsheet file is included with the submission of this paper. ****

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Table A.1: Symbols and abbreviations.

Symbol	Meaning [example units]
a	a point in the emplacement effect in rebound planes or the share parameter in the CES utility model [–]
b	a point in the emplacement effect in rebound planes
C	cost [$]
c	a point in the substitution effect in rebound planes
d	a point in the income effect on rebound planes
E	final energy [MJ]
f	expenditure share [–]
G	freed cash [$]
I	energy intensity of economic activity [MJ/$]
k	macro factor [–]
M	income [$]
N	net savings [$]
p	price [$]
q	quantity [–]
R	multiplicative term that accounts for discounting [–]
Re	rebound [–]
r	real discount rate [1/yr]
S	energy cost savings [$]
t	energy conversion device lifetime [yr]
u	utility [utils]
x	the abscissa coordinate
y	the ordinate coordinate

Appendices

A Nomenclature

Presentation of the rigorous analytical framework is aided by a nomenclature that describes energy stages and rebound effects. Table A.1 shows symbols and abbreviations, their meanings, and example units. Table A.2 shows Greek letters, their meanings, and example units. Table A.3 shows abbreviations and acronyms. Table A.4 shows symbol decorations and their meanings. Table A.5 shows subscripts and their meanings.

Differences are indicated by the Greek letter Δ and always signify subtraction of a quantity at an earlier stage of Fig. 1 from the same quantity at the next later stage of Fig. 1. E.g., $\Delta\bar{X} \equiv \bar{X} - \hat{X}$, and $\Delta\tilde{X} \equiv \tilde{X} - \bar{X}$. Lack of decoration on a difference term indicates a difference that spans all stages of Fig. 1. E.g., $\Delta X \equiv \tilde{X} - X^{\circ}$. ΔX is also the sum of differences across each stage in Fig. 1, as shown below.

Table A.2: Greek letters.

Greek letter	Meaning [example units]
α	subscript that indicates capital cost payments at beginning of life
Δ	difference (later quantity less earlier quantity, see Fig. 1)
ε	price or income elasticity [–]
$\varepsilon_{\dot{q}_s,\dot{M}}$	income ($\dot{M}$) elasticity of energy service demand ($\dot{q}_s$) [–]
$\varepsilon_{\dot{q}_o,\dot{M}}$	income ($\dot{M}$) elasticity of other goods demand ($\dot{q}_o$) [–]
$\varepsilon_{\dot{q}_s,p_s}$	uncompensated energy service price (p_s) elasticity of energy service demand ($\dot{q}_s$) [–]
$\varepsilon_{\dot{q}_o,p_s}$	uncompensated energy service price (p_s) elasticity of other goods demand ($\dot{q}_o$) [–]
$\varepsilon_{\dot{q}_s,p_s,c}$	compensated energy service price (p_s) elasticity of energy service demand ($\dot{q}_s$) [–]
$\varepsilon_{\dot{q}_o,p_s,c}$	compensated energy service price (p_s) elasticity of other goods demand ($\dot{q}_o$) [–]
η	final-energy-to-service efficiency [vehicle-km/MJ]
ω	subscript that indicates disposal cost at end of life
ρ	exponent in the CES utility function, $\rho \equiv (\sigma - 1)/\sigma$ [–]
σ	elasticity of substitution between the energy service ($\dot{q}_s^\circ$) and other goods ($\dot{q}_o^\circ$) [–]

Table A.3: Abbreviations.

Abbreviation	Meaning
APF	aggregate production function
CES	constant elasticity of substitution
CGE	computable general equilibrium
CPE	constant price elasticity
CV	compensating variation
EEU	energy efficiency upgrade
EPSRC	engineering and physical sciences research council
EV	electric vehicle
GDP	gross domestic product
LAIDS	linear approximation to almost ideal demand system
LED	light emitting diode
MPC	marginal propensity to consume
mpg	miles per U.S. gallon
RECS	residential energy consumption survey
UK	United Kingdom
UKRI	UK research and innovation
U.S.	United States
VMT	vehicle miles traveled
w.r.t.	with respect to

Table A.4: Decorations.

Decoration	Meaning [example units]
X°	X originally (before the emplacement effect)
X^*	X after the emplacement effect (before the substitution effect)
$\hat{X}$	X after the substitution effect (before the income effect)
$\bar{X}$	X after the income effect (before the macro effect)
$\tilde{X}$	X after the macro effect
$\dot{X}$	rate of X [units of X/yr]
M'	effective income [$]

Table A.5: Subscripts.

Subscript	Meaning
0	quantity at an initial time
1	a specific point on the consumption plane
c	compensated
cap	capital costs
dev	device
dempl	direct emplacement effect
dinc	direct income effect
dir	direct effects (at the energy conversion device)
dsub	direct substitution effect
E	energy
emb	embodied
empl	emplacement effect
iempl	indirect emplacement effects
iinc	indirect income effect
inc	income effect
indir	indirect effects (beyond the energy conversion device)
isub	indirect substitution effect
life	lifetime
macro	macro effect
md	maintenance and disposal
o	other expenditures (besides energy) by the device user
own	ownership duration
s	service stage of the energy conversion chain
sub	substitution effect
tot	sum of all rebound effects in the framework

$$\Delta X = \Delta\tilde{X} + \Delta\bar{X} + \Delta\hat{X} + \Delta X^{*}$$

$$\Delta X = (\tilde{X} - \bar{X}) + (\bar{X} - \hat{X}) + (\hat{X} - X^{*}) + (X^{*} - X^{\circ})$$

$$\Delta X = (\tilde{X} - \cancel{\bar{X}}) + (\cancel{\bar{X}} - \cancel{\hat{X}}) + (\cancel{\hat{X}} - \cancel{X^{*}}) + (\cancel{X^{*}} - X^{\circ})$$

$$\Delta X = \tilde{X} - X^{\circ} \tag{1}$$

B Mathematical details of rebound planes

Rebound planes show the impact of direct and indirect rebound effects for energy, expenditure, and consumption aspects. ~~Notional rebound planes can be found in Figs. ??–??.~~ Rebound planes for the car example can be found in Figs. 2–4. Rebound planes for the lamp example can be found in Figs. 5–7.

This appendix shows the mathematical details of rebound planes, specifically derivations of equations for lines and curves shown in Table B.1. The lines and curves enable construction of numerically precise and accurate paths in rebound planes as shown in Figs. 2–7.

Table B.1: Lines and curves for rebound planes.

Rebound plane	Lines and curves
Energy	Constant total energy consumption lines 0% and 100% rebound lines
Expenditure	Constant expenditure lines
Consumption	Constant expenditure lines Rays from origin to $\wedge$ point Indifference curves

B.1 Energy planes

The energy plane shows direct (on the x-axis) and indirect (on the y-axis) energy consumption associated with the energy conversion device and the device user. Lines of total energy consumption isoquants provide a scale for total rebound. For example, the 0% and 100% rebound lines are constant total energy consumption lines which pass through the original point ($\circ$) and the post-direct-emplacement-effect point (a) in the energy plane.

The equation of a constant total energy consumption line is derived from

$$\dot{E}_{tot} = \dot{E}_{dir} + \dot{E}_{indir} \tag{2}$$

at any rebound stage. Direct energy consumption is energy consumed by the energy conversion device ($\dot{E}_s$), and indirect energy consumption is the sum of embodied energy, energy associated with maintenanace and disposal, and energy associated with expenditures on other goods ($\cancel{\dot{E}_{emb} + (\dot{C}_{md} + \dot{C}_o) I_E}\dot{E}_{emb} + (\dot{C}_{OMd} + \dot{C}_o) I_E$).

For the energy plane, direct energy consumption is placed on the x-axis and indirect energy consumption is placed on the y-axis. To derive the equation of a constant energy consumption line, we first rearrange to put the y coordinate on the left of the equation:

$$\dot{E}_{indir} = -\dot{E}_{dir} + \dot{E}_{tot} \ . \tag{3}$$

Next, we substitute y for $\dot{E}_{indir}$, x for $\dot{E}_{dir}$, and $\cancel{\dot{E}_s + \dot{E}_{emb} + (\dot{C}_{md} + \dot{C}_o) I_E}$ $\dot{E}_s + \dot{E}_{emb} + (\dot{C}_{OMd} + \dot{C}_o) I_E$ for $\dot{E}_{tot}$ to obtain

$$y = -x + \dot{E}_s + \dot{E}_{emb} + (\dot{C}_{\underline{md}OMd} + \dot{C}_o) I_E \ , \tag{4}$$

where all of $\dot{E}_s$, $\dot{E}_{emb}$, $\cancel{\dot{C}_{md}}\dot{C}_{OMd}$, and $\dot{C}_o$ apply at the same rebound stage.

The constant total energy consumption line that passes through the original point ($\circ$) shows 100% rebound:

$$y = -x + \dot{E}_s^\circ + \dot{E}_{emb}^\circ + (\dot{C}^\circ{}_{md\,OMd} + \dot{C}_o^\circ) I_E \; . \tag{5}$$

The 0% rebound line is the constant total energy consumption line that accounts for expected energy savings ($\dot{S}_{dev}$) only:

$$y = -x + (\dot{E}_s^\circ - \dot{S}_{dev}) + \dot{E}_{emb}^\circ + (\dot{C}^\circ{}_{md\,OMd} + \dot{C}_o^\circ) I_E \; . \tag{6}$$

The above line passes through the a point in the energy plane.

B.2 Expenditure planes

The expenditure plane shows direct (on the x-axis) and indirect (on the y-axis) expenses associated with the energy conversion device and the device user. Lines of constant expenditure are important, because they provide budget constraints for the device user.

The equation of a constant total expenditure line is derived from the budget constraint

$$\dot{C}_{tot} = \dot{C}_{dir} + \dot{C}_{indir} \tag{7}$$

at any rebound stage. In the expenditure plane, indirect expenditures are placed on the y-axis and direct expenditures on energy for the energy conversion device are place on the x-axis. Direct expenditure is the cost of energy consumed by the energy conversion device ($\dot{C}_s = p_E \dot{E}_s$), and indirect expenses are the sum of capital costs, ~~maintenanace~~ operations, maintenanace, and disposal costs, and expenditures on other goods ($\cancel{\dot{C}_{cap} + \dot{C}_{md} + \dot{C}_o} R_\alpha \dot{C}_{cap} + \dot{C}_{OMd} + \dot{C}_o$). Rearranging to put the y-axis variable on the left side of the equation gives

$$\dot{C}_{indir} = -\dot{C}_{dir} + \dot{C}_{tot} \; . \tag{8}$$

Substituting y for $\dot{C}_{indir}$, x for $\dot{C}_{dir}$, and $\cancel{\dot{C}_s + \dot{C}_{cap} + \dot{C}_{md} + \dot{C}_o}$ $\dot{C}_s + R_\alpha \dot{C}_{cap} + \dot{C}_{OMd} + \dot{C}_o$ for $\dot{C}_{tot}$ gives

$$y = -x + \dot{C}_s + R_\alpha \dot{C}_{cap} + \dot{C}_{\cancel{md}QMd} + \dot{C}_o \ , \tag{9}$$

where all of $\dot{C}_s$, R_α, $\dot{C}_{cap}$, $\cancel{\dot{C}_{md}}\dot{C}_{QMd}$, and $\dot{C}_o$ apply at the same rebound stage.

The constant total expenditure line that passes through the original point ($\circ$) shows the budget constraint for the device user:

$$y = -x + \dot{C}_s^\circ + R^\circ{}_\alpha \dot{C}_{cap}^\circ + \dot{C}^\circ{}_{\cancel{md}QMd} + \dot{C}_o^\circ \ , \tag{10}$$

into which Eq. (81) of Part I can be substituted with $\dot{C}_s^\circ = p_E \dot{E}_s^\circ$ and $\dot{N}^\circ = 0$ to obtain

$$y = -x + \dot{M}^\circ \ . \tag{11}$$

The constant total expenditure line that accounts for expected energy savings ($\dot{S}_{dev}$) and freed cash ($\dot{G} = p_E \dot{S}_{dev}$) only is given by:

$$y = -x + (\dot{C}_s^\circ - \dot{G}) + R^\circ{}_\alpha \dot{C}_{cap}^\circ + \dot{C}^\circ{}_{\cancel{md}QMd} + \dot{C}_o^\circ \ , \tag{12}$$

or

$$y = -x + \dot{M}^\circ - \dot{G} \ . \tag{13}$$

The line given by the equation above passes through the a point in the expenditure plane.

B.3 Consumption planes

The consumption plane shows expenditures in the $\dot{C}_o/\dot{C}_o^\circ$ vs. $\dot{q}_s/\dot{q}_s^\circ$ plane, according to the utility model. (See Appendix C of Part I.) Consumption planes include (i) constant expenditure lines given prices, (ii) a ray from the origin through the $\wedge$ point, and (iii) indifference curves. Derivations for each are shown in the following subsections.

B.3.1 Constant expenditure lines

There are four constant expenditure lines in the consumption planes of Figs. ~~??, 4 ,~~ 4 and 7. The constant expenditure lines pass through the original point (line $\circ$—$\circ$), the post-emplacement point (line $*$—$*$), the post-substitution point (line $\wedge$—$\wedge$), and the post-income point (line $-$—$-$). Similar to the expenditure plane, lines of constant expenditure in the consumption plane are derived from the budget constraint of the device user at each of the four points.

Prior to the EEU, the budget constraint is given by Eq. (81) of Part I. Substituting $p_s^\circ \dot{q}_s^\circ$ for $p_E \dot{E}_s^\circ$ and recognizing that there is no net savings before the EEU ($\dot{N}^\circ = 0$) gives

$$\dot{M}^\circ = p_s^\circ \dot{q}_s^\circ + R^\circ{}_{\alpha} \dot{C}_{cap}^\circ + \dot{C}^\circ{}_{md QMd} + \dot{C}_o^\circ \ . \tag{14}$$

To create the line of constant expenditure in the consumption plane, we allow $\dot{q}_s^\circ$ and $\dot{C}_o^\circ$ to vary in a compensatory manner: when one increases, the other must decrease. To show that variation along the constant expenditure line, we remove the notation that ties $\dot{q}_s^\circ$ and $\dot{C}_o^\circ$ to the original point ($\circ$) to obtain

$$\dot{M}^\circ = p_s^\circ \dot{q}_s + R^\circ{}_{\alpha} \dot{C}_{cap}^\circ + \dot{C}^\circ{}_{md QMd} + \dot{C}_o \ , \tag{15}$$

where all of $\dot{M}^\circ$, p_s°, ~~$\dot{C}_{cap}^\circ$, and $\dot{C}_{md}^\circ$~~ $R_\alpha^\circ \dot{C}_{cap}^\circ$, and $\dot{C}_{QMd}^\circ$ apply at the same rebound stage, namely the original point ($\circ$) in this instance.

To derive the equation of the line representing the original budget constraint in $\dot{C}_o/\dot{C}_o^\circ$ vs. $\dot{q}_s/\dot{q}_s^\circ$ space (the $\circ$—$\circ$ line through the $\circ$ point in consumption planes), we solve for $\dot{C}_o$ to obtain

$$\dot{C}_o = -p_s^\circ \dot{q}_s + \dot{M}^\circ - R^\circ{}_{\alpha} \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{md QMd} \ . \tag{16}$$

Multiplying judiciously by $\dot{C}_o^\circ/\dot{C}_o^\circ$ and $\dot{q}_s^\circ/\dot{q}_s^\circ$ gives

$$\frac{\dot{C}_o}{\dot{C}_o^\circ} \dot{C}_o^\circ = -p_s^\circ \frac{\dot{q}_s}{\dot{q}_s^\circ} \dot{q}_s^\circ + \dot{M}^\circ - R^\circ{}_{\alpha} \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{md QMd} \ . \tag{17}$$

Dividing both sides by $\dot{C}_o^\circ$ yields

$$\frac{\dot{C}_o}{\dot{C}_o^\circ} = -\frac{p_s^\circ \dot{q}_s^\circ}{\dot{C}_o^\circ} \frac{\dot{q}_s}{\dot{q}_s^\circ} + \frac{1}{\dot{C}_o^\circ} (\dot{M}^\circ - R^\circ{}_{\alpha} \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{md QMd}) \ . \tag{18}$$

Noting that $\dot{q}_s/\dot{q}_s^\circ$ and $\dot{C}_o/\dot{C}_o^\circ$ are the x-axis and y-axis, respectively, of the consumption plane gives

$$y = -\frac{p_s^\circ \dot{q}_s^\circ}{\dot{C}_o^\circ} x + \frac{1}{\dot{C}_o^\circ} (\dot{M}^\circ - R^\circ{}_{\alpha} \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{md QMd}) \ . \tag{19}$$

A similar procedure can be employed to derive the equation of the $*$—$*$ line through the $*$ point after the emplacement effect. The starting point is the budget constraint at the $*$ point (Eq. (83) of Part I) with $\dot{M}^\circ$ replacing $\dot{M}^*$, $\tilde{p}_s \dot{q}_s$ replacing $p_E \dot{E}_s^*$, and $\dot{C}_o$ replacing $\dot{C}_o^*$.

$$\dot{M}^\circ = \tilde{p}_s \dot{q}_s + R_\alpha^* \dot{C}_{cap}^* + \dot{C}^*{}_{\cancel{md}QMd} + \dot{C}_o + \dot{N}^* \tag{20}$$

Substituting Eq. (92) of Part I for $\dot{N}^*$, substituting Eq. (93) of Part I to obtain $\dot{G}$, multiplying judiciously by $\dot{C}_o^\circ / \dot{C}_o^\circ$ and $\dot{q}_s^\circ / \dot{q}_s^\circ$, rearranging, and noting that $\dot{q}_s / \dot{q}_s^\circ$ is the x-axis and $\dot{C}_o / \dot{C}_o^\circ$ is the y-axis gives

$$y = -\frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} x + \frac{1}{\dot{C}_o^\circ} (\dot{M}^\circ - R^\circ{}_\alpha \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{\cancel{md}QMd} - \dot{G}) \ . \tag{21}$$

Note that the slope of Eq. (21) is less negative than the slope of Eq. (19), because $\tilde{p}_s < p_s^\circ$. The y-intercept of Eq. (21) is less than the y-intercept of Eq. (19), reflecting freed cash. Both effects are seen in the consumption planes (Figs. ~~??, 4 ,~~ 4 and 7). The $\circ$—$\circ$ and $*$—$*$ lines intersect at the coincident $\circ$ and $*$ points.

A similar derivation process can be used to find the equation of the line representing the budget constraint after the substitution effect (the $\wedge$—$\wedge$ line through the $\wedge$ point). The starting point is Eq. (96) of Part I, and the equation for the constant expenditure line is

$$y = -\frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} x + \frac{1}{\dot{C}_o^\circ} (\dot{M}^\circ - R^\circ{}_\alpha \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{\cancel{md}QMd} - \dot{G} + \tilde{p}_s \Delta \hat{\dot{q}}_s + \Delta \hat{\dot{C}}_o) \ . \tag{22}$$

Note that the $\wedge$—$\wedge$ line (Eq. (22)) has the same slope as the $*$—$*$ line (Eq. (21)) but a lower y-intercept.

Finally, the corresponding derivation for the equation of the constant expenditure line through the $-$ point (line $-$—$-$) starts with Eq. (105) of Part I and ~~ends with~~ comes to

$$y = -\frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} x + \frac{1}{\dot{C}_o^\circ} (\dot{M}^\circ - R^\circ{}_\alpha \dot{C}_{cap}^\circ - \dot{C}^\circ{}_{\cancel{md}QMd} - \Delta_{\cancel{cap}} (R_\alpha \dot{C}_{cap})^* - \Delta \dot{C}^*{}_{\cancel{md}QMd}) \ . \tag{23}$$

Simplification of Δ terms gives

$$y = -\frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} x + \frac{1}{\dot{C}_o^\circ} (\dot{M}^\circ - R_\alpha^* \dot{C}_{cap}^* - \dot{C}_{OMd}^*) \ . \tag{24}$$

B.3.2 Ray from the origin to the ∧ point

In the consumption plane, the ray from the origin to the ∧ point (line r—r) defines the path along which the income effect (lines ∧—d and d—$-$) operates. The ray from the origin to the ∧ point has slope $(\hat{\dot{C}}_o/\dot{C}_o^\circ)/(\hat{\dot{q}}_s/\dot{q}_s^\circ)$ and a y-intercept of 0. Therefore, the equation of line r—r is

$$y = \frac{\hat{\dot{C}}_o/\dot{C}_o^\circ}{\hat{\dot{q}}_s/\dot{q}_s^\circ}\, x \ . \tag{25}$$

B.3.3 Indifference curves

In the consumption plane, indifference curves represent lines of constant utility for the energy conversion device user. In the consumption plane ($\dot{C}_o/\dot{C}_o^\circ$ vs. $\dot{q}_s/\dot{q}_s^\circ$), any indifference curve is given by Eq. (162) of Part I with $f_{\dot{C}_s}^\circ$ replacing the share parameter a, as shown in Appendix C of Part I. Recognizing that $\dot{C}_o/\dot{C}_o^\circ$ is on the y-axis and $\dot{q}_s/\dot{q}_s^\circ$ is on the x-axis leads to substitution of y for $\dot{C}_o/\dot{C}_o^\circ$ and x for $\dot{q}_s/\dot{q}_s^\circ$ to obtain

$$y = \left[\frac{1}{1-f_{\dot{C}_s}^\circ}\left(\frac{\dot{u}}{\dot{u}^\circ}\right)^\rho - \frac{f_{\dot{C}_s}^\circ}{1-f_{\dot{C}_s}^\circ}(x)^\rho\right]^{(1/\rho)} \ . \tag{26}$$

At any point on the $\dot{C}_o/\dot{C}_o^\circ$ vs. $\dot{q}_s/\dot{q}_s^\circ$ plane, namely ($\dot{q}_{s,1}/\dot{q}_s^\circ$, $\dot{C}_{o,1}/\dot{C}_o^\circ$), indexed utility ($\dot{u}_1/\dot{u}^\circ$) is given by Eq. (16) of Part I as

$$\frac{\dot{u}_1}{\dot{u}^\circ} = \left[f_{\dot{C}_s}^\circ\left(\frac{\dot{q}_{s,1}}{\dot{q}_s^\circ}\right)^\rho + (1-f_{\dot{C}_s}^\circ)\left(\frac{\dot{C}_{o,1}}{\dot{C}_o^\circ}\right)^\rho\right]^{(1/\rho)} \ . \tag{27}$$

Substituting Eq. (27) into Eq. (26) for $\dot{u}/\dot{u}^\circ$ and simplifying exponents gives

$$y = \left\{\frac{1}{1-f_{\dot{C}_s}^\circ}\left[f_{\dot{C}_s}^\circ\left(\frac{\dot{q}_{s,1}}{\dot{q}_s^\circ}\right)^\rho + (1-f_{\dot{C}_s}^\circ)\left(\frac{\dot{C}_{o,1}}{\dot{C}_o^\circ}\right)^\rho\right] - \frac{f_{\dot{C}_s}^\circ}{1-f_{\dot{C}_s}^\circ}(x)^\rho\right\}^{(1/\rho)} \ . \tag{28}$$

Simplifying further yields the equation of an indifference curve passing through point ($\dot{q}_{s,1}/\dot{q}_s^\circ$, $\dot{C}_{o,1}/\dot{C}_o^\circ$):

$$y = \left\{\left(\frac{f_{\dot{C}_s}^\circ}{1-f_{\dot{C}_s}^\circ}\right)\left[\left(\frac{\dot{q}_{s,1}}{\dot{q}_s^\circ}\right)^\rho - (x)^\rho\right] + \left(\frac{\dot{C}_{o,1}}{\dot{C}_o^\circ}\right)^\rho\right\}^{(1/\rho)} \ . \tag{29}$$

Note that if x is $\dot{q}_{s,1}/\dot{q}_s^\circ$, y becomes $\dot{C}_{o,1}/\dot{C}_o^\circ$, as expected.

C Univariate sensitivity analyses

Sensitivity analyses show the effect of independently varied parameters on total rebound and rebound components. In the context of this framework, sensitivity analyses can show important trends, tendencies, and relationships between rebound parameters and rebound magnitudes. Key rebound parameters include post-EEU efficiency ($\tilde{\eta}$), post-EEU capital cost ($\tilde{C}_{cap}$), energy price (p_E), pre-EEU uncompensated price elasticity of energy service demand ($\varepsilon^{\circ}_{\dot{q}_s,p_s}$), the macro factor ($k$), and post-EEU energy service price ($\tilde{p}_s$). Univariate sensitivity analyses (the kind shown here) should be interpreted carefully, because some rebound parameters are not expected to be independent from others.

C.1 Effect of post-EEU efficiency ($\tilde{\eta}$) on rebound terms

Fig. C.1 shows that both the energy takeback rate and expected energy savings ($\dot{S}_{dev}$) increase with post-EEU efficiency ($\tilde{\eta}$), but the relationship is asymptotic. Each unit increase of fuel economy or lighting efficiency is less effective than the previous unit increase of fuel economy or lighting efficiency for saving energy. At very high levels of fuel economy or lighting efficiency, a unit increase leads to almost no additional energy savings. Thus, we can say there are diminishing returns of fuel economy and lighting efficiency, leading to saturation of energy savings at very high levels of fuel economy and lighting efficiency. A simple example illustrates. A $\eta^{\circ} = 25$ mpg car drives $q^{\circ}_s = 100$ miles using $E^{\circ}_s = 4$ gallons of gasoline. A more-efficient car ($\tilde{\eta} = 30$ mpg) is expected to use $E^{*}_s = 3.33$ gallons to drive the same distance, a savings of $\dot{S}_{dev} = 0.67$ gallons. Another 5 mpg boost in efficiency (to $\tilde{\eta} = 35$ mpg) will use $E^{*}_s = 2.86$ gal to drive 100 miles, a further expected savings of only $\dot{S}_{dev} = 0.47$ gallons. Each successive 5 mpg boost in fuel economy saves less energy than the previous 5 mpg boost in fuel economy.

Saturation can be seen mathematically, too. Taking the limit as $\tilde{\eta} \to \infty$ in Eq. (12) of Part I gives $\dot{S}_{dev} = \dot{E}^{\circ}_s$, not ∞. Thus, efficiency saturation must occur. Fig. C.1 shows that this framework correctly replicates expected efficiency saturation trends.

Saturation is especially noticeable in the lamp example compared to the car example, the difference being that the LED lamp is already much more efficient than the incandescent lamp (9.26×), whereas the hybrid car is only 1.68× more efficient than the conventional gasoline car.

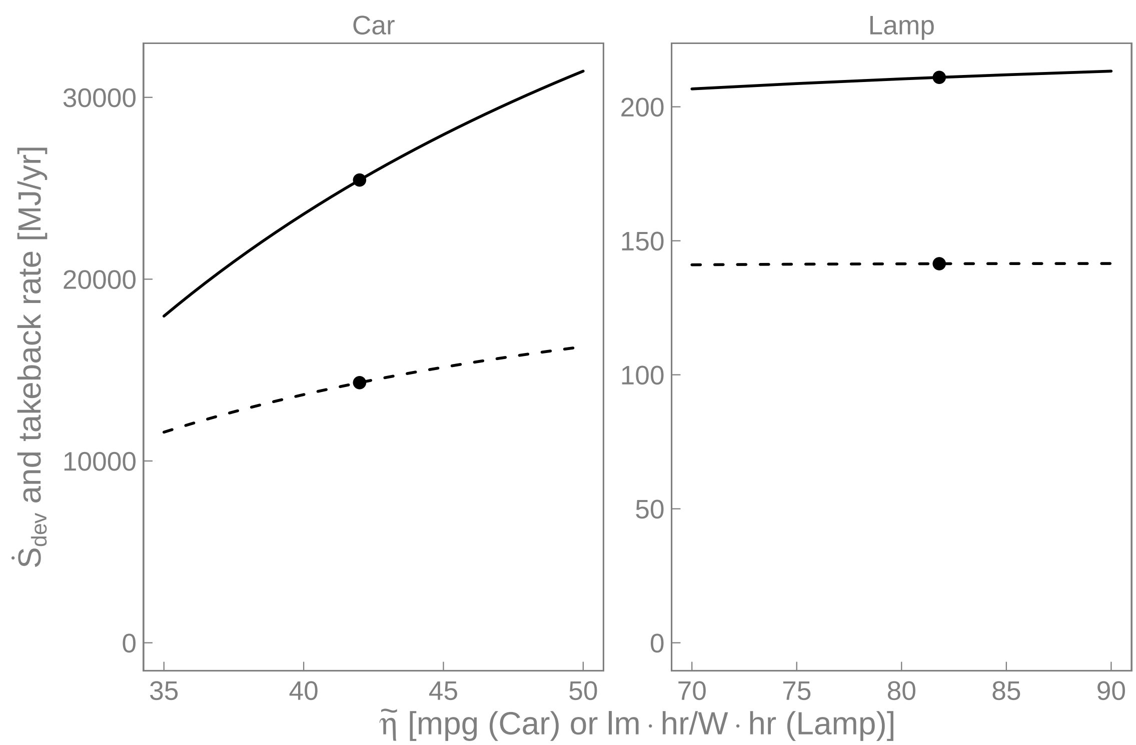

Fig. C.1: Expected energy savings rate ($\dot{S}_{dev}$, solid line) and takeback rate (dashed line) sensitivity to post-EEU efficiency ($\tilde{\eta}$). The macro factor is set to its calibrated value ($k = 3$). (Note different x- and y-axis scales.)

Thus, at $\tilde{\eta} = 81.8$ lm·hr/W·hr, the energy efficient LED is far closer to efficiency saturation than the hybrid vehicle (at $\tilde{\eta} = 42$ mpg). As a result, further increases in the LED lamp's efficiency are less effective than further increases in the hybrid car's efficiency.

That said, actual savings is the difference between the expected energy savings line (solid line) and the takeback line (dashed line) in Fig. C.1. Because the gap between the lines grows, higher efficiency yields greater energy savings, even after accounting for rebound effects. But the actual savings are always less than expected savings, due to takeback.

Fig. C.1 shows that expected energy savings ($\dot{S}_{dev}$) increase faster than takeback as $\tilde{\eta}$ increases. Thus, total rebound (Re_{tot}, the ratio of takeback rate to expected energy savings rate in Eq. (3) of Part I), decreases as efficiency grows. The lamp exhibits a relatively smaller rebound decline with efficiency, because the lamp example is closer to saturation than the car example.

Fig. C.2 shows the variation of all rebound components with post-EEU efficiency ($\tilde{\eta}$). In the car and lamp examples, direct substitution rebound (Re_{dsub}) is the rebound component most sensitive to changes in post-EEU efficiency ($\tilde{\eta}$).

Note that the sensitivity analysis on post-upgrade efficiency ($\tilde{\eta}$, Fig. C.2) is the only sensitivity analysis that requires careful explication of both the numerator and denominator of Eq. (3) in Part I, as in Fig. C.1, because both the numerator and denominator of Eq. (3) in Part I change when post-upgrade efficiency ($\tilde{\eta}$) changes. The denominator of Eq. (3) in Part I doesn't change for the sensitivity analyses of Figs. C.3–C.6. Thus, for the remaining sensitivity analyses, when the rebound percentage increases (decreases), the energy takeback rate in the numerator of Eq. (3) in Part I increases (decreases) proportionally, and the actual energy savings rate decreases (increases) accordingly.

C.2 Effect of capital cost ($\tilde{C}_{cap}$) on rebound terms

The sensitivity of energy rebound to capital cost ($\tilde{C}_{cap}$) is shown in Fig. C.3. All other things being equal, as capital cost of the EEU rises, less net savings result from the emplacement effect, leading to smaller income, macro, and total rebound. The same effects would be observed with increasing maintenance and disposal cost rate ($\tilde{\dot{C}}_{md}$).

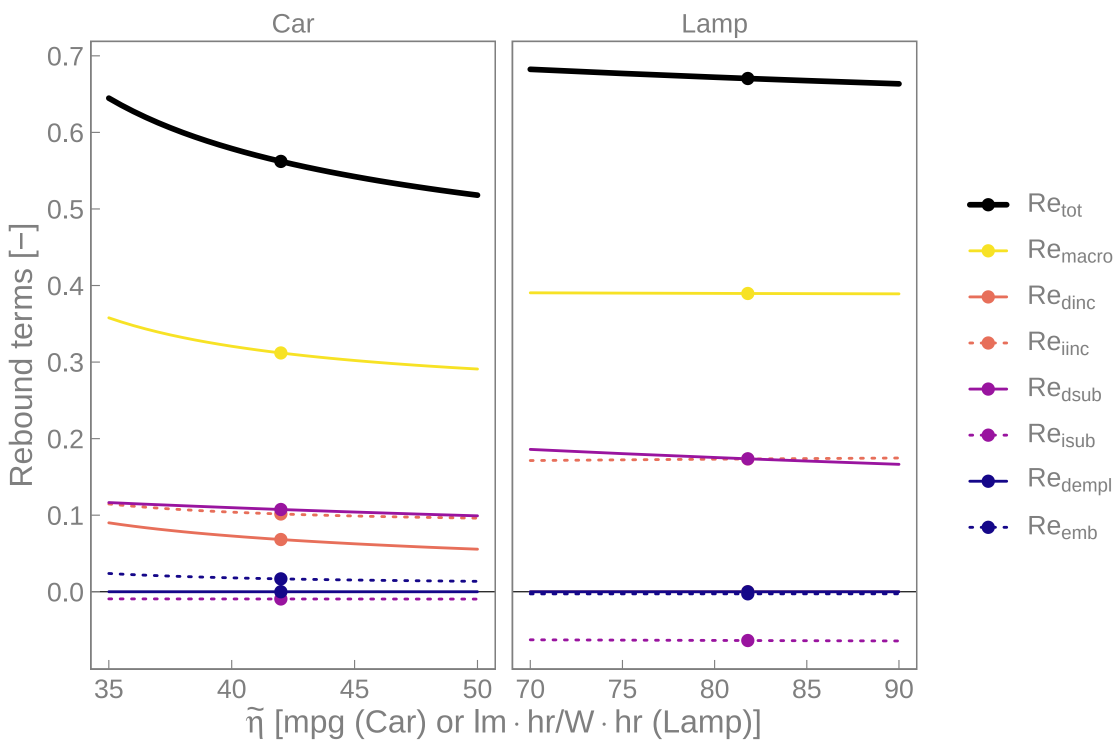

Fig. C.2: Sensitivity of rebound components to post-EEU efficiency ($\tilde{\eta}$). The macro factor is set to its calibrated value ($k = 3$).

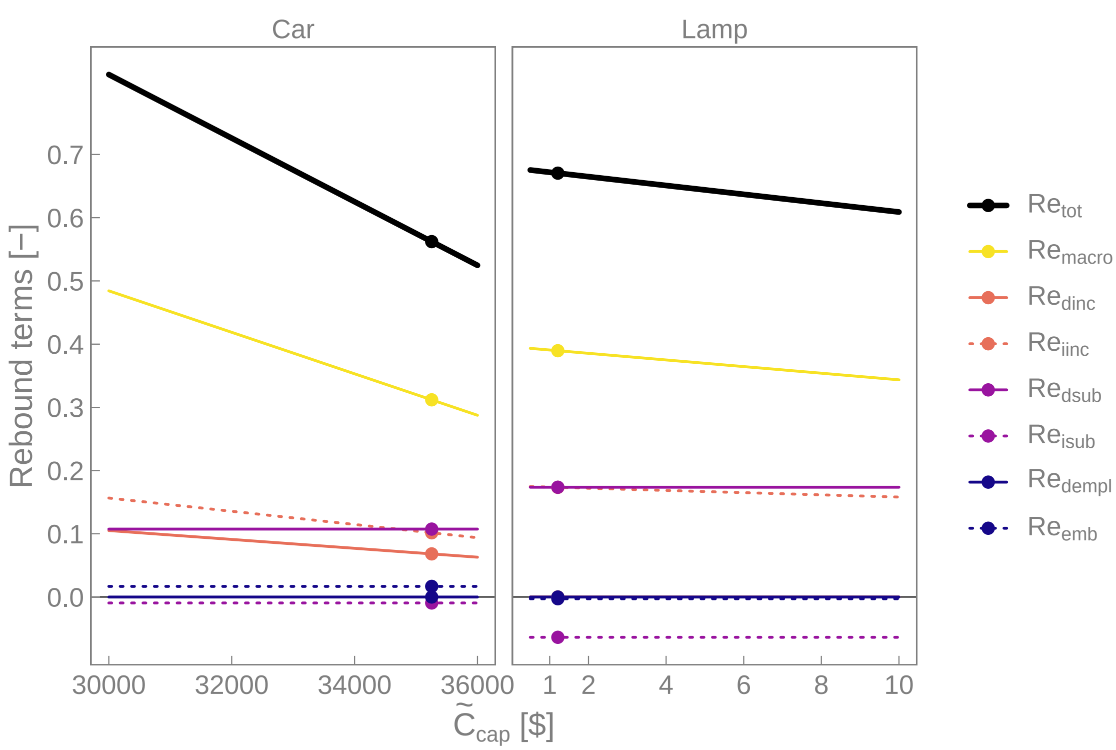

Fig. C.3: Sensitivity of rebound components to capital cost ($\tilde{C}_{cap}$). The macro factor is set to its calibrated value ($k = 3$).

C.3 Effect of energy price (p_E) on rebound terms

The effect of energy price on rebound is shown in Fig. C.4. Increasing energy prices lead to larger total rebound (Re_{tot}), because higher energy prices lead to more net savings ($\dot{\hat{N}}$) to be spent by the device user. All other things being equal, more net savings leads to more spending on other goods and services that demand energy.

Fig. C.4 also shows the effect of energy price (p_E) on all rebound components. Most rebound components increase with energy price, with the car and lamp examples exhibiting different sensitivities. Substitution effects (Re_{dsub} and Re_{isub}) are the only rebound components that decrease with energy price (p_E). Substitution effects decrease with energy price, because at high energy price, less behavior adjustment is needed to re-equilibrate after emplacement of the efficient device.

In Fig. C.4, German energy prices[6] are shown as vertical lines, providing an indication of possible energy price variations. All other things being equal, if U.S. residents paid Germany's energy prices, total energy rebound (Re_{tot}) would be ~~84.0~~93.0% for the car example and 148.0% for the lamp example.

C.4 Effect of original uncompensated own price elasticity ($\varepsilon^{\circ}_{\dot{q}_s,p_s}$) on rebound terms

Fig. C.5 shows the variation of total rebound (Re_{tot}) with the original uncompensated price elasticity of energy service demand ($\varepsilon^{\circ}_{\dot{q}_s,p_s}$). The effect is exponential, and total rebound increases with larger negative values of $\varepsilon^{\circ}_{\dot{q}_s,p_s}$, as expected. The lamp example also shows stronger exponential variation than the car example. The main reason that total rebound values are different between the two examples is the larger absolute value of original uncompensated own price elasticity ($\varepsilon^{\circ}_{\dot{q}_s,p_s}$) for the lamp ($-0.4$) compared to the car ($-0.2$). Were the car to have the same original uncompensated own price elasticity as the lamp (i.e., -0.4), total rebound would be closer for both examples (~~64.1~~73.4% for the car and ~~67.1~~67.0% for the lamp). Fig. C.5 shows that direct substitution rebound (Re_{dsub}) is

[6]For the car example, the gasoline price in Germany is taken as 1.42 €/liter for the average "super gasoline" (95 octane) price in 2018 (finanzen.net, 2021). For the lamp example, the electricity price in Germany is taken as 0.3 €/kW·hrfor the 2018 price of a household using 3.5 MWh/yr, an average value for German households (Bundesministerium für Wirtschaft und Energie, 2018). Converting currency (at 1 € = \$1.21) and physical units gives 6.5 \$/US gallon and 0.363 \$/kW·hr.

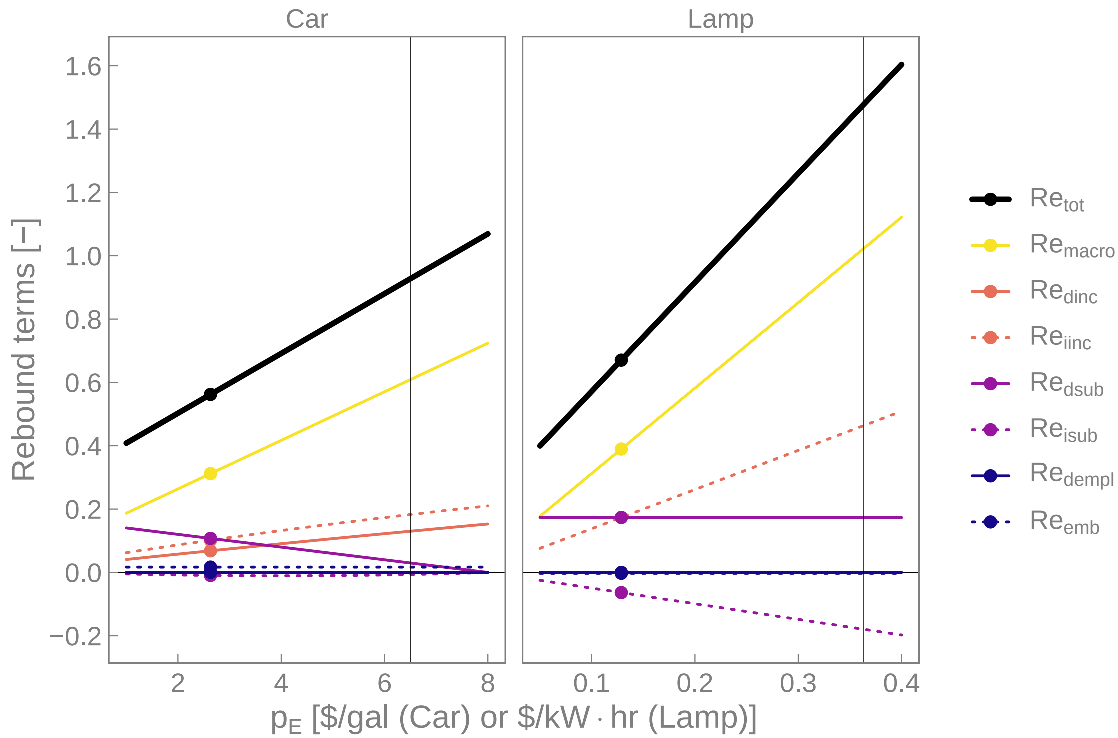

Fig. C.4: Sensitivity of rebound components to energy price (p_E). German energy prices denoted by vertical lines. The macro factor is set to its calibrated value ($k = 3$).

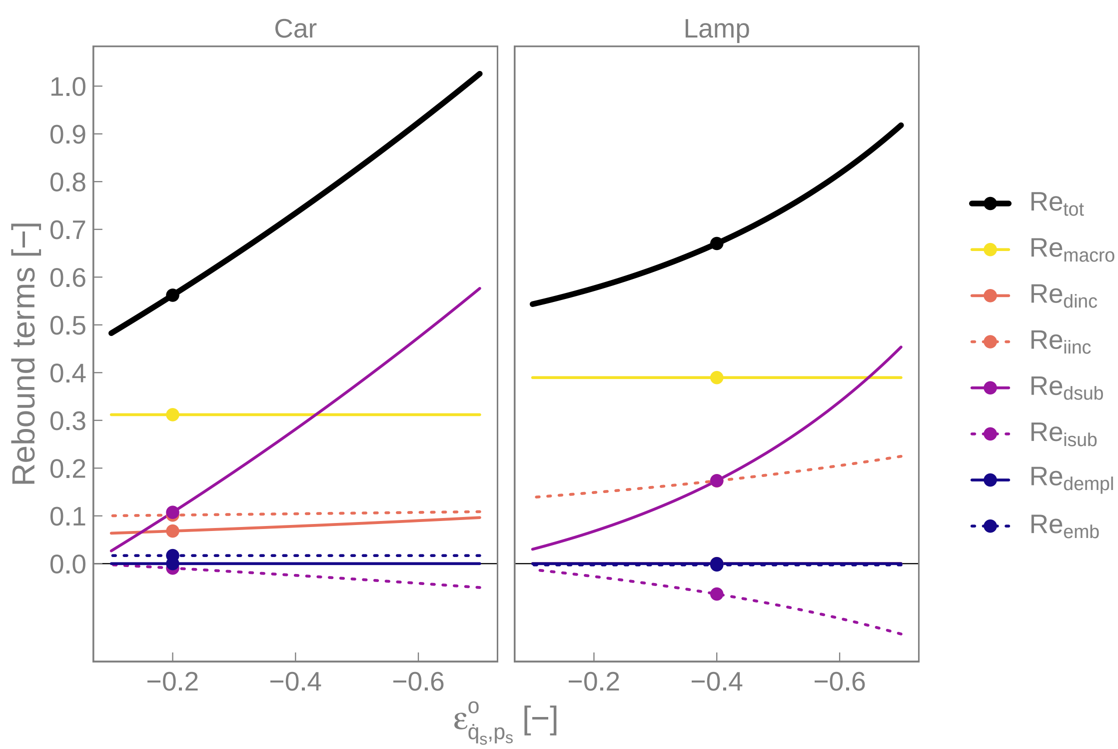

Fig. C.5: Sensitivity of rebound components to uncompensated own price elasticity of energy service demand ($\varepsilon^{\circ}_{\dot{q}_s,p_s}$). The macro factor is set to its calibrated value ($k = 3$). (Note reversed x-axis scale.)

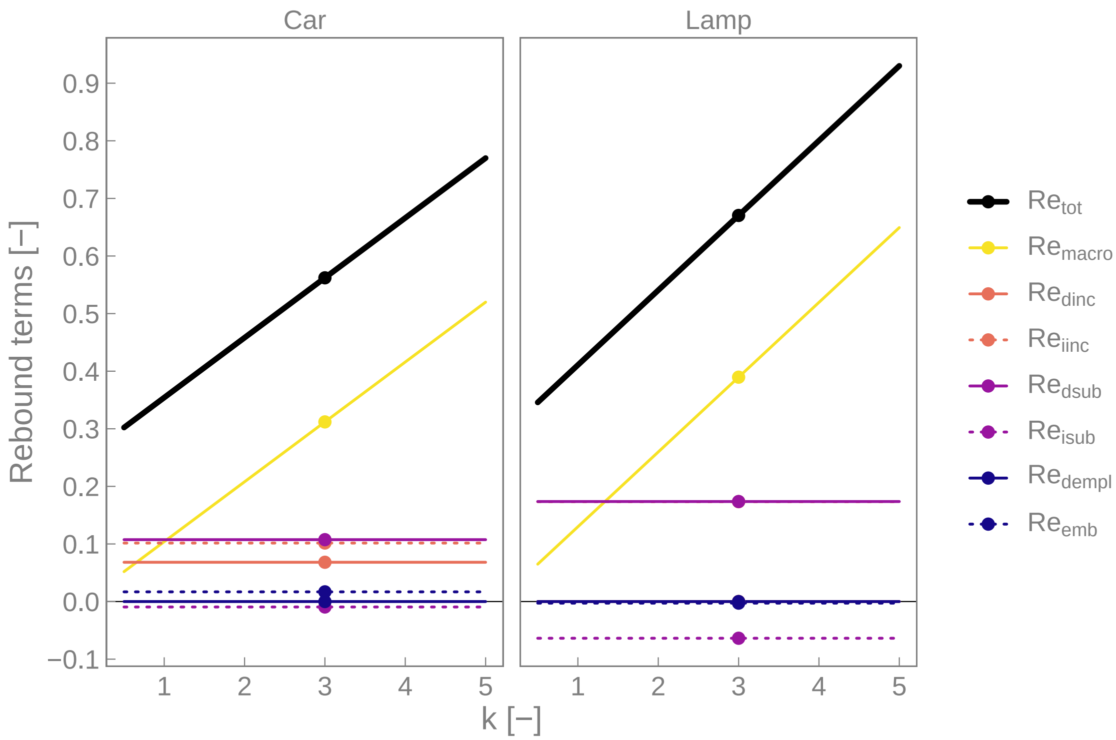

Fig. C.6: Sensitivity of rebound components to the macro factor (k).

the most sensitive rebound component to changes in $\varepsilon^{\circ}_{\dot{q}_s,p_s}$. For the lamp example, indirect income rebound (Re_{iinc}) also increases substantially with $\varepsilon^{\circ}_{\dot{q}_s,p_s}$, because net savings increases substantially with $\varepsilon^{\circ}_{\dot{q}_s,p_s}$.

C.5 Effect of macro factor (k) on rebound terms

The sensitivity of energy rebound to the macro factor (k) is shown in Fig. C.6. The macro factor has a linear effect on total rebound (Re_{tot}) through the macro rebound component (Re_{macro}). All other rebound components are constant when k is varied independently.

C.6 Effect of discount rate (r) on rebound terms

The effect of discount rate on rebound is shown in Fig. C.7. Discounting has little effect on rebound terms compared to other parameters such as upgraded efficiency ($\tilde{\eta}$, Fig. C.2), capital cost ($\tilde{C}_{cap}$, Fig. C.3), energy price (p_E, Fig. C.4), and own price elasticity of energy service demand ($\varepsilon^{\circ}_{\dot{q}_s,p_s}$, Fig. C.5).

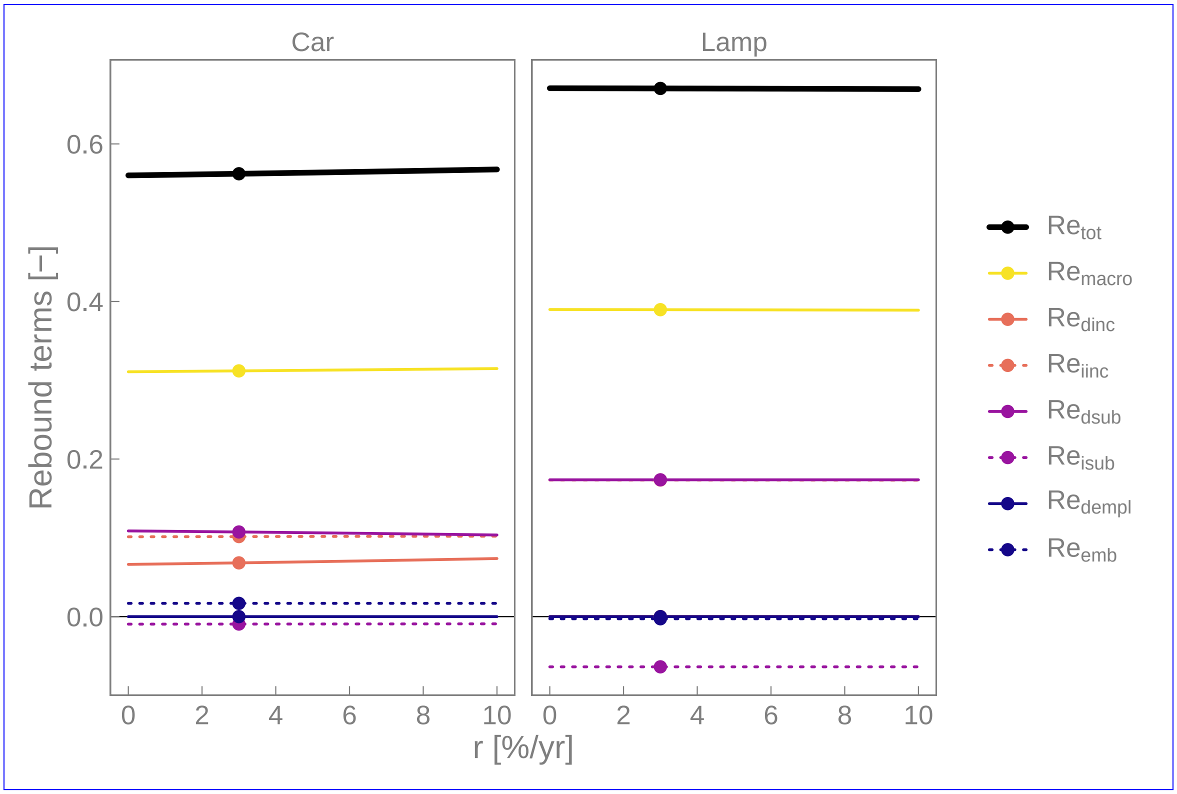

Fig. C.7: Sensitivity of rebound components to discount rate (r).

C.7 Effect of energy service price ($\tilde{p}_s$) on price elasticities ($\hat{\varepsilon}$)

The sensitivity of post-substitution effect price elasticities ($\hat{\varepsilon}$) to post-upgrade energy service price ($\tilde{p}_s$) is shown in Fig. C.8 for the CES utility model described in Section 2.5.2 and Appendix C of Part I. Note that the left side of each graph ($\tilde{p}_s = 0$) represents unattainable infinite efficiency ($\tilde{\eta}_s \rightarrow \infty$), i.e., delivery of the energy service without energy consumption.

First, note the sign of the elasticities. As expected, both of the uncompensated price elasticities ($\hat{\varepsilon}_{\dot{q}_s,p_s}$ and $\hat{\varepsilon}_{\dot{q}_o,p_s}$, dashed lines in Fig. C.8) are negative, regardless of the energy service price ($\tilde{p}_s$): a lower price means more consumption of both goods, all other things being equal. The compensated own price elasticity ($\hat{\varepsilon}_{\dot{q}_s,p_s,c}$) is negative and the compensated cross price elasticity ($\hat{\varepsilon}_{\dot{q}_o,p_s,c}$) is positive. As $\tilde{p}_s$ declines, the consumers substitute the energy service for other goods.

Second, the magnitude of price elasticities varies. Fig. C.8 shows that the car example exhibits more variation of price elasticities ($\hat{\varepsilon}$) with energy service price ($\tilde{p}_s$) than the lamp example, because the expenditure share ($f^{\circ}_{\dot{C}_s}$) for the lamp example is very small compared to the car example. Using the constant price elasticity (CPE) utility model may be a good enough approximation in the

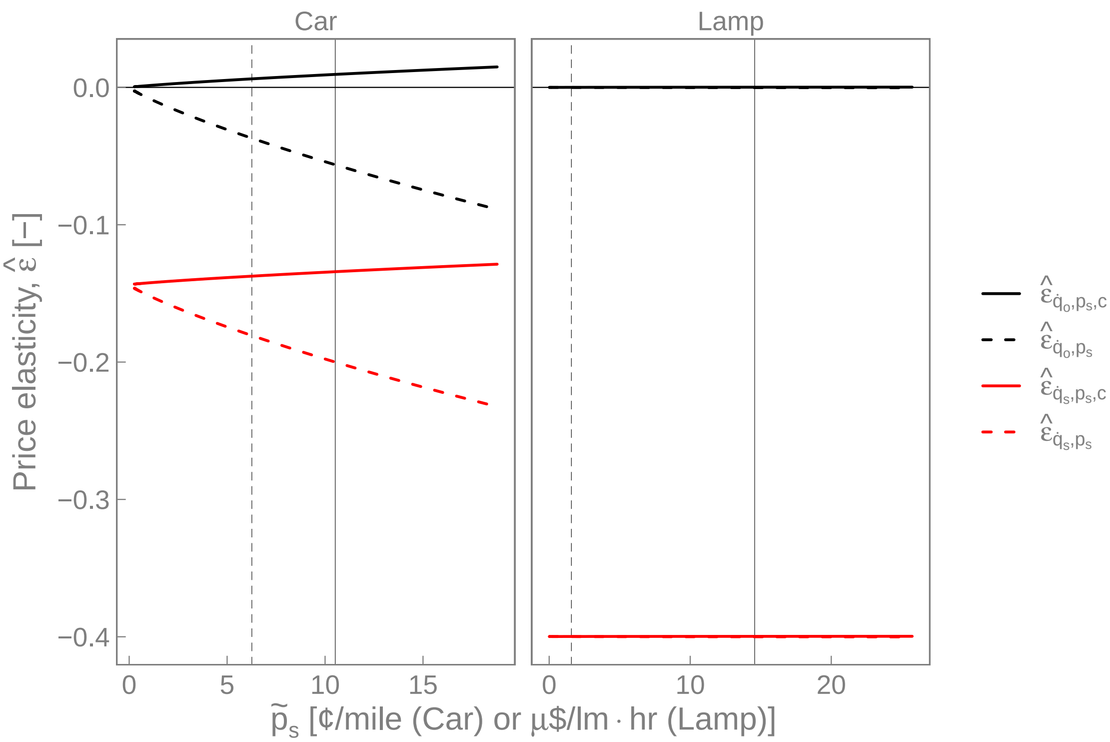

Fig. C.8: Sensitivity of post substitution effect price elasticities ($\hat{\varepsilon}$) to post-EEU energy service price ($\tilde{p}_s$) for the CES utility model. This graph is a visualization of Eqs. 206, 209, 198, 208, and of Part I for the car and lamp examples. The solid vertical line indicates the original energy service price (p_s°), and the dashed vertical line indicates the upgraded energy service price ($\cancel{\tilde{p}_s = \bar{p}_s = \hat{p}_s = p_s^*} p_s^* = \hat{p}_s = \bar{p}_s = \tilde{p}_s$) for the two examples. See Tables 8 and 10 for p_s in different units.

lamp example. However, for the car example, using the CES utility function will be necessary to eliminate errors that will be present in the CPE approximation. This result is an important finding that should encourage analysts implementing analytical rebound calculations with substitution and income effects to prefer the CES utility model over the CPE approximation.

Fig. C.8 shows that as efficiency increases (and $\tilde{p}_s$ decreases), the absolute value of the uncompensated price elasticities ($\hat{\varepsilon}_{\dot{q}_s,p_s}$ and $\hat{\varepsilon}_{\dot{q}_o,p_s}$) decreases, a change that exceeds the slightly increasing (in absolute value terms) compensated own price elasticity ($\hat{\varepsilon}_{\dot{q}_s,p_s,c}$). Thus, direct rebound is attenuated as efficiency increases, relative to a constant price elasticity model. (See also the patterns of lines of Fig. C.2, which show a declining trend.)