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), 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 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%) and an electric lamp (67%). 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.

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

JEL codes: O13, Q40, Q43

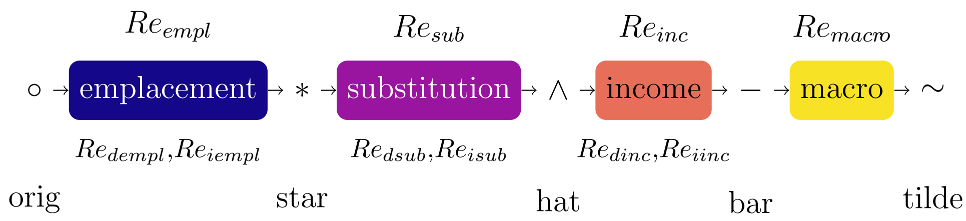

Fig. 1: Flowchart of rebound effects and decorations.

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 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 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 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 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 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 the process of calculating the magnitude of rebound effects. Here, we collect parameter values for the equations to calculate eight rebound components: Re_{dempl}, Re_{emb}, Re_{md}, 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. (34) 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 expenditure rate $\dot{C}^{\circ}_{cap}$, $\dot{C}^{*}_{cap}$ [$/yr]	4,778	4,720	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).
Ownership duration t°_{own}, t^{*}_{own} [yr]	7	7	U.S. car ownership (from new) duration from Businesswire.com (2015), and has risen from 52 months (2005) to 79 months (2015), so taken as 84 months in 2018 (7 years) for our example.
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).
Maintenance and disposal expenditure rate $\dot{C}^{\circ}_{md}$, $\dot{C}^{*}_{md}$ [$/yr]	2,731	2,710	Seven year annual, averaged maintenance costs = sum of insurance, maintenance, repairs, taxes, and fees (excluding financing, depreciation, fuel). Ford Fusion maintenance costs from Edmunds.com (2020a). Ford Fusion Hybrid maintenance costs from Edmunds.com (2020b).

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	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	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.
Macro factor k [–]	1.0	An initial value. See Section 4.1 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	Calculated via the Slutsky Equation (Eq. (131) 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. (137) 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 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).
Ownership duration t°_{own}, t^*_{own} [yr]	1.8	10	Assumed same as lamp lifespan
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.
Maintenance and disposal expenditure rate $\dot{C}^\circ_{md}$, $\dot{C}^*_{md}$ [$/yr]	0.00	0.00	Assumed negligible.

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	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.
Macro factor k [–]	1.0	An initial value. See Section 4.1 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. (131) 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. (137) 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 (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.

Axes of the rebound planes represent direct and indirect effects, with direct effects shown on the x-axis, and indirect effects shown on the y-axis. 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 $\dot{C}_{indir}$) 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. 2–4 show notional energy, expenditure, and consumption planes, respectively. The notional planes are not quantified, i.e., there are no scales on the axes. Later (Section 3), rebound planes with numerical scales illustrate the car and lamp examples.

Table 7: Segments in rebound planes.

Segment	Rebound effect	Symbol
$\circ$ — a	Direct emplacement	Re_{dempl}
$a \cdots b$	Embodied energy	Re_{emb}
b — $*$	Maintenance and disposal	Re_{md}
$*$ — c	Indirect substitution	Re_{isub}
c — $\wedge$	Direct substitution	Re_{dsub}
$\wedge$ — d	Direct income	Re_{dinc}
d — $-$	Indirect income	Re_{iinc}
$-$ — $\sim$	Macro	Re_{macro}

2.2.1 The energy plane

Fig. 2 shows a notional energy plane, with 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. 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.

In the notional energy plane of Fig. 2, 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 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. 2 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

[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).

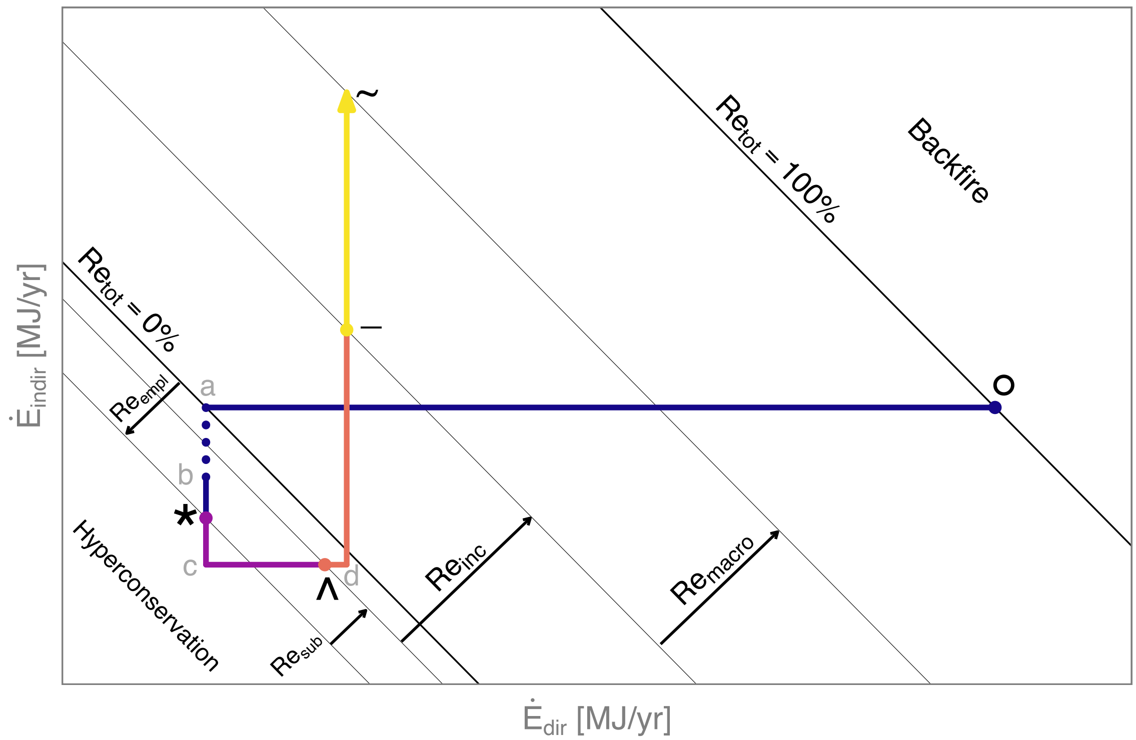

Fig. 2: Notional energy plane. See Table 7 for meanings of path segments.

consumption after the EEU than before it.

In the notional energy plane (Fig. 2), 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. 3 segments a ⋯ b and b — $*$ 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]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.

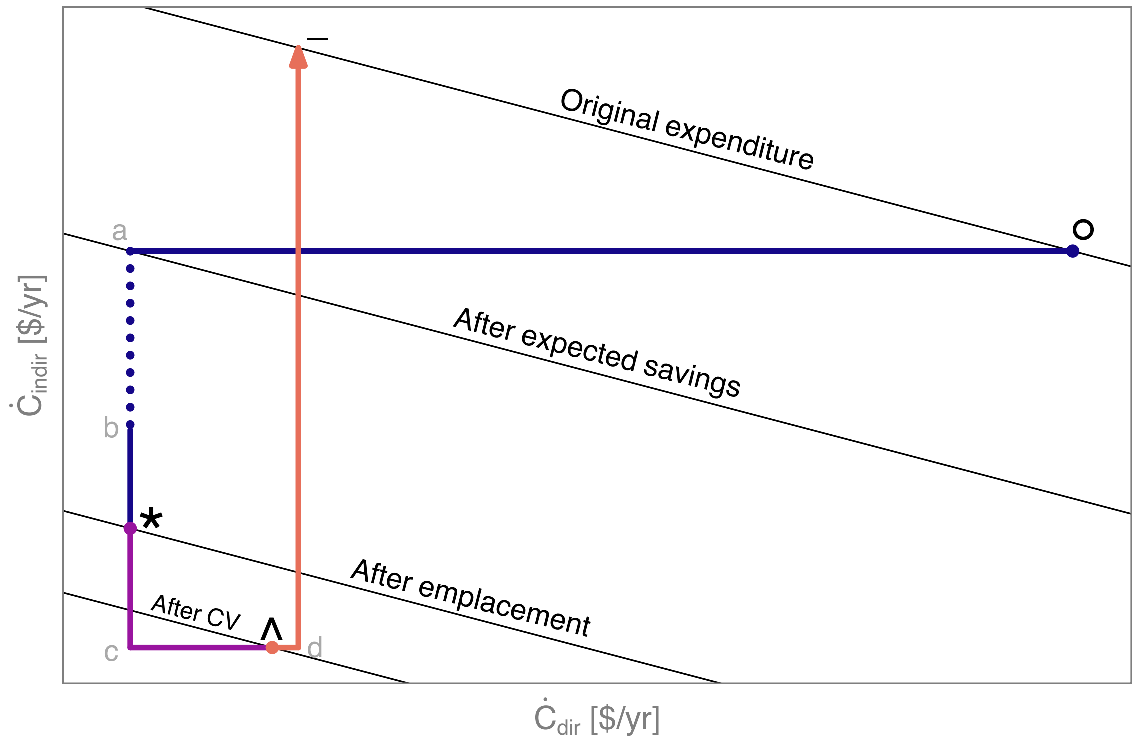

Fig. 3: Notional expenditure plane. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments.

2.2.2 The expenditure plane

A notional expenditure plane is shown in Fig. 3, with the direct expenditure rate on the energy service ($\dot{C}_{dir}$) on the x-axis and the indirect expenditure rate ($\dot{C}_{indir}$) 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 new prices.

In the notional planes of Figs. 2 and 3, embodied energy rates and capital cost rates (represented by segments a⋯b and b—$*$) move in the same direction (both in the negative y direction). However, segments a⋯b and b—$*$ could both move in the positive 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 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. 4. 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. 4 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 are denoted by i°—i° and $\bar{\text{i}}$—$\bar{\text{i}}$ 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 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 the

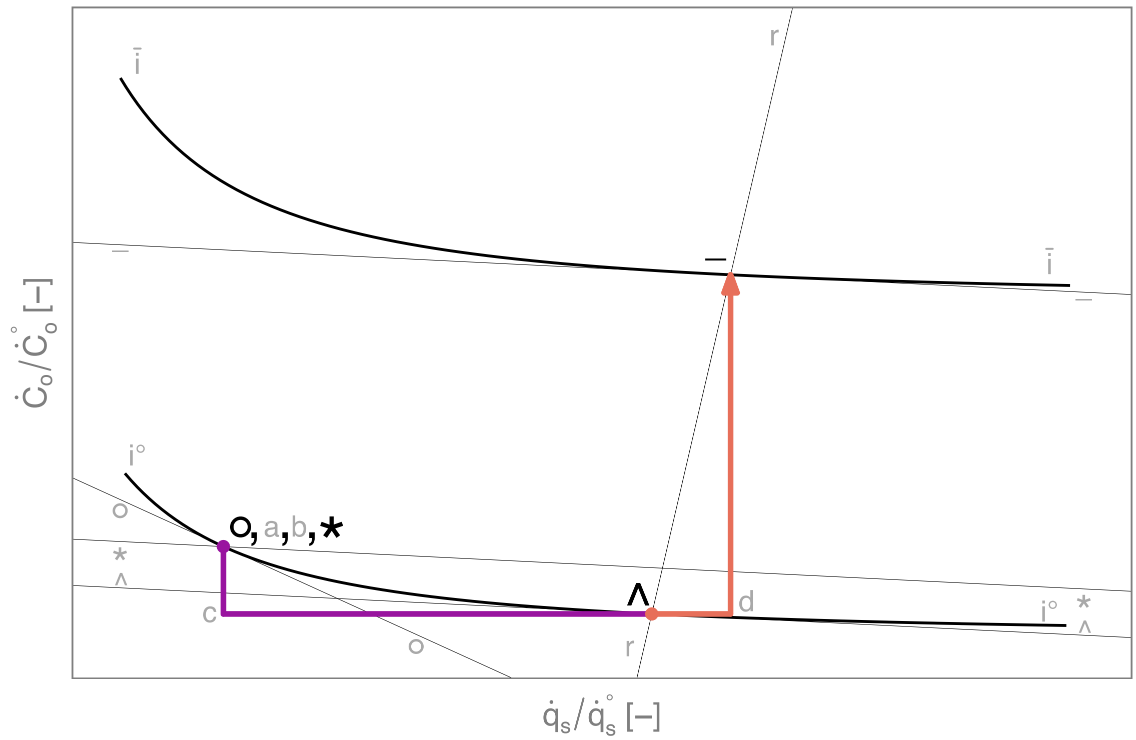

Fig. 4: Notional consumption plane. See Table 7 for meanings of path segments.

consumption plane, its impact can be seen in the energy and expenditures planes (Figs. 2 and 3, respectively).

The income expansion path is a ray (r—r) from the origin through the $\wedge$ point in the consumption plane. In the consumption plane, 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. 2–4. The increased consumption rate of other goods and services is represented by segments d—$-$ in Figs. 2–4.

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 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. 5), 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.

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 car example. Rebound components for the car upgrade are shown in Table 9.

The emplacement effect has three components: the direct emplacement effect, the embodied energy effect, and the maintenance and disposal effect. Rebound from the direct emplacement

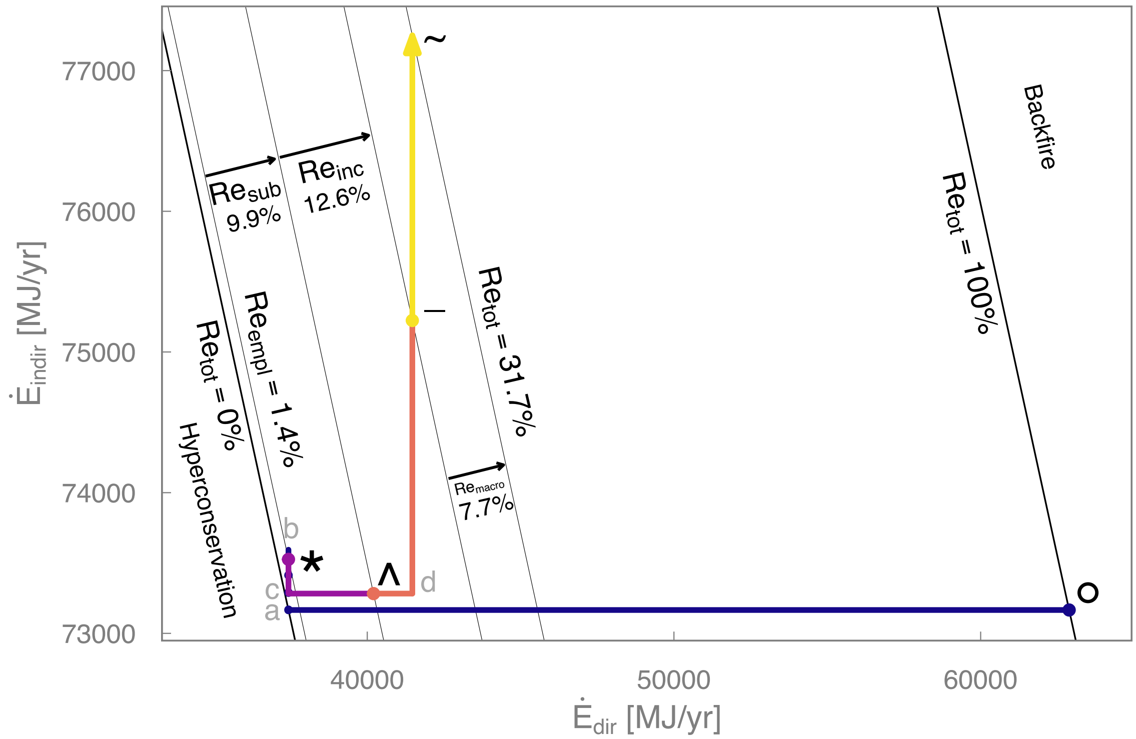

Fig. 5: The energy plane for the car example. Macro factor (k) is assumed to be 1. See Table 7 for meanings of path segments.

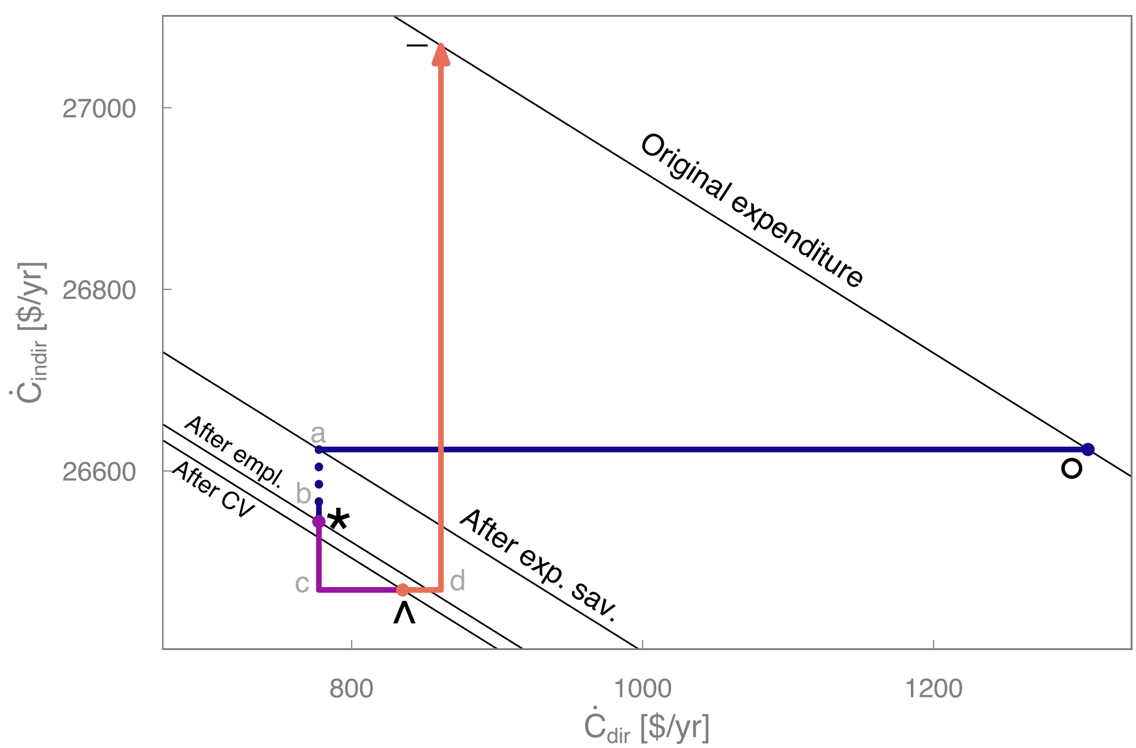

Fig. 6: The expenditure plane for the car example. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments.

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

	$\circ$ (orig)	$*$ (star)	$\wedge$ (hat)	$-$ (bar)	$\sim$ (tilde)
η [mile/gal]	25.0	42.0	42.0	42.0	42.0
η [mile/MJ]	0.197	0.332	0.332	0.332	0.332
p_s [$/mile]	0.105	0.063	0.063	0.063	0.063
$\dot{q}_s$ [mile/yr]	12,416	12,416	13,336	13,756	13,756
$\dot{E}_s$ [MJ/yr]	62,885	37,432	40,204	41,470	41,470
$\dot{E}_{emb}$ [MJ/yr]	2,429	2,857	2,857	2,857	2,857
$\dot{C}_s$ [$/yr]	1,306	777	835	861	861
$\dot{C}_{cap}$ [$/yr]	4,778	4,720	4,720	4,720	4,720
$\dot{C}_{md}$ [$/yr]	2,731	2,710	2,710	2,710	2,710
$\dot{C}_o$ [$/yr]	19,115	19,115	19,040	19,639	19,639
$\dot{N}$ [$/yr]	0	608	626	0	0
$\dot{M}$ [$/yr]	27,930	27,930	27,930	27,930	27,930

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}	-0.3
Re_{dsub}	10.9
Re_{isub}	-1.0
Re_{dinc}	5.0
Re_{iinc}	7.6
Re_{macro}	7.7
Re_{tot}	31.7

effect (Re_{dempl}) is 0.0% always, because energy takeback (and, therefore, rebound) occurs after the upgraded device is emplaced. Indirect 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}) is small and negative (-0.3%), because of the slightly lower 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%). 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% further each year. Conversely, the indirect substitution effect (Re_{isub}) is slightly negative (-1.0%) to achieve the same level of utility after increased driving. Indeed, across

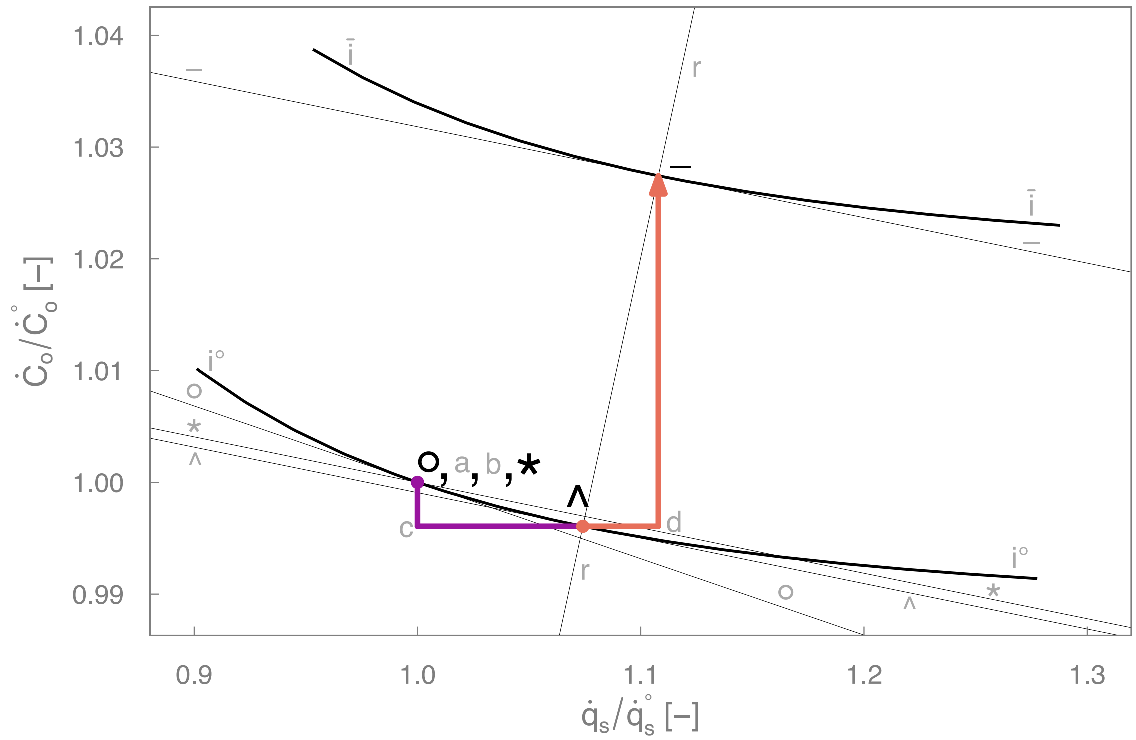

Fig. 7: The consumption plane for the car example. See Table 7 for meanings of path segments.

the substitution effect, less money is spent on other goods ($\Delta\hat{\dot{C}}_o = -75.18$ \$/yr). In Appendix C.6 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 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%), because the car user allocates some net savings to additional driving. Rebound from the indirect income effect (Re_{iinc}) is positive (7.6%) due to higher spending on other goods. Thus, the net savings after the substitution effect ($\hat{\dot{N}} = 625.79$ \$/yr) translates into positive direct and indirect income rebound at the microeconomic level. Total microeconomic rebound (emplacement, substitution, and income effects) sums to $Re_{micro} = 24.0\%$.

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 k in the Discussion (Section 4.1). With k assumed to be 1, the macro effect leads to macroeconomic rebound (Re_{macro}) of 7.7% 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 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.

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

	$\circ$ (orig)	$*$ (star)	$\wedge$ (hat)	$-$ (bar)	$\sim$ (tilde)
η [lm·hr/kW·hr]	8,833	81,800	81,800	81,800	81,800
η [lm·hr/MJ]	2,454	22,722	22,722	22,722	22,722
p_s [\$/lm·hr]	0.00001457	0.00000157	0.00000157	0.00000157	0.00000157
$\dot{q}_s$ [lm·hr/yr]	580,350	580,350	1,412,867	1,413,439	1,413,439
$\dot{E}_s$ [MJ/yr]	236.5	25.5	62.2	62.2	62.2
$\dot{E}_{emb}$ [MJ/yr]	1.222	0.650	0.650	0.650	0.650
$\dot{C}_s$ [\$/yr]	8.46	0.91	2.22	2.22	2.22
$\dot{C}_{cap}$ [\$/yr]	1.04	0.12	0.12	0.12	0.12
$\dot{C}_{md}$ [\$/yr]	0.00	0.00	0.00	0.00	0.00
$\dot{C}_o$ [\$/yr]	27,920	27,920	27,916	27,927	27,927
$\dot{N}$ [\$/yr]	0.00	8.47	11.31	0.00	0.00
$\dot{M}$ [\$/yr]	27,930	27,930	27,930	27,930	27,930

Results are represented graphically on energy, expenditure, and consumption planes in Figs. 8–10. The energy plane (Fig. 8) 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}) is 0.0%, because we assume no difference in maintenance and disposal costs between the incandescent lamp and the 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. 10. 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. 10, 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 ($\hat{\dot{N}} = 11.31$ \$/yr). Direct income effect rebound (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 ($Re_{iinc} = 17.4$%), 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).

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_{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

[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.

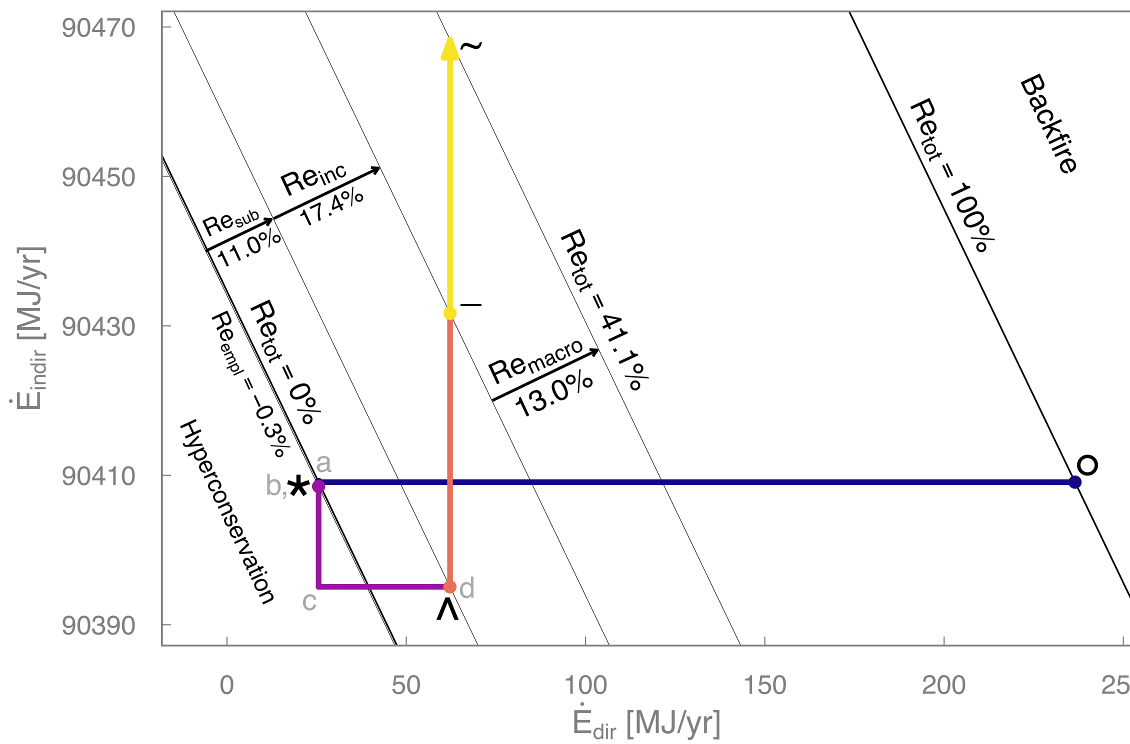

Fig. 8: The energy plane for the lamp example. Macro factor (k) is assumed to be 1. See Table 7 for meanings of path segments.

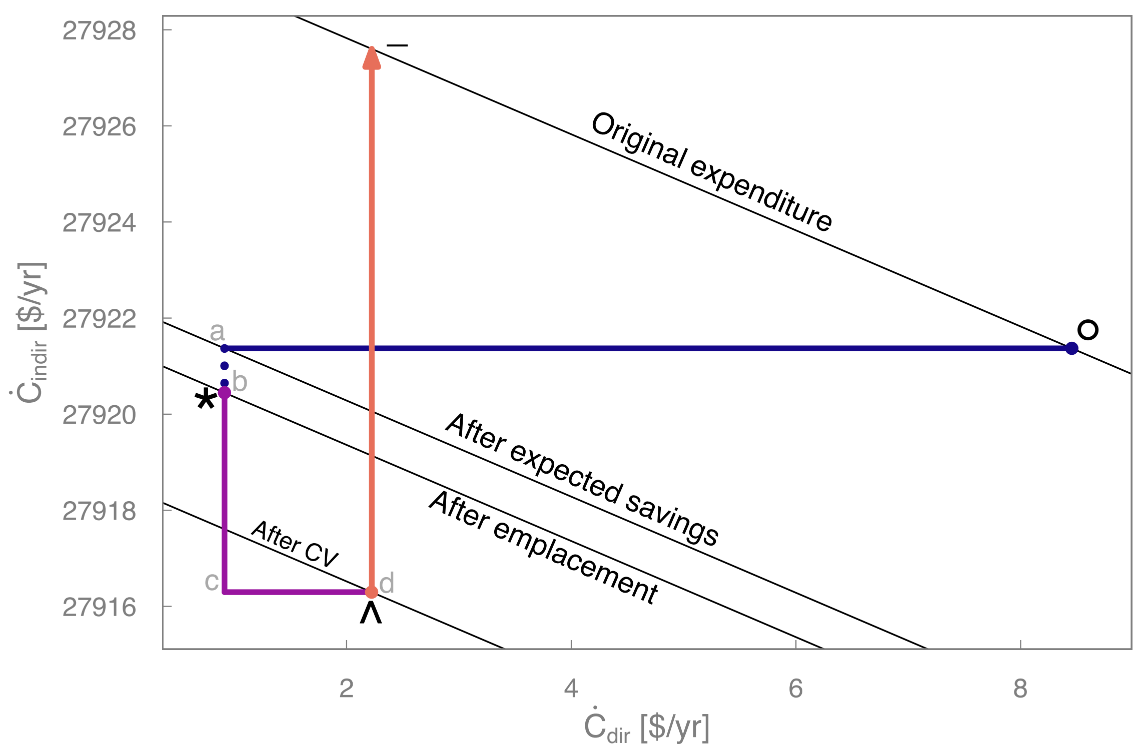

Fig. 9: Expenditure plane for the lamp example. CV is compensating variation, the increase in consumption of the energy service and decrease in consumption of other goods and services to maintain constant utility. See Table 7 for meanings of path segments.

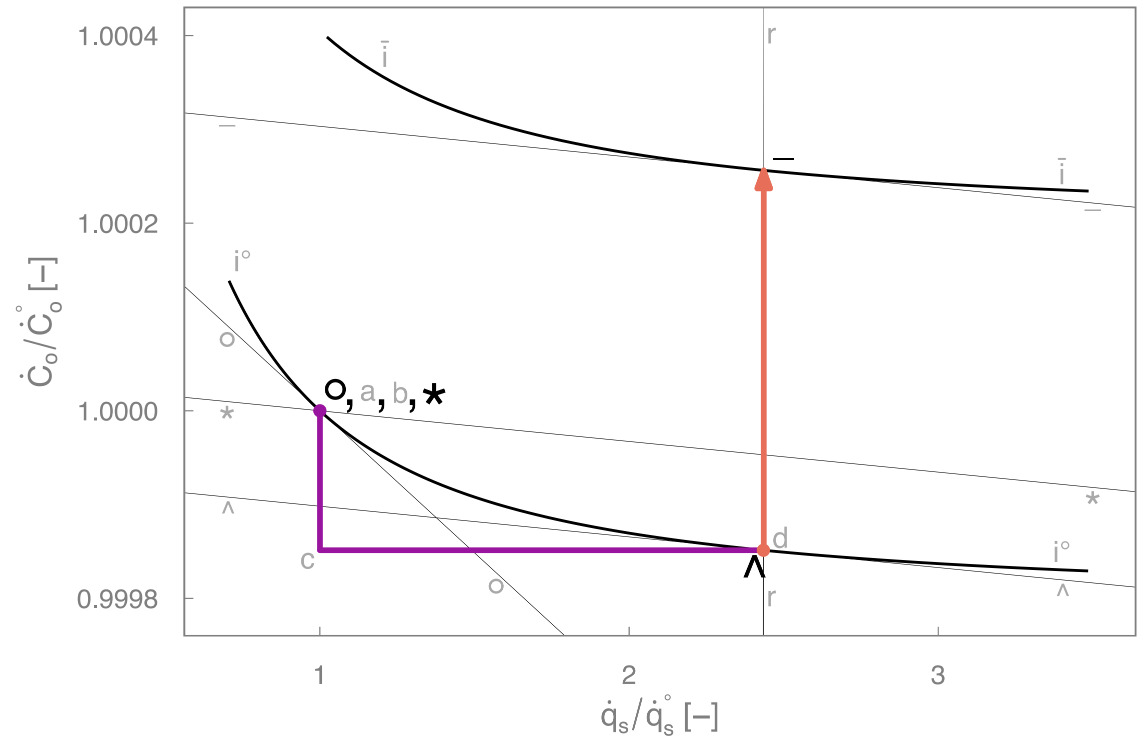

Fig. 10: Consumption plane for the lamp example. See Table 7 for meanings of path segments.

4 Discussion

4.1 A first attempt at calibrating k

Few previous studies explored 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 k, macro rebound and total rebound can be calculated.

To calibrate the macro factor (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%.[5] 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.

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 \$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.

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 \$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 3. (See Fig. F.1 in Appendix F 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

[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.

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

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.

After calibrating $k \approx 3$, 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 $k \approx 3$. 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. 5 and 8, the macro effect segments ($-$ — $\sim$) 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% and 39.0%, and the values of total rebound (Re_{tot}) should increase to 47.2% and 67.1% for the car and lamp examples, respectively. For the remainder of this paper, we use the calibrated value of $k \approx 3$.

4.2 Comparison between the car and lamp case studies

Tables 9 and 11 and our calibration of $k \approx 3$ in Section 4.1 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'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 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%. 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.

4.3 Comparison to previous rebound estimates

Tables 12 and 13 compare car and lamp results (with $k \approx 3$) to results from previous studies. The comparison studies are 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 12 and 13 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 12: 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)	U.S., 2020	Energy, expenditure, and consumption planes	1.4	9.9	12.6	23.2	15.9	31.3	47.2
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 run) 52 (long run)

Table 13: 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 $Re_{tot} = Re_{dir} + Re_{indir}$.

					Re_{micro}					
	Rebound study	Coverage	Analysis method	Re_{empl}	Re_{sub}	Re_{inc}	Re_{macro}	Re_{dir}	Re_{indir}	Re_{tot}
	This paper (2023)	U.S., 2020	Energy, expenditure, and consumption planes	−0.3	11.0	17.4	39.0	17.4	49.7	67.1
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 4.1. Also, no previous studies report either emplacement rebound ($Re_{empl} = Re_{emb} + Re_{md}$) 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 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 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.[6]

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 12 and 13. Our car (15.9%) 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)).[7]

For indirect rebound (Re_{indir}), there is little agreement on the magnitude of rebound effects. Our values for car (31.3%) and lamp (49.7%) indirect rebound magnitudes are higher than those found

[6] That said, without the top-down approaches, we would not have the information needed to calibrate the macro factor (k) in Section 4.1.

[7] 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).

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 12 and 13 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% (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% (car) and 67.1% (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.

5 Conclusions

In this paper (Part II), we advance clarity to 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 the macro factor ($k \approx 3$), (iii) documenting in detail new calculations of rebound for car and lighting upgrades, and (iv) 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 the distribution of MPC values across socioeconomic 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) 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 14.

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

Table 14: 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			●

this paper. ****

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