

Energy, expenditure, and consumption aspects of rebound,



Part I: A rigorous analytical 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. A new clarity is needed, one that involves both economics and energy analysis. In this paper (Part I of two), we advance a rigorous analytical framework that starts at the microeconomic level and is approachable for both energy analysts and economists. We develop a rebound analysis framework that (i) clarifies the energy, expenditure, and consumption aspects of rebound, (ii) combines embodied energy effects with operations, maintenance, and disposal effects (under a new “emplacement effect” term), and (iii) provides the first operationalized link between rebound effects on microeconomic and macroeconomic levels. Furthermore, our framework enables exact analytical determination of the effect of non-marginal energy service price decrease, the effect of satiation of energy service demand for the energy service, and the effect of reduced energy demand on energy price.

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

JEL codes: O13, Q40, Q43

1 Introduction

Energy efficiency is often considered to be the most important means of reducing energy consumption and CO₂ emissions (International Energy Agency, 2017, Fig. 3.15, p. 139). But energy rebound makes energy efficiency less effective at decreasing energy consumption by taking back (or reversing, in the case of “backfire”) energy savings expected from energy efficiency improvements (Sorrell, 2009). As such, energy rebound is a threat to a low-carbon future (van den Bergh, 2017; Brockway et al., 2017).

Recent evidence shows that rebound is both larger than commonly assumed (Stern, 2020) and mostly missing from large energy and climate models (Brockway et al., 2021). Thus, rebound could be an important reason why energy consumption and carbon emissions have never been absolutely decoupled from economic growth (Haberl et al., 2020; Brockway et al., 2021).

1.1 A short history of rebound

Famously, the roots of energy rebound trace back to Jevons who said “[i]t is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth” (Jevons, 1865, p. 103, emphasis in original). Less famously, the origins of rebound extend further backward from Jevons to Williams (1840) and Parkes who wrote “[t]he economy of fuel is the secret of the economy of the steam-engine; it is the fountain of its power, and the adopted measure of its effects. Whatever, therefore, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations” (Parkes, 1838, p. 161). For nearly 200 years, then, it has been understood that efficiency gains may be taken back or, paradoxically, cause *growth* in energy consumption, as Jevons suggested.

The oil crises of the 1970s shone a light back onto energy efficiency, and research into rebound

appeared late in the decade (Madlener & Turner, 2016; Saunders et al., 2021). A modern debate over the magnitude of energy rebound commenced. On one side, scholars including Brookes (1979, 1990) and Khazzoom (1980) suggested rebound could be large. Others, including Lovins (1988) and Grubb (1990, 1992), claimed rebound was likely to be small. Debate over the size of energy rebound continues today. Advocates of small rebound (less than, say, 50%), suggest “the rebound effect is overplayed” (Gillingham et al., 2013, p. 475), while others claim (i) that the evidence for large rebound (greater than 50%) is growing (Saunders, 2015; Berner et al., 2022) and (ii) that rebound will reduce the effectiveness of energy efficiency to decrease carbon emissions (van den Bergh, 2017).

1.2 Absence of solid analytical foundations

Turner contends that the lack of consensus on the magnitude of energy rebound in the modern empirical literature is caused by “a rush to empirical estimation in the absence of solid analytical foundations” (Turner, 2013, p. 25). Progress has been made recently on how price changes affect economy-wide rebound in general equilibrium frameworks (Lemoine, 2020; Fullerton & Ta, 2020; Blackburn & Moreno-Cruz, 2020). Arguments from microeconomics (i.e., at sectoral and individual level) have been used from the outset of the modern debate (e.g., Khazzoom (1980) and Greening et al. (2000)), and Borenstein (2015) and Chan & Gillingham (2015) recently made progress toward solidifying the microeconomic analytical foundations.

Yet more is needed to support empirical efforts. For instance, while the microeconomic categories of substitution and income effects provide analytical clarity about how behavior changes affect energy service consumption, it has been unclear how they could be used for precise numerical rebound calculations. Where previous numerical calculations were made, they tended to approximate the substitution effect from other goods to the cheaper energy service, without maintaining constant utility for the device user. They also used constant price elasticities for non-marginal efficiency improvements, even though constant price elasticities typically provide only approximations of substitution and income effects for small efficiency changes. Further, previous analytical studies have stressed the importance of the cost of buying an upgraded device as well as the energy embodied in the device. Yet, there is no clearly formulated approach for how to incorporate these cost and

energy components into rebound calculations. And rebound involves simultaneous changes in energy, expenditure, and consumption aspects—keeping an overview of all aspects is hard, with no approach to our knowledge documenting all changes in a straightforward and consistent manner. Finally, while recent general equilibrium rebound modeling has led to important insights about the effects of changing prices, dynamic aspects of a macroeconomic rebound have been neglected by these approaches.

In the absence of solid analytical foundations, the wide variety of rebound calculation approaches contributes to a wide range of rebound values, giving the appearance of uncertainty and leading some energy and climate modelers to either (i) use questionable rebound values or (ii) ignore rebound altogether. Insufficient inclusion of rebound in energy and climate models could lead to overly optimistic projections of the capability of energy efficiency to reduce carbon emissions (Brockway et al., 2021). We suggest that improving the conceptual foundations of rebound and solidifying the analytical frameworks will (i) help generate more robust estimates of rebound, (ii) lead to better rebound calculations in energy and climate models, and (iii) provide improved evidence for policymaking around energy efficiency.

But why is there an “absence of solid analytical foundations?” We propose that development of solid analytical frameworks for rebound is hampered by the fact that rebound is a decidedly interdisciplinary topic, involving both economics and energy analysis. Birol & Keppler (2000, p. 458) note that “different implicit and explicit assumptions of different research communities (‘economists’, ‘engineers’) . . . have in the past led to vastly differing points of view.”¹ Turner states that “[d]ifferent definitions of energy efficiency will be appropriate in different circumstances. However, . . . it is often not clear what different authors mean by energy efficiency” (Turner, 2013, p. 237–38). If authors from the two disciplines cannot even agree on the key terms, it is unsurprising that only modest progress has been made on analytical foundations. To fully understand rebound, economists need to have an energy analyst’s understanding of energy, and energy analysts need to have an economist’s understanding of finance and human behavior.² Developing the knowledge and skills required to

¹We prefer the term “energy analysts” over “engineers,” because “energy analysts” better describes the group of people engaged in “energy analysis.” For this paper, we define “energy analysis” to be the study of energy transformations from stocks to flows and wastes along society’s energy conversion chain for the purpose of generating energy services, economic activity, and human well-being.

²Indeed, this is why the authors for these papers come from the energy analysis (MKH, PEB) and economics (GS)

77 assess and calculate, let alone mitigate, rebound effects is a tall order, indeed.

78 1.3 New clarity is needed



79 We contend that new clarity is needed. A description of rebound that is (i) consistent across energy,
80 expenditure, and consumption aspects, (ii) technically rigorous, and (iii) approachable from both
81 sides (economics and energy analysis) will be a good starting point toward that clarity. In other
82 words, the finance and human behavior aspects of rebound need to be presented in ways energy
83 analysts can understand. And the energy aspects of rebound need to be presented in ways economists
84 can understand.

85 Summarizing, we surmise that reducing global carbon emissions has been hampered, in part, by
86 the fact that rebound is not sufficiently included in energy and climate models. We suspect that one
87 reason rebound is not sufficiently included is the lack of consensus on rebound calculation methods
88 and, hence, rebound magnitude. We agree with Turner that lack of consensus on rebound magnitude
89 is a symptom of the absence of solid analytical foundations for rebound. We posit that developing
90 solid analytical frameworks is difficult because energy rebound is an inherently interdisciplinary
91 topic. We believe that providing a detailed explication of a rigorous analytical framework for energy
92 rebound, which is approachable by both energy analysts and economists alike, will go some way
93 toward providing additional clarity in the field.

94 1.4 Objective, contributions, and structure

95 The *objective* of this paper is to help advance clarity in the field of energy rebound by supporting the
96 development of a rigorous analytical framework, one that (i) starts at the microeconomics of rebound
97 (building especially upon Borenstein (2015)) and (ii) is approachable for both energy analysts and
98 economists. We strive to keep the framework as simple as possible and in this spirit limit our
99 attention to a model of consumer demand for energy services, while noting that the approach is
100 transferable to a producer model with few modifications.

101 The key *contributions* of this paper are (i) a novel and clear explication of interrelated energy,
disciplines.



expenditure, and consumption aspects of energy rebound, (ii) development of a rebound analysis framework that combines embodied energy effects, operations, maintenance, and disposal effects, and exact expressions for substitution and income effects under non-marginal energy efficiency increases and (by implication) non-marginal energy service price decreases, (iii) an operationalized link between rebound effects on microeconomic and macroeconomic levels, and (iv) an application of the framework to an energy price effect.

The remainder of this paper is *structured* as follows. Section 2 describes the rebound analysis framework. Section 3 discusses this framework relative to previous frameworks and provides an initial assessment of an energy price effect. Section 4 concludes. Results from the application of our framework to energy efficiency upgrades to a car and an electric lamp can be found in Part II.

2 Methods: development of the framework

In this section, we develop an energy rebound framework for an individual consumer who upgrades the energy efficiency of a single device (concisely, “the framework,” “this framework,” or “our framework”). We endeavor to help advance clarity in the field of energy rebound by providing sufficient detail to assist energy analysts to understand the economics and economists to understand the energy analysis.

2.1 Rebound typology

Table 1 shows our typology of rebound effects. We follow others, including Jenkins et al. (2011) and Walnum et al. (2014), in identifying and including both direct and indirect rebound effects, which occur at (direct) and beyond (indirect) the level of the device and its user. Again following others, such as Gillingham et al. (2016), we distinguish between rebound effects at the microeconomic and macroeconomic levels.

Microeconomic rebound occurs at the level of the single device and its user and in our framework comprises three effects: an emplacement effect, a substitution effect, and an income effect, with direct and indirect partitions for each. All combinations are possible

“Emplacement” is a new term we introduce to collect indirect effects of the devices, including

Table 1: Rebound typology for our framework.

	Direct rebound (Re_{dir})	Indirect rebound (Re_{indir})
Microeconomic rebound (Re_{micro}) These mechanisms occur at the single device/user level within a static economy based on responses to the reduction in implicit price of an energy service.	Emplacement effect (Re_{dempl}) Accounts for performance of the Energy Efficiency Upgrade (EEU) only. No behavior changes occur. The direct energy effect of emplacement of the EEU is expected device-level energy savings. By definition, there is no rebound from direct emplacement effects ($Re_{dempl} \equiv 0$).	Emplacement effect (Re_{iempl}) Differential energy adjustments beyond the usage of the upgraded device, via (i) the embodied energy associated with the manufacturing phase (Re_{emb}) and (ii) the implied energy demand from maintenance and disposal (Re_{md}). Re_{iempl} can be > 0 or < 0 , depending on the characteristics of the EEU.
	Substitution effect (Re_{dsub}) Change in preference toward the energy service relative to other goods as a result of the EEU. Excludes by definition the effects of freed cash (income effects). $Re_{dsub} > 0$ is typical due to greater consumption of the energy service.	Substitution effect (Re_{isub}) Change in preference away from other goods relative to the energy service as a result of the EEU. Excludes by definition the effects of freed cash (income effects). $Re_{isub} < 0$ is typical due to reduced consumption of other goods and services.
	Income effect (Re_{dinc}) Spending of some of the freed cash to obtain more of the energy service. $Re_{dinc} > 0$ is typical due to increased consumption of the energy service.	Income effect (Re_{iinc}) Spending of some of the freed cash on other goods and services. $Re_{iinc} > 0$ is typical due to increased consumption of other goods and services.
Macroeconomic rebound (Re_{macro}) These mechanisms originate from the dynamic response of the economy to reach a stable equilibrium (between supply and demand for energy services and other goods). These mechanisms combine various short and long run effects.		Macroeconomic effect (Re_{macro}) Increased energy consumption in the broader macroeconomic system, i.e., beyond responses at the micro-economic (device/user) level. $Re_{macro} > 0$ is typical, due to spending of freed cash (at the micro-economic level) causing greater consumption in the wider economy.



(i) embodied energy of their manufacture (emb), (ii) operations and maintenance (OM), and (iii) disposal (d) activities. Although none of the embodied, operations and maintenance, or disposal effects are new (see Borenstein (2015, footnote 5, p. 3), Saunders et al. (2021), Sorrell et al. (2009), Borenstein (2015, footnote 37, p. 16), and Sorrell et al. (2020)), we separate them from substitution and income microeconomic effects (Table 1) to calculate rebound according to the steps in our framework. (See Section 2.5.)

The direct rebound effect can be partitioned into a direct emplacement effect, a direct substitution effect, and a direct income effect. At the level of the device, all of the direct rebound effects change the consumption of energy by the device whose efficiency has been upgraded, according to a microeconomic behavioral model of the consumer who responds to the cheaper energy service.

Similarly, the indirect rebound effect can be partitioned into an indirect emplacement effect, an indirect substitution effect, and an indirect income effect. All of the indirect effects change the induced energy consumption beyond the upgraded device, again according to a microeconomic behavioral model. We assume a *partial equilibrium* response to the energy efficiency upgrade (EEU) at the microeconomic level; other prices in the economy (p_o) remain unchanged in response to the EEU.

In contrast, macroeconomic rebound is a broader, economy-wide response to the single device upgrade. Like other authors, we recognize many macroeconomic rebound effects, even if we don't later distinguish among them.³ At the macroeconomic level, *general equilibrium* effects can occur as prices for all goods and services (even energy) may change in response to the EEU. Further treatment of macroeconomic rebound can be found in Section 2.5.4 of this paper (Part I) and in Section 4.2 of Part II. Discussion of an energy price effect can be seen in Section 3.2 below.

Fig. 1 shows rebound effects arranged in the left-to-right order of their discussion in this paper. The left-to-right order does not necessarily represent the progression of rebound effects through time. Rebound symbols are shown above each effect (Re_{empl} , etc.). Nomenclature for partitions of direct and indirect rebound is shown beneath each effect (Re_{dempl} , etc.). Decorations for each stage are

³For example, Sorrell (2009) sets out five macroeconomic rebound effects: embodied energy effects, responding effects, output effects, energy market effects, and composition effects. (We place the embodied energy effect at the microeconomic level.) Santarius (2016) and Lange et al. (2021) introduce meso (i.e., sectoral) level rebound between the micro and macro levels. van den Bergh (2011) distinguishes 14 types of rebound, providing, perhaps, the greatest complexity.

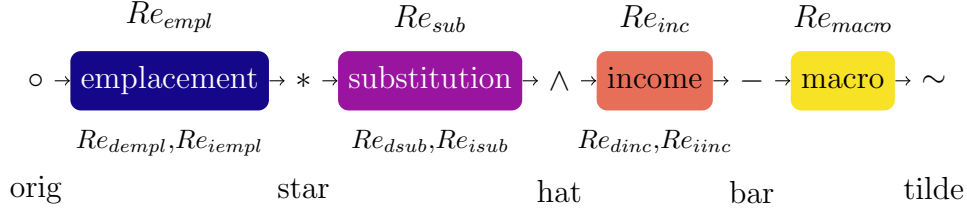


Fig. 1: Flowchart of rebound effects and decorations.

shown between rebound effects (\circ , $*$, etc.). Names for the decorations are given at the bottom of the figure (“orig,” “star,” etc.).⁴

2.2 Rebound relationships

Energy rebound is defined as

$$Re \equiv 1 - \frac{\text{actual final energy savings rate}}{\text{expected final energy savings rate}}, \quad (1)$$

where both actual and expected final energy savings rates are in MJ/yr (megajoules per year) and expected positive. The final energy “takeback” rate is defined as the expected final energy savings rate less the actual final energy savings rate.⁵ Rewriting Eq. (1) with the definition of takeback gives

$$Re = 1 - \frac{\text{expected final energy savings rate} - \text{takeback rate}}{\text{expected final energy savings rate}}. \quad (2)$$

Simplifying gives

$$Re = \frac{\text{takeback rate}}{\text{expected final energy savings rate}}. \quad (3)$$

We define rebound at the final energy⁶ stage of the energy conversion chain, because the final energy stage is the point of energy purchase by the device user. To simplify derivations, we choose not

⁴Note that the vocabulary and mathematical notation for rebound effects is important; Fig. 1 and Appendix A provide guides to notational elements used throughout this paper, including symbols, Greek letters, abbreviations, decorations, and subscripts. The notational elements can be mixed to provide a rich and expressive symbolic “language” for energy rebound. In several places, including Fig. 1, we use colored backgrounds on rebound effects for visual convenience. The colors are carried through to figures in Part II for consistency.

⁵Note that the takeback rate can be negative, indicating that the actual final energy savings rate is greater than the expected final energy savings rate, a condition called hyperconservation.

⁶Conventionally, stages of the energy conversion chain are primary energy (e.g., coal, oil, natural gas, wind, and solar), final energy (e.g., electricity and refined petroleum), useful energy (e.g., heat, light, and mechanical drive), and energy services (e.g., transport, illumination, and space heating).

to apply final-to-primary energy multipliers to final energy rates in the numerators and denominators of rebound expressions derived from Eqs. (1) and (3); they divide out anyway.⁷ Henceforth, we drop the adjective “final” from the noun “energy,” unless there is reason to indicate a specific stage of the energy conversion chain.

2.3 The energy conversion device and energy efficiency upgrade (EEU)

We assume an energy conversion device (say, a car) that consumes energy (say, gasoline) at a rate \dot{E}° (in MJ/yr). We use “rate” to indicate any quantity measured per unit time, such as a flow of energy per year or a flow of income per year. None of the rates in this paper indicate exponential (%/yr) changes. Rates are identified by a single dot above the symbol, a convention adopted from the engineering literature where, e.g., \dot{x} often indicates a velocity in m/s (meters per second), \dot{m} often indicates a mass flow rate in kg/s (kilograms per second), and \dot{E} often indicates an energy flow rate in kW (kilowatts). The overdot is an important notational element in this paper, as it provides clarity between stocks (without overdots) and flows (with overdots). For example, E is a quantity of energy in, say, MJ, while \dot{E} is a rate of energy in, say, MJ/yr. We later annualize capital costs (C_{cap} in \$), disposal costs (C_d in \$), and energy embodied in the device during its production (E_{emb} in MJ) to create undiscounted cost rates (\dot{C}_{cap} and \dot{C}_d in \$/yr) and embodied energy rates (\dot{E}_{emb} in MJ/yr). (Cost discounting is captured by the variables R_α and R_ω . See Appendix B.1 for details.)

Energy is available at price p_E (in \$/MJ). The original energy conversion device provides a rate of energy service \dot{q}_s° (in, say, vehicle-km/yr) with final-to-service efficiency η° (in, say, vehicle-km/MJ). An energy efficiency upgrade (EEU) increases final-to-service efficiency⁸ such that $\eta^\circ < \tilde{\eta}$. The EEU is not costless, so the upgraded device may be more expensive to purchase than a like-for-like replacement of the original device. We call this increased “capital cost” ($C_{cap}^\circ < \tilde{C}_{cap}$). It may also be more costly to operate and maintain (OM) and dispose (d) of the upgraded device ($\dot{C}_{OM}^\circ < \tilde{C}_{OM}$ and $\dot{C}_d^\circ < \tilde{C}_d$). However, the opposite may hold, too. As final-to-service efficiency increases ($\eta^\circ < \tilde{\eta}$),

⁷Primary energy may be important when the upgraded device consumes a different final energy carrier compared to the original device, i.e., when fuel-switching occurs (Chan & Gillingham, 2015).

⁸Note that energy service efficiency (η) improves between the original (\circ) and post-emplacement ($*$) stages of Fig. 1, remaining constant thereafter. Thus, $\eta^\circ < \eta^* = \hat{\eta} = \bar{\eta} = \tilde{\eta}$, as shown in Table B.1. We refer to all post-emplacement efficiencies (η^* , $\hat{\eta}$, $\bar{\eta}$, and $\tilde{\eta}$) as $\tilde{\eta}$ to match the nomenclature of Borenstein (2015). When convenient, the same approach to nomenclature is taken with other quantities such as the capital, operations and maintenance, and disposal cost rates (\dot{C}_{cap} , \dot{C}_{OM} , and \dot{C}_d , respectively).

the price of the energy service declines ($p_s^\circ > \tilde{p}_s$). The energy price (p_E) is assumed exogenous at the microeconomic level ($p_E^\circ = p_E^* = \hat{p}_E = \bar{p}_E = \tilde{p}_E$), so the energy purchaser (the device user) is a price taker.⁹ Initially, the device user spends income (\dot{M}°) on energy for the device ($\dot{C}_s^\circ = p_E \dot{E}_s^\circ$), annualized capital costs for the device (undiscounted: \dot{C}_{cap}° ; discounted: $R_\alpha^\circ \dot{C}_{cap}^\circ$), annualized costs for operations and maintenance (\dot{C}_{OM}°) and disposal of the device (undiscounted: \dot{C}_d° ; discounted: $R_\omega^\circ \dot{C}_d^\circ$), and other goods and services (\dot{C}_o°). The budget constraint for the device user is

$$\dot{M}^\circ = R_\alpha^\circ \dot{C}_{cap}^\circ + \dot{C}_s^\circ + \dot{C}_{OM}^\circ + R_\omega^\circ \dot{C}_d^\circ + \dot{C}_o^\circ + \dot{N}^\circ \quad (4)$$

where R_α° and R_ω° account for discounting, \dot{C}_{cap}° and \dot{C}_{OM}° are undiscounted cost rates given by $C_{cap}^\circ/t_{life}^\circ$ and C_d°/t_{life}° , and net savings prior to the EEU (\dot{N}°) is zero, by definition. See Appendix B.1 for details. After substituting the original price and quantity of energy service consumption, after substituting the original price and quantity of other goods consumption, after substituting $\dot{C}_{OMd}^\circ \equiv \dot{C}_{OM}^\circ - R_\omega^\circ \dot{C}_d^\circ$, and after some rearrangement, Eq. (4) becomes

$$\dot{M} - R_\alpha^\circ \dot{C}_{cap} - \dot{C}_{OMd} = p_s \dot{q}_s + p_o \dot{q}_o, \quad (5)$$

which is the usual discounted budget constraint for the microeconomic consumer after subtracting capital, operations and maintenance, and disposal costs.

Later (Sections 2.5.1–2.5.4), we walk through the four rebound effects (emplacement, substitution, income, and macro), deriving rebound expressions for each, but first we show typical energy and cost relationships (Section 2.4).

2.4 Typical energy and cost relationships

With the rebound notation of Appendix A, four typical relationships emerge. First, the consumption rate of the energy service (\dot{q}_s) is the product of final-to-service efficiency (η) and the rate of energy consumption by the energy conversion device (\dot{E}_s). Typical units for automotive transport and illumination (the examples in Part II) are shown beneath each equation.¹⁰

⁹Relaxing the exogenous energy price assumption would require a general equilibrium model that is beyond the scope of this paper. However, see Section 3.2 where we discuss an energy price effect as an extension of the framework.

¹⁰Note that “pass” is short for “passenger,” and “lm” is the SI notation for the lumen, a unit of lighting energy rate.

$$\dot{q}_s = \eta \dot{E}_s \quad (6)$$

$$[\text{pass} \cdot \text{km} / \text{yr}] = [\text{pass} \cdot \text{km} / \text{MJ}] [\text{MJ} / \text{yr}]$$

$$[\text{lm} \cdot \text{hr} / \text{yr}] = [\text{lm} \cdot \text{hr} / \text{MJ}] [\text{MJ} / \text{yr}]$$

209 Second, the energy service price (p_s) is the ratio of energy price (p_E) to the final-to-service effi-
 210 ciency (η).

$$p_s = \frac{p_E}{\eta} \quad (7)$$

$$[\$/\text{pass} \cdot \text{km}] = \frac{[\$/\text{MJ}]}{[\text{pass} \cdot \text{km} / \text{MJ}]}$$

$$[\$/\text{lm} \cdot \text{hr}] = \frac{[\$/\text{MJ}]}{[\text{lm} \cdot \text{hr} / \text{MJ}]}$$

211 Third, energy service expenditure rates (\dot{C}_s) are the product of energy price (p_E) and device energy
 212 consumption rates (\dot{E}_s).

$$\dot{C}_s = p_E \dot{E}_s \quad (8)$$

$$[\$/\text{yr}] = [\$/\text{MJ}] [\text{MJ} / \text{yr}]$$

213 Fourth, indirect energy rates for operations and maintenance (\dot{E}_{OM}), disposal (\dot{E}_d), and other
 214 goods expenditures (\dot{E}_o) are the product of undiscounted expenditures rates (\dot{C}_{OM} , \dot{C}_d , and \dot{C}_o) and
 215 the energy intensity of the economy (I_E).

$$\dot{E}_{OM} = \dot{C}_{OM} I_E \quad (9)$$

$$\dot{E}_d = R_\omega \dot{C}_d I_E \quad (10)$$

$$\dot{E}_o = \dot{C}_o I_E \quad (11)$$

$$[\text{MJ} / \text{yr}] = [\$/\text{yr}] [\text{MJ} / \$]$$

216 Indirect energy rates for disposal costs include discounting. (See Appendix B.1 for details on cost
 217 discounting.)

2.5 Rebound effects

The four rebound effects (emplacement, substitution, income, and macro) are discussed in subsections below. In each subsection, we define the effect and show mathematical expressions for rebound (Re) caused by the effect. Detailed derivations of all rebound expressions can be found in Appendix B. See, in particular, Tables B.3–B.6, which provide a parallel structure for energy and financial accounting across all rebound effects. We begin with the emplacement effect.

2.5.1 Emplacement effect

The emplacement effect accounts for performance changes of the device due to the fact that a higher-efficiency device has been put in service (and will need to be decommissioned at a later date); behavior changes are addressed later, in the substitution and income effects.

Direct emplacement effect (Re_{dempl}) The direct emplacement effects of the EEU include device energy savings (\dot{S}_{dev}) and device energy cost savings ($\Delta\dot{C}_s^*$). \dot{S}_{dev} can be written conveniently as

$$\dot{S}_{dev} = \left(\frac{\tilde{\eta}}{\eta^\circ} - 1 \right) \frac{\eta^\circ}{\tilde{\eta}} \dot{E}_s^\circ. \quad (12)$$

(See Appendix B.4.1 for the derivation.)

Because the original and upgraded device are assumed to have equal performance¹¹ and because behavior changes are not considered in the direct emplacement effect, actual and expected energy savings rates are identical, and there is no takeback. By definition, then, the direct emplacement effect causes no rebound. Thus,

$$Re_{dempl} = 0. \quad (13)$$

Indirect emplacement effects (Re_{iempl}) Although the direct emplacement effect does not cause rebound, indirect emplacement effects may indeed cause rebound. Indirect emplacement effects

¹¹Of course, it is often the case that the original and upgraded devices have small performance differences. E.g., a high-efficiency LED lamp may have slightly greater or slightly lesser lumen output than the incandescent lamp it replaces. For the purpose of explicating this framework, we assume that the performance of the upgraded device can be matched closely enough to the performance of the original device such that the differences are immaterial to the user.

account for the life cycle of the energy conversion device, including (i) changes in the embodied energy rate ($\Delta \dot{E}_{emb}^*$), (ii) changes in the operations and maintenance energy and expenditure rates ($\Delta \dot{E}_{OM}^*$ and $\Delta \dot{C}_{OM}^*$), and (iii) changes in the disposal energy and expenditure rates ($\Delta \dot{E}_d^*$ and $\Delta \dot{C}_d^*$).

Embodied energy effect (Re_{emb}) One of the unique features of this framework is that independent analyses of embodied energy and capital costs of the EEU are required. We note that the different terms (embodied energy rate, \dot{E}_{emb} , and capital cost rate, \dot{C}_{cap}) might seem to imply different processes, but they actually refer to the same emplacement effect. Purchasing an upgraded device (which likely leads to $\dot{C}_{cap}^\circ \neq \dot{C}_{cap}^*$) will likely mean a changed embodied energy rate ($\dot{E}_{emb}^\circ \neq \dot{E}_{emb}^*$) to provide the same energy service. Our names for these aspects of rebound (embodied energy and capital cost) reflect common usage in the energy and economics fields, respectively.

Consistent with the energy analysis literature, we define embodied energy to be the sum of all energy consumed in the production of the energy conversion device, all the way back to resource extraction.¹² Energy is embodied in the device within manufacturing and distribution supply chains prior to consumer acquisition of the device. We assume no energy is embodied in the device while in service. The EEU causes the embodied energy of the energy conversion device to change from E_{emb}° to E_{emb}^* .

For simplicity, we spread all embodied energy over the lifetime of the device to provide a constant embodied energy rate (\dot{E}_{emb}). A justification for spreading embodied energy and purchase costs comes from considering device replacements by many consumers across several years. In the aggregate, evenly spaced (in time) replacements work out to the same embodied energy in every period.

Thus, we allocate embodied energy over the life of the original and upgraded devices (t_{life}° and t_{life}^* , respectively) without discounting to obtain embodied energy rates, such that $\dot{E}_{emb}^\circ = E_{emb}^\circ / t_{life}^\circ$ and $\dot{E}_{emb}^* = E_{emb}^* / t_{life}^*$. The change in embodied final energy due to the EEU (expressed as a rate) is given by $\Delta \dot{E}_{emb}^* = \dot{E}_{emb}^* - \dot{E}_{emb}^\circ$. The expression for embodied energy rebound is

$$Re_{emb} = \frac{\left(\frac{E_{emb}^* t_{life}^\circ}{E_{emb}^\circ t_{life}^*} - 1 \right) \dot{E}_{emb}^\circ}{\dot{S}_{dev}} . \quad (14)$$

¹²We take an energy approach here, consistent with the literature on energy rebound. One could use an alternative quantification of energy, such as exergy, the work potential of energy (Sciubba & Wall, 2007) or emergy, the solar content of energy (Brown & Herendeen, 1996).

(See Appendix B.4.2 for details of the derivation.)

Embodied energy rebound (Re_{emb}) can be either positive or negative, depending on the sign of the term $(E_{emb}^*/E_{emb}^\circ)(t_{life}^\circ/t_{life}^*) - 1$. Rising energy efficiency can be associated with increased device complexity, additional energy consumption in manufacturing, and more embodied energy, such that $E_{emb}^\circ < E_{emb}^*$ and $Re_{emb} > 0$, all other things being equal. However, if the upgraded device has longer life than the original device ($t_{life}^* > t_{life}^\circ$), $\dot{E}_{emb}^* - \dot{E}_{emb}^\circ$ could be negative, meaning that the upgraded device has a lower embodied energy rate than the original device.

Operations, maintenance, and disposal effects (Re_{OMd}) In addition to embodied energy, indirect emplacement effect rebound accounts for energy demanded by operations and maintenance (subscript OM) and disposal (subscript d) activities. Operations and maintenance expenditures are typically modeled as a per-year expense, a rate (e.g., \dot{C}_{OM}°). On the other hand, disposal costs (e.g., C_d°) are incurred at the end of the useful life of the energy conversion device (subscript ω). We annualize disposal costs (with discounting) across the lifetime of the original and upgraded devices (t_{life}° and t_{life}^* , respectively) to form discounted expenditure rates such that $\dot{C}_{OMd}^\circ = \dot{C}_{OM}^\circ + R_\omega \dot{C}_d^\circ$ and $\dot{C}_{OMd}^* = \dot{C}_m^* + R_\omega \dot{C}_d^*$.

For simplicity, we assume that operations, maintenance, and disposal expenditures imply energy consumption elsewhere in the economy at its overall energy intensity (I_E). Therefore, the change in energy consumption rate caused by a change in maintenance and disposal expenditures is given by $\Delta \dot{C}_{OMd}^* I_E = (\dot{C}_{OMd}^* - \dot{C}_{OMd}^\circ) I_E$. Rebound from operations, maintenance, and disposal activities is given by

$$Re_{OMd} = \frac{\left(\frac{\dot{C}_{OMd}^*}{\dot{C}_{OMd}^\circ} - 1\right) \dot{C}_{OMd}^\circ I_E}{\dot{S}_{dev}}. \quad (15)$$

(See Appendix B.4.2 for details of the derivation.)

2.5.2 Substitution effect

Neoclassical consumer theory determines consumer behavior through utility maximization. It decomposes price-induced behavior change into (i) substituting energy service consumption for other goods consumption due to the lower post-EEU price of the energy service (the substitution effect)

and (ii) spending the higher real income (the income effect).¹³ This section develops mathematical expressions for substitution effect rebound (Re_{sub}), thereby accepting the standard neoclassical microeconomic assumptions about consumer behavior.¹⁴ (The next section addresses income effect rebound, Re_{inc} .) The substitution effect determines compensated demand, which is the demand for the expenditure-minimizing consumption bundle that maintains utility at the pre-EEU level, given the new prices. Compensated demand is a technical term for a thought experiment from welfare economics: the device user's budget is altered so that the user is "compensated" for the change in price so as to maintain the same level of utility as before. In the case of an EEU, this implies the budget is reduced because the energy service price has fallen, so that it becomes cheaper to maintain a given level of utility. The change in the budget is called "compensating variation" (CV). The substitution effect involves (i) an increase in consumption of the energy service, the direct substitution effect (subscript $dsub$) and (ii) a decrease in consumption of other goods, the indirect substitution effect (subscript $isub$). Thus, two terms comprise substitution effect rebound: direct substitution rebound (Re_{dsub}) and indirect substitution rebound (Re_{isub}).

After emplacement of the more efficient device (but before the substitution effect), the price of the energy service decreases ($p_s^o > p_s^*$). After compensating variation tightens the budget constraint, consumption at the new energy service price (p_s^*) yields utility at the same level as prior to the EEU by consuming more of the now-lower-cost energy service and less of the now-relatively-more-expensive other goods.

A constant price elasticity (CPE) utility model is often used in the literature (e.g., see Borenstein (2015, p. 17, footnote 43)) for determining post-substitution effect consumption and therefore Re_{dsub} and Re_{isub} . (See Appendix B.4.3.) However, the CPE utility model can deliver only an approximation of the substitution effect for two reasons. First, because it is a reduced form model and only uncompensated elasticities are observed, the CPE utility model reports the sum of direct substitution effect and direct income effect rebound ($Re_{dsub} + Re_{dinc}$). Second, price elasticities typically change as consumption bundles change, whereas the CPE price elasticity remains constant

¹³For the original development of the decomposition see Slutsky (1915) and Allen (1936). For a modern introduction see Nicholson & Snyder (2017).

¹⁴Alternative assumptions on behavior would arise from, e.g., adopting a behavioral economic framework (Dütschke et al., 2018; Dorner, 2019) or an informational entropy-constrained economic framework (Foley, 2020).

by definition. Typically, constant price elasticities (as in the CPE utility model) are approximations that are applicable only to marginal price changes. As shown in Part II, these approximations can lead to small or large errors depending on the case, in our two case studies overstating substitution rebound by 0.3% (car) and 5.5% (lamp), **** Change previous numbers to calculations. —MKH **** relative to our exact model, which we introduce next. Appendix C derives changes in price elasticities for non-CPE models.

Here, we present a constant elasticity of substitution (CES) utility model that allows all of the uncompensated own price elasticity ($\varepsilon_{\dot{q}_s p_s}$), the uncompensated cross price elasticity ($\varepsilon_{\dot{q}_o p_s}$), the compensated own price elasticity ($\varepsilon_{\dot{q}_s p_s, c}$), and the compensated cross price elasticity ($\varepsilon_{\dot{q}_o p_s, c}$) to vary along an indifference curve, thereby enabling numerically precise analysis of non-marginal energy service price changes ($p_s^\circ \gg p_s^*$). The CES utility model allows the direct calculation of the utility-maximizing consumption bundle for any constraint, describing the device user's behavior as

$$\frac{\dot{u}}{\dot{u}^\circ} = \left[f_{\dot{C}_s}^\circ \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^\rho + (1 - f_{\dot{C}_s}^\circ) \left(\frac{\dot{C}_o}{\dot{C}_o^\circ} \right)^\rho \right]^{(1/\rho)}. \quad (16)$$

The device user's utility rate (relative to the original condition, \dot{u}/\dot{u}°) is determined by the consumption rate of the energy service (\dot{q}_s) and the consumption rate of other goods and services (\dot{C}_o). The share parameter ($f_{\dot{C}_s}^\circ$) between \dot{q}_s and \dot{C}_o is taken from the original (pre-EEU) consumption basket. The exponent ρ is calculated from the (constant) elasticity of substitution (σ) as $\rho \equiv (\sigma - 1)/\sigma$. All quantities are normalized to pre-EEU values so that the cost share of other goods can be used straightforwardly in empirical applications rather than having to construct quantity and price indices. The normalized specification is commonly used in empirical CES *production* function applications (Klump et al., 2012; Temple, 2012; Gechert et al., 2021). See Appendix C for further details of the CES utility model.

Direct substitution effect rebound (Re_{dsub}) is

$$Re_{dsub} = \frac{\Delta \hat{E}_s}{\dot{S}_{dev}}, \quad (17)$$

which can be rearranged to

$$Re_{dsub} = \frac{\frac{\hat{q}_s}{\dot{q}_s^\circ} - 1}{\frac{\hat{\eta}}{\eta^\circ} - 1}. \quad (18)$$

Indirect substitution effect rebound (Re_{isub}) is given by

$$Re_{isub} = \frac{\Delta \hat{C}_o I_E}{\dot{S}_{dev}}, \quad (19)$$

which can be rearranged to

$$Re_{isub} = \frac{\frac{\hat{C}_o}{\dot{C}_o^\circ} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \frac{\tilde{\eta}}{\eta^\circ} \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ}. \quad (20)$$

To find the post-substitution effect point (\wedge), we solve for the location on the indifference curve where its slope is equal to the slope of the expenditure line after the EEU, assuming the CES utility model.¹⁵ The results are

$$\frac{\hat{q}_s}{\dot{q}_s^\circ} = \left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho} \quad (21)$$

and

$$\frac{\hat{C}_o}{\dot{C}_o^\circ} = \left(1 + f_{\dot{C}_s}^\circ \left\{ \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho}. \quad (22)$$

Eq. (21) can be substituted directly into Eq. (18) to obtain an expression for direct substitution rebound (Re_{dsub}) via the CES utility model.

$$Re_{dsub} = \frac{\left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \quad (23)$$

Eq. (22) can be substituted directly into Eq. (20) to obtain an expression for indirect substitution rebound (Re_{isub}) via the CES utility model.

$$Re_{isub} = \frac{\left(1 + f_{\dot{C}_s}^\circ \left\{ \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \frac{\tilde{\eta}}{\eta^\circ} \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ} \quad (24)$$

(See Appendix B.4.3 for details of the derivations of Eqs. (18), (20), and (21)–(24).)

¹⁵Other utility models could be used; however, the Cobb-Douglas utility model is inappropriate for this framework, because it assumes that the sum of substitution and income rebound is 100% *always*. Regardless of the utility model, expressions for $\hat{q}_s/\dot{q}_s^\circ$ and $\hat{C}_o/\dot{C}_o^\circ$ must be determined and substituted into Eqs. (18) and (20), respectively.

2.5.3 Income effect

The monetary income rate of the device user (\dot{M}°) remains unchanged across the rebound effects, such that $\dot{M}^\circ = \dot{M}^* = \hat{\dot{M}} = \bar{\dot{M}} = \tilde{\dot{M}}$. Thanks to the energy service price decline, real income rises, and freed cash from the EEU is given by as $\dot{G} = p_E \dot{S}_{dev}$. (See Eq. (93) in Appendix B.3.) Emplacement effect adjustments and compensating variation modify freed cash to leave the device user with *net* savings ($\hat{\dot{N}}$) from the EEU, as shown in Eq. (103) in Appendix B.3. (Derivations of expressions for freed cash from the emplacement effect (\dot{G}) and net savings after the substitution effect ($\hat{\dot{N}}$) are presented in Tables B.3 and B.4.) Rebound from the income effect quantifies the rate of additional energy demand that arises when the energy conversion device user spends net savings from the EEU.

Additional energy demand from the income effect is determined by several constraints. The income effect under utility maximization satisfies the budget constraint, so that net savings are zero after the income effect ($\bar{\dot{N}} = 0$). (See Appendix D for a mathematical proof that the income preference equations below (Eqs. (25) and (29)) satisfy the budget constraint.)

A second constraint is that net savings are spent completely on (i) additional consumption of the energy service ($\hat{q}_s < \bar{q}_s$) and (ii) additional consumption of other goods ($\hat{q}_o < \bar{q}_o$). The proportions in which income-effect spending is allocated depends on the utility model, which prescribes the income expansion path for consumption. Given post-EEU prices, maximized CES utility means spending in the same proportion on the energy service and other goods across the income effect, a property known as homotheticity. This constraint is satisfied by construction below, particularly via an effective income term ($\hat{\dot{M}}'$).

However, this framework could accommodate non-homothetic preferences for spending across the income effect (turning the income expansion path into a more general curve instead of a line). Demand for certain energy services could satiate as consumers become more affluent, implying income elasticities of the energy service of less than one (Greening et al., 2000). At the lower bound, the consumer spends all income after the substitution effect on other goods and none on the energy service, choices that serve to reduce rebound due to typically lower energy intensity of other goods

373 compared to the energy service.¹⁶

374 We next show expressions for direct and indirect income effect rebound.

375 **Direct income effect** (Re_{dinc}) The income elasticity of energy service demand ($\varepsilon_{\hat{q}_s, \hat{M}}$) quantifies
 376 the amount of net savings spent on more of the energy service ($\hat{q}_s < \bar{q}_s$). (See Appendix C for
 377 additional information about elasticities.) Spending of net savings on additional energy service
 378 consumption leads to direct income effect rebound (Re_{dinc}).

379 The ratio of rates of energy service consumed across the income effect is given by

$$\frac{\bar{q}_s}{\hat{q}_s} = \left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_s, \hat{M}}} . \quad (25)$$

380 Under the CES utility model, homotheticity means that $\varepsilon_{\hat{q}_s, \hat{M}} = 1$.

381 Effective income (\hat{M}') is given by

$$\hat{M}' \equiv \dot{M}^\circ - R_\alpha^* \dot{C}_{cap}^* - \dot{C}_{OMd}^* - \hat{N} . \quad (26)$$

382 For the purposes of the income effect, effective income (Eq. (26)) adjusts original income (\dot{M}°) to
 383 account for sunk costs ($R_\alpha^* \dot{C}_{cap}^*$ and \dot{C}_{OMd}^*) and net savings (\hat{N}).

384 Direct income rebound is defined as

$$Re_{dinc} \equiv \frac{\Delta \bar{E}_s}{\dot{S}_{dev}} . \quad (27)$$

385 (See Table B.5.) After substitution, rearranging, and canceling of terms (Appendix B.4.4), the
 386 expression for direct income rebound under the CES utility model is

$$Re_{dinc} = \frac{\left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_s, \hat{M}}} - 1}{\frac{\hat{\eta}}{\eta^\circ} - 1} \left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho} . \quad (28)$$

387 If there are no net savings after the substitution effect ($\hat{N} = 0$), direct income effect rebound is zero
 388 ($Re_{dinc} = 0$), as expected.¹⁷

¹⁶In principle, the energy service could be an “inferior good” whose consumption declines as incomes rise. However, energy service elasticities of income have been estimated to be positive over the long run, so we do not expect the inferior good case to be relevant (Fouquet, 2014).

¹⁷Zero net savings ($\hat{N} = 0$) could occur if increases in the capital cost rate ($\Delta \dot{C}_{cap}^*$) and/or the maintenance and disposal cost rate ($\Delta \dot{C}_{md}^*$) consume all freed cash (\dot{G}) plus savings from the compensating variation.

Under a non-homothetic utility model, the bounding condition is that as the device owner becomes richer, none of the income (\hat{N}) is spent on more of the energy service, and thus $Re_{dinc} = 0$ would occur.

Indirect income effect (Re_{iinc}) Not all net savings (\hat{N}) are spent on more energy for the energy conversion device. The income elasticity of other goods demand ($\varepsilon_{\hat{q}_o, \hat{M}}$) quantifies the amount of net savings spent on additional other goods ($\hat{q}_o < \bar{q}_o$). Spending of net savings on additional other goods and services leads to indirect income effect rebound (Re_{iinc}).

The ratio of rates of other goods consumed across the income effect is given by

$$\frac{\bar{q}_o}{\hat{q}_o} = \left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_o, \hat{M}}} . \quad (29)$$

Under the assumption that prices of other goods are exogenous (see Appendix E), the ratio of rates of other goods consumption (\bar{q}_o/\hat{q}_o) is equal to the ratio of rates of other goods expenditures (\bar{C}_o/\hat{C}_o) such that

$$\frac{\bar{C}_o}{\hat{C}_o} = \left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_o, \hat{M}}} . \quad (30)$$

Homotheticity means that $\varepsilon_{\hat{q}_o, \hat{M}} = 1$. As shown in Table B.5, indirect income rebound is defined as

$$Re_{iinc} \equiv \frac{\Delta \bar{C}_o I_E}{\dot{S}_{dev}} . \quad (31)$$

After substitution, rearranging, and canceling of terms, the expression for indirect income for the CES utility model rebound is

$$Re_{iinc} = \frac{\left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_o, \hat{M}}} - 1}{\frac{\hat{\eta}}{\eta^\circ} - 1} \left(\frac{\hat{\eta}}{\eta^\circ}\right) \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ} \left(1 + f_{\dot{C}_s}^\circ \left\{ \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho} . \quad (32)$$

(See Appendix B.4.4 for details of the derivation of direct and indirect income effect rebound.)

Under the bounding non-homothetic utility model, consumption of the energy service is already satiated, all income (\hat{N}) is spent on other goods, and indirect rebound becomes simply $Re_{iinc} \equiv \frac{\hat{N} I_E}{\dot{S}_{dev}}$.

2.5.4 Macro effect

The previous rebound effects (emplacement effect, substitution effect, and income effect) occur at the microeconomic level. However, changes at the microeconomic level can have important impacts at the macroeconomic or economy-wide level.

It is one of the basic tenets of economics that productivity gains have been the main long-run driver of economic growth in the last couple of centuries (Smith, 1776; Marx, 1867; Solow, 1957). Interest in the impact of individual sectors on the whole economy reaches arguably even farther back (Quesnay, 1759; Leontief, 1986). Recent work revived interest in firm- and sector-specific shocks on aggregate output and demonstrates that due to interlinkages between firms and sectors, productivity shocks in a firm or sector can have larger macroeconomic consequences than the original shock (Gabaix, 2011; Acemoglu et al., 2012; Baqaee & Farhi, 2019). Foerster et al. (2022) estimate that 3/4 of long-run US growth since 1950 can be attributed to sector-specific (as opposed to aggregate) trend factors. Because the EEU represents a positive productivity shock, the same principles apply. These kinds of rebounds can be captured by a general equilibrium model (Stern, 2020), but we propose a simple rule for incorporating this macroeconomic effect of productivity growth into our partial equilibrium framework.

Before establishing a formalism for Re_{macro} , we clarify the link between consumer theory and economic growth. Turner (2013) cautions that when households see the productivity of their non-market activities increase, GDP remains unchanged.¹⁸ That may be true in the short run. But the question over longer periods is whether the more productive household energy services do not also feed through into economic growth accounted for by GDP. People in affluent countries spend about as much time on unpaid (i.e., non-market) work as on paid work (Folbre, 2021). Therefore productivity improvements in unpaid work can spill over into paid work, which enters GDP. One channel could be time-saving. If the EEU saves time, then saved time could be spent on more paid work or on increasing human capital (Sorrell & Dimitropoulos, 2008; Gautham & Folbre, 2022). If the EEU saves

¹⁸To appreciate the difference between production for the market and production for the household, consider the case where increased mileage leads to the household saving on energy per car trip. The household takes more trips (direct rebound), without effect on GDP. In the other case, the household buys the energy service (transport) directly from a taxi company. Here, the taxi company lowers the price but gains more customers, leading immediately to growth in inflation-adjusted (i.e., real) GDP, as more driving services are produced. Yet, the physical change of more car trips is the same in both cases.

money (but no time), then the freed cash could be spent to create additional demand for products that translate into higher GDP and possibly faster productivity growth (Magacho & McCombie, 2018). It could also be spent on more effective (and more costly) human capital-increasing activities or even be used to start a venture. In all cases, it would be rash to conclude that just because some EEU lead to productivity increases not captured directly by GDP, they do not eventually lead to additional economic growth.

Borenstein also addressed these macro effects from consumer behavior noting that “income effect rebound will be larger economy-wide than would be inferred from evaluating only the direct income gain from the end user’s transaction” (Borenstein, 2015, p. 11) and likened it to a macroeconomic multiplier.¹⁹ The sectoral growth shock literature also uses multipliers to conceptualize the impacts of sectoral productivity shocks on aggregate output (Foerster et al., 2022; Buera & Trachter, 2024). Using multipliers has the advantage that they can be directly linked to the income effect (minus compensating variation) and its consequence for macroeconomic rebound. Borenstein also notes that scaling from net savings (\dot{N}^*) at the device level to productivity-driven growth at the macro level is unexplored territory.

We operationalize the macro rebound multiplier idea by noting that higher productivity makes the device cheaper to operate (and possibly purchase), which allows consumers to purchase a larger bundle of goods and services. If the overall expansion of the economy is a multiple of the direct increase in productivity to follow-on productivity gains in other sectors, then the macro effect can simply be represented as a multiple of the (indirect) emplacement effect at the “*” stage of Fig. 1, a multiplier that we represent by a macro factor (k).²⁰

The macro factor (k) represents responding in the broader economy after the emplacement effect has occurred and is not tied to any particular EEU or economic sector. $k \geq 0$ is expected. $k = 0$ means there is no macroeconomic effect resulting from the energy efficiency upgrade. $k > 0$ means that productivity-driven macroeconomic growth has occurred with consequent implications

¹⁹It is important to distinguish this multiplier from an autonomous expansion of expenditure, a demand-side shock, in an otherwise unchanged economy, i.e. the Keynesian multiplier (Kahn, 1931; Keynes, 1936), that risks crowding out other economic activity (Gillingham et al., 2016). This energy productivity improvement is a supply-side shock. After the EEU, it takes less energy (and therefore less energy cost) to generate the same economic activity, because energy efficiency has improved, so the concept of crowding-out as defined by macroeconomics does not apply.

²⁰The macro factor (k) appears unitless, but its units are actually \$ of economy-wide expansion created per \$ of net savings gained by the device user in the emplacement effect (\dot{N}^*).

456 for additional energy consumption in the wider economy.

457 We assume as a first approximation (following Antal & van den Bergh (2014) and Borenstein
458 (2015)) that macro effect responding implies energy consumption according to the average energy
459 intensity of the economy (I_E). Macro rebound is therefore given by

$$Re_{macro} = \frac{k\dot{N}^* I_E}{\dot{S}_{dev}} . \quad (33)$$

460 (See Table B.6.) After some algebra (Appendix B.4.5), we arrive at an expression for macro effect
461 rebound:

$$Re_{macro} = k(p_E I_E - Re_{cap} - Re_{OMd}) . \quad (34)$$

462 Another macroeconomic rebound could arise from the energy price, which could fall due to lower
463 demand (Gillingham et al., 2016; Borenstein, 2015). The size of the energy price effect depends on
464 the size of the energy savings from the EEU relative to the energy demand in the economy. Therefore,
465 calculating the energy price effect requires additional assumptions about how many households
466 adopt the new device, which we consider to be outside the scope of our core framework. However,
467 we show how it could be incorporated by adding an assumption about EEU adoption shares and a
468 model of the energy market to derive a rebound expression for the energy price effect in Appendix F.

469 2.6 Rebound sum

470 The sum of all rebound emerges from the four rebound effects (emplacement effect, substitution
471 effect, income effect, and macro effect). Macro effect rebound (Re_{macro} in Eq. (34)) is expressed in
472 terms of other rebound effects. (Derivation details can be found in Appendix B.4.6.) After algebra
473 and canceling of terms, we find

$$Re_{tot} = Re_{emb} + k(p_E I_E - Re_{cap}) + (1 - k)Re_{OMd} + Re_{dsub} + Re_{isub} + Re_{dinc} + Re_{iinc} . \quad (35)$$

3 Discussion

3.1 Comparison to other rebound frameworks

We developed above a rebound framework for consumers. We note that many of its components are similar to those for a producer-sided framework due to the symmetry between neoclassical microeconomic producer and consumer theory. Ours is a partial equilibrium framework at the microeconomic level that provides a detailed assessment of individual EEUs with tractable, easy-to-understand mathematics. Partial equilibrium frameworks are easier to understand, in part, because they constrain price variation to the energy service only; all other prices remain constant (at least at the microeconomic level).²¹ In our framework, general equilibrium effects and other dynamic effects at the macroeconomic level are captured by a simplified, one-dimensional rebound effect discussed in Section 2.5.4.

We are not the first to develop a rebound analysis framework, so it is worthwhile to compare our framework to others for key features: analysis of all rebound effects; analysis of energy, expenditure, and consumption aspects of rebound; level of detail in the consumer preference model; allowance for non-marginal energy efficiency changes; and empirical application. When all of the above characteristics are present, a fuller picture of rebound can emerge.²² Table 2 shows our assessment of selected previous partial equilibrium frameworks (in columns) relative to the characteristics discussed above (in rows).

Because all frameworks evaluate the expected decrease in direct energy consumption from the EEU, the “Direct emplacement effect” row contains ● in all columns. Three early papers (Nässén & Holmberg, 2009; Thomas & Azevedo, 2013a,b) estimate rebound quantitatively, earning high marks (●) in the “Empirical application” row. Both Nässén & Holmberg and Thomas & Azevedo motivate their frameworks at least partially with microeconomic theory (consumer preferences and substitution and income effects) but use simple linear demand functions in their empirical analyses. Thus, the connection between economic theory and empirics is tenuous, leading to intermediate ratings (◐ or less) in the “substitution effects,” “income effects,” and “Detailed model of consumer

²¹General equilibrium frameworks provide detail and precision on economy-wide price adjustments, but they give up specificity about individual device upgrades, make assumptions during calibration, and lose simplicity of exposition.

²²See Section 2.2 of Part II for literal pictures of rebound in energy, expenditure, and consumption planes.

Table 2: Comparison among relevant rebound analysis frameworks. Empty (white) circles indicate no treatment of a subject by a framework. Partly and fully filled circles indicate partial and comprehensive treatment of a subject by a framework.

	Nässén & Holmberg (2009)	Thomas & Azevedo (2013a,b)	Borenstein (2015)	Chan & Gillingham (2015)	Wang et al. (2021)	This paper (2024)
<i>Rebound effects</i>						
Direct emplacement effect	●	●	●	●	●	●
Capital cost and embodied energy effect	●	●	●	○	○	●
Maintenance and disposal effect	○	○	●	○	○	●
Direct and indirect substitution effects	●	●	●	●	●	●
Direct and indirect income effects	●	●	●	●	●	●
Macro effect	○	○	○	○	○	●
<i>Other characteristics</i>						
Analysis on energy, expenditure, and consumption planes	●	●	●	●	●	●
Detailed model of device user behavior and preferences	○	●	●	●	●	●
Non-marginal energy service price changes	○	○	○	○	○	●
Empirical application	●	●	●	○	○	●

preferences” rows. More recently, Chan & Gillingham (2015) and Wang et al. (2021) anchor the rebound effect firmly in consumer theory, earning high ratings (●) in the “substitution effects,” “income effects,” and “Detailed model of consumer preferences” rows. They extend their frameworks to advanced topics that our framework does not presently incorporate, such as multiple fuels, energy services, and nested utility functions with intermediate inputs. However, neither Chan & Gillingham nor Wang et al. provide empirical applications, earning ○ in the last row of Table 2. In the middle of the table (and between the other studies in time), the framework by Borenstein (2015) touches on nearly all important characteristics. However, the Borenstein framework cannot separate substitution and income effects cleanly in empirical analysis, reverting to partial analyses of both, leading to a ● rating in the “Detailed model of consumer preferences” and “Empirical application” rows.

No previous framework engages fully with either the differential financial effects or the differential energetic effects of the upfront purchase of the upgraded device, leading to low ratings across all previous frameworks in the “Capital cost and embodied energy effect” row. In fact, except for Nässén & Holmberg (2009), no framework engages with capital costs, although all note its importance.

514 (Nässén & Holmberg note that capital costs and embodied energy can have very strong effects on
 515 rebound.) Thomas & Azevedo (2013a,b) provide the only framework that traces embodied energy
 516 effects of every consumer good using input-output methods, but they do not analyze embodied
 517 energy of the upgraded device. Borenstein (2015) notes the embodied energy of the upgraded device
 518 and the embodied energy of other goods but does not integrate embodied energy or financing costs
 519 into the framework for empirical analysis. Borenstein is, however, the only author to treat the
 520 financial side of embodied energy or maintenance and disposal effects. Borenstein (2015) postulates
 521 the macro effect, but does not operationalize the link between micro and macro levels, earning ○
 522 in the “Macro effect” row. No other framework even discusses the link between macro and micro
 523 rebound effects, leading to ○ in the “Macro effect” row for all previous frameworks (apart from
 524 Borenstein (2015)). Our framework operationalizes the link between micro and macro levels, via
 525 the macro factor (k), but more work can be done in this area. Thus, “This paper (2024)” earns ●
 526 in the “Macro effect” row. Finally, all previous frameworks assume constant price elasticities and
 527 implicitly marginal or small improvements in efficiency, excluding the numerically precise analysis
 528 of important non-incremental upgrades where price elasticities are likely to vary. Therefore, all
 529 previous frameworks earn ○ in the “Non-marginal energy service price changes” row.

530 Table 2 shows that previous frameworks contain many key pieces, providing starting points from
 531 which to develop our rebound analysis framework. A left-to-right reading of the table demonstrates
 532 that previous frameworks start from microeconomic consumer theory and move towards more rigorous
 533 theoretical treatment over time, with recent frameworks making important advanced theoretical
 534 contributions at the expense of empirical applicability. In the end, no previous rebound analysis
 535 framework combines all rebound effects across energy, expenditure, and consumption aspects with a
 536 detailed model of consumer preferences, non-marginal energy service price changes, and empirical
 537 applicability for the simplest case (understandable across disciplines) of a single fuel and a single
 538 energy service. In particular, assessing the rebound implications of differential capital costs, non-
 539 marginal price changes, and the macro effect required conceptual development as in Section 2.5.4
 540 and Appendix B.4.5. (Development of empirical applications is left for Part II.) This paper addresses
 541 most of the gaps in Table 2; hence we fill the “This paper (2024)” column with filled circles (●) in
 542 nearly all rows. By so doing, we help advance clarity in the field of energy rebound.

3.2 Notes on income expansion and an energy price effect

The income effect (Section 2.5.3) captures the energy and rebound implications of expanding real income at the level of the upgraded device. Our partial equilibrium framework described herein enables calculation of income effect rebound (Re_{inc}) without regard to changes in energy price (p_E), because the energy price is assumed exogenous.

But there are other effects at work beyond the device level and outside the boundaries of a partial equilibrium analysis. One of those effects is an energy price effect. This section (and Appendix F) shows that our partial equilibrium framework can be extended to obtain an initial estimate of the rebound implications of an energy price effect (Re_{p_E}) with an analysis that remains short of full equilibrium.

The energy price effect can lead to rebound when EEUs are applied to energy conversion devices at a scale that is substantial relative to the economy-wide use of energy. Examples of conditions under which the energy price effect could be significant include replacing all cars in the economy by hybrids and replacing all domestic electric lamps in the economy by LEDs, to use the examples from Part II. With reduced energy demand throughout the economy, an energy price reduction can be expected ($p_E^o > \bar{p}_E$) as the lower energy price rebalances supply and demand. With the now-lower energy price (\bar{p}_E), the device owner has additional freed cash (\dot{G}_{p_E}) to spend, in addition to the adjustments described by the substitution and income effects. (See Sections 2.5.2 and 2.5.3.)

A complete analysis of the price effect would amount to introducing a full model of the energy market and involve solving a system of simultaneous equations for the new economy-wide energy demand, the new energy price, and a new consumption bundle. But in this instance, as we desire a simple estimate of energy price effect rebound, we conservatively assume the device owner spends the additional freed cash (the result of the lower energy price) exclusively on other goods, with energy implications at the energy intensity of the economy (I_E). Under these assumptions, Appendix F derives an expression for rebound from the energy price effect as


$$Re_{p_E} = \frac{\dot{G}_{p_E} I_E}{\dot{S}_{dev}}, \quad (36)$$

where \dot{G}_{p_E} is the freed cash arising from the reduction in energy price due to widespread adoption

569 of the EEU throughout the economy.

570 4 Conclusions



571 In this paper (Part I), we developed a rigorous analytical framework that includes all rebound
572 effects across energy, expenditure, and consumption aspects with a detailed model of consumer
573 preferences and non-marginal energy service price changes in an operational manner for the simplest
574 case of a single fuel and a single energy service. With careful explication of rebound effects and
575 clear derivation of rebound expressions, we help advance the analytical foundations for empirical
576 analyses and facilitate interdisciplinary understanding of rebound phenomena toward the goal of
577 enhancing clarity in the field of energy rebound and enabling more robust rebound calculations for
578 sound energy and climate policy. 

579 Future work could be pursued in several areas. (i) Other utility models (besides the CES utility
580 model, but not a Cobb-Douglas utility model) could be explored for the substitution effect. (ii) This
581 framework could be extended to include fuller consideration of producer-sided energy rebound
582 effects. (iii) This framework could be extended to include some of the advanced topics in Chan &
583 Gillingham (2015) and Wang et al. (2021), such as multiple fuels or energy services, more than one
584 other consumption good, and nested utility functions with intermediate inputs. (iv) This framework
585 could be extended to include fuel-switching EEUs, wherein the upgraded device uses a different fuel
586 from the original device. (v) The greenhouse gas emissions implications of energy rebound could
587 be evaluated using this framework, provided that the primary energy associated with final energy
588 purchases were available. Borenstein (2015) went some way to analyzing emissions and could provide
589 a starting point for such work. The capability to analyze fuel-switching EEUs will be important for
590 analyzing the greenhouse gas emissions implications of many EEUs that involve electrification, such
591 as the transition to all-electric vehicles and the conversion of natural gas and oil furnaces to heat
592 pumps for home heating.

593 In Part II of this paper, we further help advance clarity in rebound analysis in three ways. First,
594 we develop a way to visualize the energy, expenditure, and consumption aspects of rebound effects.
595 Second, we apply the framework to two EEUs: an upgraded car and an upgraded electric lamp.

596 Finally, we provide results of rebound calculations for the two examples.

597 Competing interests

598 Declarations of interest: none.

599 Author contributions

600 Author contributions for this paper (Part I of the two-part paper) are shown in Table 3.

Table 3: 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			●

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Table A.1: Symbols and abbreviations.

Symbol	Meaning [example units]
A	annualized cost [\$/yr]
a	the share parameter in the CES utility model [-]
C	cost [\$]
E	final energy [MJ]
f	expenditure share [-]
G	freed cash [\$]
g	a constant in the derivation of $\varepsilon_{\dot{q}_{ss},p_{ss},c}$ and $\varepsilon_{\dot{q}_{os},p_{ss},c}$ [-]
h	a constant in the derivation of $\varepsilon_{\dot{q}_{ss},p_{ss},c}$ and $\varepsilon_{\dot{q}_{os},p_{ss},c}$ [-]
I	energy intensity of economic activity [MJ/\$]
i	summation index for present value calculations [-]
k	macro factor [-]
M	income [\$]
m	mass [kg]
n	an exponent in the derivation of $\varepsilon_{\dot{q}_{ss},p_{ss},c}$ and $\varepsilon_{\dot{q}_{os},p_{ss},c}$ [-]
N	net savings [\$]
n	an exponent in the derivation of $\varepsilon_{\dot{q}_{ss},p_{ss},c}$ and $\varepsilon_{\dot{q}_{os},p_{ss},c}$ [-]
P	present value [\$]
p	price [\$]
q	quantity [-]
R	multiplicative term that accounts for discounting [-]
Re	rebound [-]
r	real discount rate [1/yr]
S	energy cost savings [\$]
t	time variable [yr]
u	utility [utils]
x	position [m]
z	a constant in the derivation of $\varepsilon_{\dot{q}_{ss},p_{ss},c}$ and $\varepsilon_{\dot{q}_{os},p_{ss},c}$ [-]



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]
γ	term in the derivation of end-of-life payment discounting [-]
ω	subscript that indicates disposal cost at end of life
ϕ	term in the derivation of beginning-of-life payment discounting [-]
ρ	exponent in the CES utility function, $\rho \equiv (\sigma - 1)/\sigma$ [-]
σ	elasticity of substitution between the energy service (\dot{q}_s°) and other goods (\dot{q}_o°) [-]

Table A.3: Abbreviations.

Abbreviation	Meaning
CES	constant elasticity of substitution
CPE	constant price elasticity
CV	compensating variation
EEU	energy efficiency upgrade
EPSRC	engineering and physical sciences research council
GDP	gross domestic product
MPC	marginal propensity to consume
UK	United Kingdom
UKRI	UK research and innovation
U.S.	United States

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
<i>c</i>	compensated
<i>cap</i>	capital costs
<i>dev</i>	device
<i>dempl</i>	direct emplacement effect
<i>d</i>	disposal
<i>dinc</i>	direct income effect
<i>dsub</i>	direct substitution effect
<i>E</i>	energy
<i>emb</i>	embodied
<i>empl</i>	emplacement effect
<i>iempl</i>	indirect emplacement effects
<i>iinc</i>	indirect income effect
<i>inc</i>	income effect
<i>isub</i>	indirect substitution effect
<i>life</i>	lifetime
<i>m</i>	maintenance
<i>macro</i>	macro effect
<i>OM</i>	operations and maintenance
<i>OMd</i>	operations, maintenance, and disposal
<i>o</i>	other expenditures (besides energy) by the device user
<i>s</i>	service stage of the energy conversion chain
<i>sub</i>	substitution effect
<i>tot</i>	sum of all rebound effects in the framework

$$\begin{aligned}
\Delta X &= \Delta \tilde{X} + \Delta \bar{X} + \Delta \hat{X} + \Delta X^* \\
\Delta X &= (\tilde{X} - \bar{X}) + (\bar{X} - \hat{X}) + (\hat{X} - X^*) + (X^* - X^\circ) \\
\Delta X &= (\tilde{X} - \bar{X}) + (\bar{X} - \hat{X}) + (\hat{X} - X^*) + (X^* - X^\circ) \\
\Delta X &= \tilde{X} - X^\circ
\end{aligned} \tag{37}$$

B Derivation of the analytical framework

This appendix provides a detailed derivation of the analytical framework, beginning with the budget constraint for the device owner.

B.1 Budget constraint

We assume the device owner has four expense categories related to the device: capital cost (C_{cap}), energy service cost (C_s), operations and maintenance cost (C_{OM}), and disposal cost (C_d). We count one expense category for all other goods and services (C_o), one category for annual income (M), and net savings (N), the difference between income and expenses. Capital (cap) and disposal (d) costs are applied at the beginning (α) and end (ω), respectively, of the device lifetime (t_{life}). All

762 other budget categories are applied at the beginning of each year. A budget can be constructed for
 763 the device owner for each stage of Figure 1, leading to a different budget before emplacement (\circ),
 764 after emplacement ($*$), after the substitution effect (\wedge), after the income effect ($-$), and after the
 765 macro effect (\sim). When needed, the different budgets can be distinguished by symbol decorations
 766 shown in Table A.4. We allow the device owner to purchase the device with a loan and assume a
 767 real discount rate r . For a device not purchased on credit, $r = 0$ applies. The device owner may
 768 save (with real discount rate r) to pay for future disposal costs.

769 Each budget category is analyzed in perpetuity to allow comparisons at different rebound stages
 770 (\circ , $*$, etc.) where the device lifetime (t_{life}) may be different. The present value (P) of each expense
 771 category is obtained with an infinite sum as follows

$$P_{cap} = C_{cap} + \frac{C_{cap}}{(1+r)^{t_{life}}} + \frac{C_{cap}}{(1+r)^{2t_{life}}} + \dots + \frac{C_{cap}}{(1+r)^{i t_{life}}} + \dots = C_{cap} \sum_{i=0}^{\infty} \frac{1}{(1+r)^{i t_{life}}} \\ = \phi_{t_{life}} C_{cap} \quad (38)$$

$$P_s = C_s + \frac{C_s}{(1+r)^{1 \text{ yr}}} + \frac{C_s}{(1+r)^{2 \text{ yr}}} + \dots + \frac{C_s}{(1+r)^{i \text{ yr}}} + \dots = C_s \sum_{i=0}^{\infty} \frac{1}{(1+r)^{i \text{ yr}}} \\ = \phi_{1 \text{ yr}} C_s \quad (39)$$

$$P_{OM} = C_{OM} + \frac{C_{OM}}{(1+r)^{1 \text{ yr}}} + \frac{C_{OM}}{(1+r)^{2 \text{ yr}}} + \dots + \frac{C_{OM}}{(1+r)^{i \text{ yr}}} + \dots = C_{OM} \sum_{i=0}^{\infty} \frac{1}{(1+r)^{i \text{ yr}}} \\ = \phi_{1 \text{ yr}} C_{OM} \quad (40)$$

$$P_d = \frac{C_d}{(1+r)^{t_{life}}} + \frac{C_d}{(1+r)^{2t_{life}}} + \dots + \frac{C_d}{(1+r)^{i t_{life}}} + \dots = C_d \sum_{i=1}^{\infty} \frac{1}{(1+r)^{i t_{life}}} \\ = \gamma_{t_{life}} C_d \quad (41)$$

$$P_o = C_o + \frac{C_o}{(1+r)^{1 \text{ yr}}} + \frac{C_o}{(1+r)^{2 \text{ yr}}} + \dots + \frac{C_o}{(1+r)^{i \text{ yr}}} + \dots = C_o \sum_{i=0}^{\infty} \frac{1}{(1+r)^{i \text{ yr}}} \\ = \phi_{1 \text{ yr}} C_o \quad (42)$$

$$P_M = M + \frac{M}{(1+r)^{1 \text{ yr}}} + \frac{M}{(1+r)^{2 \text{ yr}}} + \dots + \frac{M}{(1+r)^{i \text{ yr}}} + \dots = M \sum_{i=0}^{\infty} \frac{1}{(1+r)^{i \text{ yr}}} \\ = \phi_{1 \text{ yr}} M \quad (43)$$

$$P_N = N + \frac{N}{(1+r)^{1 \text{ yr}}} + \frac{N}{(1+r)^{2 \text{ yr}}} + \dots + \frac{N}{(1+r)^{i \text{ yr}}} + \dots = N \sum_{i=0}^{\infty} \frac{1}{(1+r)^{i \text{ yr}}} \\ = \phi_{1 \text{ yr}} N \quad (44)$$

where $\phi_t \equiv \frac{(1+r)^t}{(1+r)^t - 1}$ and $\gamma_t \equiv \frac{1}{(1+r)^t - 1}$.

For simplicity, we desire annual values (A) with equivalent present value for each cost category.

Using the capital cost to illustrate, we begin with the present value equivalence of the infinite series

and annual costs:

$$P_{cap} = P_{A_{cap}} \quad (45)$$

Substituting expressions for present values (P) gives

$$\phi_{t_{life}} C_{cap} = \phi_{1 \text{ yr}} A_{cap} \quad (46)$$

777 Rearranging gives

$$A_{cap} = \frac{\phi_{t_{life}}}{\phi_{1\text{ yr}}} C_{cap} . \quad (47)$$

778 Further, we desire annualized rates defined as $\dot{A} \equiv A/1\text{ yr}$ such that $\dot{A}_{cap} = A_{cap}/1\text{ yr}$ and $\dot{C}_{cap} \equiv$
 779 C_{cap}/t_{life} . Solving for A_{cap} and C_{cap} and substituting gives

$$\dot{A}_{cap}(1\text{ yr}) = \frac{\phi_{t_{life}}}{\phi_{1\text{ yr}}} \dot{C}_{cap} t_{life} . \quad (48)$$

780 Defining $R_\alpha \equiv \frac{\phi_{t_{life}}}{\phi_{1\text{ yr}}} \frac{t_{life}}{1\text{ yr}}$ (with subscript α indicating payments at the beginning of each device
 781 lifetime) gives

$$\dot{A}_{cap} = R_\alpha \dot{C}_{cap} . \quad (49)$$

782 Similar derivations can be employed for all other budget categories.

$$\dot{A}_s = \dot{C}_s \quad (50)$$

$$\dot{A}_{OM} = \dot{C}_{OM} \quad (51)$$

$$\dot{A}_d = R_\omega \dot{C}_d \quad (52)$$

$$\dot{A}_o = \dot{C}_o \quad (53)$$

$$\dot{A}_N = \dot{N} \quad (54)$$

$$\dot{A}_M = \dot{M} \quad (55)$$

783 where $R_\omega \equiv \frac{\gamma_{t_{life}}}{\phi_{1\text{ yr}}} \frac{t_{life}}{1\text{ yr}}$ (with subscript ω indicating payments at the end of each device lifetime), and
 784 $\dot{C}_d \equiv C_d/t_{life}$, the annualized disposal cost without discounting.

785 The budget constraint expressed in annualized present-value equivalent terms is

$$\dot{A}_M = \dot{A}_{cap} + \dot{A}_s + \dot{A}_{OM} + \dot{A}_d + \dot{A}_o + \dot{A}_N . \quad (56)$$

786 Substituting cost rates gives

$$\dot{M} = R_\alpha \dot{C}_{cap} + \dot{C}_s + \dot{C}_{OM} + R_\omega \dot{C}_d + \dot{C}_o + \dot{N} . \quad (57)$$

787 Substituting $\dot{C}_s = p_s \dot{q}_s$, $\dot{C}_o = p_o \dot{q}_o$, $\dot{C}_{OMd} \equiv \dot{C}_{OM} + R_\omega \dot{C}_d$, and rearranging gives the budget constraint
 788 used in this paper.

$$\dot{M} - R_\alpha \dot{C}_{cap} - \dot{C}_{OMd} = p_s \dot{q}_s + p_o \dot{q}_o \quad (5)$$

789 The term R_α represents the additional cost of annual interest payments when the device is
 790 purchased with a loan. When $r > 0$, $R_\alpha > 1$. When $r = 0$, $R_\alpha = 1$, as proved below (Section B.1.1).
 791 The term R_ω represents the reduction of disposal costs if the device owner pays for disposal costs
 792 with money invested annually assuming real discount rate r . When $r > 0$, $0 < R_\omega < 1$. When $r = 0$,
 793 $R_\omega = 1$, as proved below (Section B.1.2).

794 **B.1.1 Proof: $R_\alpha = 1$ when $r = 0$**

795 We expect that $R_\alpha = 1$ when $r = 0$. However, direct substitution of $r = 0$ into the expression for R_α
 796 gives $\frac{0}{0}$, so we rather assess $\lim_{r \rightarrow 0^+} R_\alpha \stackrel{?}{=} 1$.

797 Substituting for R_α gives

$$\lim_{r \rightarrow 0^+} \left(\frac{\phi_{t_{life}}}{\phi_{1 \text{ yr}}} \frac{t_{life}}{1 \text{ yr}} \right) \stackrel{?}{=} 1 . \quad (58)$$

798 Substituting for ϕ terms gives

$$\lim_{r \rightarrow 0^+} \left[\frac{\frac{(1+r)^{t_{life}}}{(1+r)^{t_{life}-1}}}{\frac{(1+r)^{1 \text{ yr}}}{(1+r)^{1 \text{ yr}-1}}} \cdot \frac{t_{life}}{1 \text{ yr}} \right] \stackrel{?}{=} 1 . \quad (59)$$

799 Distributing double-fractions gives

$$\lim_{r \rightarrow 0^+} \left[\frac{(1+r)^{t_{life}}}{(1+r)^{1 \text{ yr}}} \cdot \frac{(1+r)^{1 \text{ yr}} - 1}{(1+r)^{t_{life}} - 1} \cdot \frac{t_{life}}{1 \text{ yr}} \right] \stackrel{?}{=} 1 . \quad (60)$$

800 Multiplying terms in numerator and demoninator gives

$$\lim_{r \rightarrow 0^+} \left\{ \frac{[(1+r)^{t_{life}}(1+r)^{1 \text{ yr}} - (1+r)^{t_{life}}] \frac{t_{life}}{1 \text{ yr}}}{(1+r)^{t_{life}}(1+r)^{1 \text{ yr}} - (1+r)^{1 \text{ yr}}} \right\} \stackrel{?}{=} 1 . \quad (61)$$

801 Applying L'Hôpital's rule gives

$$\lim_{r \rightarrow 0^+} \left(\frac{\frac{\partial}{\partial r} \left\{ [(1+r)^{t_{life}}(1+r)^{1 \text{ yr}} - (1+r)^{t_{life}}] \frac{t_{life}}{1 \text{ yr}} \right\}}{\frac{\partial}{\partial r} [(1+r)^{t_{life}}(1+r)^{1 \text{ yr}} - (1+r)^{1 \text{ yr}}]} \right) \stackrel{?}{=} 1 . \quad (62)$$

802 Applying the chain rule repeatedly gives

$$\lim_{r \rightarrow 0^+} \left(\frac{\frac{t_{life}}{1 \text{ yr}} \left\{ \frac{\partial}{\partial r} [(1+r)^{t_{life}} (1+r)^{1 \text{ yr}}] - \frac{\partial}{\partial r} [(1+r)^{t_{life}}] \right\}}{\frac{\partial}{\partial r} [(1+r)^{t_{life}} (1+r)^{1 \text{ yr}}] - \frac{\partial}{\partial r} [(1+r)^{1 \text{ yr}}]} \right) \stackrel{?}{=} 1. \quad (63)$$

803 Several intermediate results are helpful.

$$\lim_{r \rightarrow 0^+} \left\{ \frac{\partial}{\partial r} [(1+r)^{t_{life}}] \right\} = t_{life} \quad (64)$$

$$\lim_{r \rightarrow 0^+} \left\{ \frac{\partial}{\partial r} [(1+r)^{1 \text{ yr}}] \right\} = 1 \text{ yr} \quad (65)$$

$$\lim_{r \rightarrow 0^+} \left\{ \frac{\partial}{\partial r} [(1+r)^{t_{life}} (1+r)^{1 \text{ yr}}] \right\} = t_{life} (1+r)^{1 \text{ yr}} + 1 \text{ yr} (1+r)^{t_{life}} \quad (66)$$

804 Substituting the intermediate results gives

$$\lim_{r \rightarrow 0^+} \left\{ \frac{\frac{t_{life}}{1 \text{ yr}} [(1+r)^{1 \text{ yr}} (t_{life}) + (1+r)^{t_{life}} (1 \text{ yr}) - t_{life}]}{(1+r)^{1 \text{ yr}} (t_{life}) + (1+r)^{t_{life}} (1 \text{ yr}) - 1 \text{ yr}} \right\} \stackrel{?}{=} 1. \quad (67)$$

805 Setting $r = 0$ in the remaining terms gives

$$\frac{\frac{t_{life}}{1 \text{ yr}} [(1)(t_{life}) + (1)(1 \text{ yr}) - t_{life}]}{(1)(t_{life}) + (1)(1 \text{ yr}) - 1 \text{ yr}} \stackrel{?}{=} 1. \quad (68)$$

806 Simplifying gives

$$\frac{\left(\frac{t_{life}}{1 \text{ yr}} \right) (1 \text{ yr})}{t_{life}} \stackrel{?}{=} 1 \quad (69)$$

$$1 \stackrel{\checkmark}{=} 1, \quad (70)$$

807 thereby completing the proof with the expected result.

808 **B.1.2 Proof: $R_\omega = 1$ when $r = 0$**

809 We expect that $R_\omega = 1$ when $r = 0$. However, direct substitution of $r = 0$ into the expression for R_ω

810 gives $\frac{0}{0}$, so we rather assess $\lim_{r \rightarrow 0^+} R_\omega \stackrel{?}{=} 1$.

811 Substituting for R_ω gives

$$\lim_{r \rightarrow 0^+} \left(\frac{\gamma_{t_{life}}}{\phi_{1 \text{ yr}}} \frac{t_{life}}{1 \text{ yr}} \right) \stackrel{?}{=} 1 . \quad (71)$$

812 Substituting for γ and ϕ terms gives

$$\lim_{r \rightarrow 0^+} \left[\frac{\frac{1}{(1+r)^{t_{life}} - 1} t_{life}}{\frac{(1+r)^{1 \text{ yr}}}{(1+r)^{1 \text{ yr}} - 1}} \frac{1}{1 \text{ yr}} \right] \stackrel{?}{=} 1 . \quad (72)$$

813 Distributing double-fractions gives

$$\lim_{r \rightarrow 0^+} \left[\frac{1}{(1+r)^{1 \text{ yr}}} \cdot \frac{(1+r)^{1 \text{ yr}} - 1}{(1+r)^{t_{life}} - 1} \cdot \frac{t_{life}}{1 \text{ yr}} \right] \stackrel{?}{=} 1 . \quad (73)$$

814 Multiplying terms in numerator and demoninator gives

$$\lim_{r \rightarrow 0^+} \left\{ \frac{[(1+r)^{1 \text{ yr}} - 1] \left(\frac{t_{life}}{1 \text{ yr}} \right)}{(1+r)^{t_{life}} (1+r)^{1 \text{ yr}} - (1+r)^{1 \text{ yr}}} \right\} \stackrel{?}{=} 1 . \quad (74)$$

815 Applying L'Hôpital's rule gives

$$\lim_{r \rightarrow 0^+} \left\{ \frac{\frac{t_{life}}{1 \text{ yr}} \frac{\partial}{\partial r} [(1+r)^{1 \text{ yr}} - 1]}{\frac{\partial}{\partial r} [(1+r)^{t_{life}} (1+r)^{1 \text{ yr}}] - \frac{\partial}{\partial r} [(1+r)^{1 \text{ yr}}]} \right\} \stackrel{?}{=} 1 . \quad (75)$$

816 Applying the intermediate results from Section B.1.1 yields

$$\lim_{r \rightarrow 0^+} \left[\frac{\left(\frac{t_{life}}{1 \text{ yr}} \right) (1 \text{ yr})}{(1+r)^{1 \text{ yr}} (t_{life}) + (1+r)^{t_{life}} (1 \text{ yr}) - 1 \text{ yr}} \right] \stackrel{?}{=} 1 . \quad (76)$$

817 Setting $r = 0$ in the remaining terms gives

$$\frac{\left(\frac{t_{life}}{1 \text{ yr}} \right) (1 \text{ yr})}{(1)(t_{life}) + (1)1 \text{ yr} - 1 \text{ yr}} \stackrel{?}{=} 1 . \quad (77)$$

818 Simplifying the denominator gives

$$\frac{\left(\frac{t_{life}}{1 \text{ yr}} \right) (1 \text{ yr})}{t_{life}} \stackrel{?}{=} 1 \quad (78)$$

$$1 \stackrel{\checkmark}{=} 1 , \quad (79)$$

819 thereby completing the proof with the expected result.

B.2 Relationships for rebound effects

For each energy rebound effect in Fig. 1, energy and financial analysis must be performed. The purposes of the analyses are to determine for each effect (i) an expression for energy rebound (Re) for the effect and (ii) an equation for net savings (\dot{N}) remaining after the effect.

Analysis of each rebound effect involves a set of assumptions and constraints as shown in Table B.1. In Table B.1, relationships for emplacement effect embodied energy rates (\dot{E}_{emb}° and \dot{E}_{emb}^*), capital expenditure rates (\dot{C}_{cap}° and \dot{C}_{cap}^*), and operations, maintenance, and disposal expenditure rates (\dot{C}_{OMd}° and \dot{C}_{OMd}^*) are typical, and inequalities could switch direction for a specific EEU. Macro effect relationships are given for a single device only. If the EEU is deployed at scale across the economy, the energy service consumption rate (\tilde{q}_s), device energy consumption rate (\tilde{E}_s), embodied energy rate (\tilde{E}_{emb}), capital expenditure rate (\tilde{C}_{cap}), and operations, maintenance, and disposal expenditure rate (\tilde{C}_{OMd}) will all increase in proportion to the number of devices emplaced.

Table B.1: Assumptions and constraints for analysis of rebound effects.

Parameter	Emplacement Effect	Substitution Effect	Income Effect	Macro Effect
Energy price	$p_E^\circ = p_E^*$	$p_E^* = \hat{p}_E$	$\hat{p}_E = \bar{p}_E$	$\bar{p}_E = \tilde{p}_E$
Energy service efficiency	$\eta^\circ < \eta^*$	$\eta^* = \hat{\eta}$	$\hat{\eta} = \bar{\eta}$	$\bar{\eta} = \tilde{\eta}$
Energy service price	$p_s^\circ > p_s^*$	$p_s^* = \hat{p}_s$	$\hat{p}_s = \bar{p}_s$	$\bar{p}_s = \tilde{p}_s$
Other goods price	$p_o^\circ = p_o^*$	$p_o^* = \hat{p}_o$	$\hat{p}_o = \bar{p}_o$	$\bar{p}_o = \tilde{p}_o$
Energy service consumption rate	$\dot{q}_s^\circ = \dot{q}_s^*$	$\dot{q}_s^* < \dot{q}_s$	$\dot{q}_s < \bar{\dot{q}}_s$	$\bar{\dot{q}}_s = \tilde{\dot{q}}_s$
Other goods consumption rate	$\dot{q}_o^\circ = \dot{q}_o^*$	$\dot{q}_o^* > \dot{q}_o$	$\dot{q}_o < \bar{\dot{q}}_o$	$\bar{\dot{q}}_o = \tilde{\dot{q}}_o$
Device energy consumption rate	$\dot{E}_s^\circ > \dot{E}_s^*$	$\dot{E}_s^* < \dot{E}_s$	$\dot{E}_s < \bar{\dot{E}}_s$	$\bar{\dot{E}}_s = \tilde{\dot{E}}_s$
Embodied energy rate	$\dot{E}_{emb}^\circ < \dot{E}_{emb}^*$	$\dot{E}_{emb}^* = \hat{\dot{E}}_{emb}$	$\hat{\dot{E}}_{emb} = \bar{\dot{E}}_{emb}$	$\bar{\dot{E}}_{emb} = \tilde{\dot{E}}_{emb}$
Device lifetime	$t_{life}^\circ < t_{life}^*$	$t_{life}^* = \hat{t}_{life}$	$\hat{t}_{life} = \bar{t}_{life}$	$\bar{t}_{life} = \tilde{t}_{life}$
Beginning-of-life discount factor	$R_\alpha^\circ < R_\alpha^*$	$R_\alpha^* = \hat{R}_\alpha$	$\hat{R}_\alpha = \bar{R}_\alpha$	$\bar{R}_\alpha = \tilde{R}_\alpha$
End-of-life discount factor	$R_\omega^\circ > R_\omega^*$	$R_\omega^* = \hat{R}_\omega$	$\hat{R}_\omega = \bar{R}_\omega$	$\bar{R}_\omega = \tilde{R}_\omega$
Capital expenditure rate	$\dot{C}_{cap}^\circ < \dot{C}_{cap}^*$	$\dot{C}_{cap}^* = \hat{\dot{C}}_{cap}$	$\hat{\dot{C}}_{cap} = \bar{\dot{C}}_{cap}$	$\bar{\dot{C}}_{cap} = \tilde{\dot{C}}_{cap}$
Ops., maint., and disp. expenditure rate	$\dot{C}_{OMd}^\circ < \dot{C}_{OMd}^*$	$\dot{C}_{OMd}^* = \hat{\dot{C}}_{OMd}$	$\hat{\dot{C}}_{OMd} = \bar{\dot{C}}_{OMd}$	$\bar{\dot{C}}_{OMd} = \tilde{\dot{C}}_{OMd}$
Energy service expenditure rate	$\dot{C}_s^\circ > \dot{C}_s^*$	$\dot{C}_s^* < \dot{C}_s$	$\dot{C}_s < \bar{\dot{C}}_s$	$\bar{\dot{C}}_s = \tilde{\dot{C}}_s$
Other goods expenditure rate	$\dot{C}_o^\circ = \dot{C}_o^*$	$\dot{C}_o^* > \dot{C}_o$	$\dot{C}_o < \bar{\dot{C}}_o$	$\bar{\dot{C}}_o = \tilde{\dot{C}}_o$
Income	$\dot{M}^\circ = \dot{M}^*$	$\dot{M}^* = \hat{\dot{M}}$	$\hat{\dot{M}} = \bar{\dot{M}}$	$\bar{\dot{M}} = \tilde{\dot{M}}$
Net savings	$0 = \dot{N}^\circ < \dot{N}^*$	$\dot{N}^* < \hat{\dot{N}}$	$\hat{\dot{N}} > \bar{\dot{N}} = 0$	$\bar{\dot{N}} = \tilde{\dot{N}} = 0$

Table B.2: Justification for zeroed terms in Tables B.3–B.6.

Zeroed term	Justification (from Table B.1).
$\cancel{\Delta \dot{C}_o^*} \xrightarrow{0}$	$\dot{C}_o^\circ = \dot{C}_o^*$ (\dot{C}_o unchanged across emplacement effect.)
$\cancel{\dot{N}^\circ} \xrightarrow{0}$	$0 = \dot{N}^\circ$ (Net savings are zero prior to the EEU.)
$\cancel{\Delta \dot{E}_{emb}} \xrightarrow{0}$	$\dot{E}_{emb}^* = \hat{\dot{E}}_{emb}$ (\dot{E}_{emb} unchanged across substitution effect.)
$\cancel{\Delta \dot{C}_{OMd}} \xrightarrow{0}$	$\dot{C}_{OMd}^* = \hat{\dot{C}}_{OMd}$ (\dot{C}_{OMd} unchanged across substitution effect.)
$\cancel{\Delta \bar{\dot{E}}_{emb}} \xrightarrow{0}$	$\hat{\dot{E}}_{emb} = \bar{\dot{E}}_{emb}$ (\dot{E}_{emb} unchanged across income effect.)
$\cancel{\Delta \bar{\dot{C}}_{OMd}} \xrightarrow{0}$	$\hat{\dot{C}}_{OMd} = \bar{\dot{C}}_{OMd}$ (\dot{C}_{OMd} unchanged across income effect.)
$\cancel{\bar{\dot{N}}} \xrightarrow{0}$	$\bar{\dot{N}} = 0$ (All net savings are spent in the income effect.)

B.3 Derivations

Derivations for rebound definitions and net savings equations are presented in Tables B.3–B.6, one for each rebound effect in Fig. 1. Energy and financial analyses are shown side by side, because each informs the other.

Several terms in Tables B.3–B.6 are zeroed, e.g. $\cancel{\Delta \dot{C}_o^*} \xrightarrow{0}$. These zeroes can be traced back to Table B.1. Table B.2 highlights the equations in Table B.1 that justify zeroing each term.

Table B.3. **Emplacement Effect**

Energy analysis

Financial analysis

$$\text{before } (\circ) \quad \dot{E}^\circ = \dot{E}_s^\circ + \dot{E}_{emb}^\circ + (\dot{C}_{OMd}^\circ + \dot{C}_o^\circ) I_E \quad (80)$$

$$\dot{M}^\circ = p_E \dot{E}_s^\circ + R_\alpha^\circ \dot{C}_{cap}^\circ + \dot{C}_{OMd}^\circ + \dot{C}_o^\circ + \dot{N}^\circ \quad (81)$$

$$\text{after } (*) \quad \dot{E}^* = \dot{E}_s^* + \dot{E}_{emb}^* + (\dot{C}_{OMd}^* + \dot{C}_o^*) I_E \quad (82)$$

$$\dot{M}^* = p_E \dot{E}_s^* + R_\alpha^* \dot{C}_{cap}^* + \dot{C}_{OMd}^* + \dot{C}_o^* + \dot{N}^* \quad (83)$$

Note: $\dot{C}_{OMd} \equiv \dot{C}_{OM} + R_\omega \dot{C}_d$.

Take differences to obtain the change in energy consumption,
 $\Delta \dot{E}^* \equiv \dot{E}^* - \dot{E}^\circ$.

Use the monetary constraint ($\dot{M}^\circ = \dot{M}^*$) and constant spending on other items ($\dot{C}_o^\circ = \dot{C}_o^*$) to cancel terms to obtain

$$\Delta \dot{E}^* = \Delta \dot{E}_s^* + \Delta \dot{E}_{emb}^* + (\Delta \dot{C}_{OMd}^* + \cancel{\Delta \dot{C}_o^*}^0) I_E \quad (84)$$

$$\begin{aligned} p_E \dot{E}_s^\circ + R_\alpha^\circ \dot{C}_{cap}^\circ + \dot{C}_{OMd}^\circ + \cancel{\dot{C}_o^\circ}^0 + \dot{N}^\circ &= p_E \dot{E}_s^* + R_\alpha^* \dot{C}_{cap}^* + \dot{C}_{OMd}^* + \cancel{\dot{C}_o^*}^0 + \dot{N}^* . \end{aligned} \quad (89)$$

Thus,

$$\Delta \dot{E}^* = \Delta \dot{E}_s^* + \Delta \dot{E}_{emb}^* + \Delta \dot{C}_{OMd}^* I_E . \quad (85)$$

Solving for $\Delta \dot{N}^* \equiv \dot{N}^* - \dot{N}^\circ$ gives

Define

$$\dot{S}_{dev} \equiv -\Delta \dot{E}_s^* \quad (86)$$

$$\Delta \dot{N}^* = p_E (\dot{E}_s^\circ - \dot{E}_s^*) + R_\alpha^\circ \dot{C}_{cap}^\circ - R_\alpha^* \dot{C}_{cap}^* + \dot{C}_{OMd}^\circ - \dot{C}_{OMd}^* . \quad (90)$$

(Also see Eqs. (117) and (12)). Use Eq. (1) to obtain

Rewriting with Δ terms gives

$$Re_{empl} = 1 - \frac{-\Delta \dot{E}^*}{\dot{S}_{dev}} = 1 - \frac{-\Delta \dot{E}_s^*}{\dot{S}_{dev}} - \frac{-\Delta \dot{E}_{emb}^*}{\dot{S}_{dev}} - \frac{-\Delta \dot{C}_{OMd}^* I_E}{\dot{S}_{dev}} . \quad (87)$$

$$\Delta \dot{N}^* = -p_E \Delta \dot{E}_s^* - \Delta (R_\alpha \dot{C}_{cap})^* - \Delta \dot{C}_{OMd}^* . \quad (91)$$

Substituting Eq. (86) gives

Define $Re_{dempl} \equiv 1 - \frac{-\Delta \dot{E}_s^*}{\dot{S}_{dev}} (= 0)$, $Re_{iempl} \equiv Re_{emb} + Re_{OMd}$, $Re_{emb} \equiv \frac{\Delta \dot{E}_{emb}^*}{\dot{S}_{dev}}$, $Re_{OMd} \equiv \frac{\Delta \dot{C}_{OMd}^* I_E}{\dot{S}_{dev}}$, $Re_{OMd} = Re_{OM} + Re_d$, $Re_{OM} \equiv \frac{\Delta \dot{C}_{OM}^* I_E}{\dot{S}_{dev}}$, and $Re_d \equiv \frac{\Delta (R_\omega \dot{C}_d)^* I_E}{\dot{S}_{dev}}$ such that

$$\Delta \dot{N}^* = \dot{N}^* = p_E \dot{S}_{dev} - \Delta (R_\alpha \dot{C}_{cap})^* - \Delta \dot{C}_{OMd}^* . \quad (92)$$

Freed cash (\dot{G}) resulting from the EEU, before any energy takeback, is given by

$$Re_{empl} = Re_{dempl} + Re_{iempl} . \quad (88)$$

$$\dot{G} = p_E \dot{S}_{dev} . \quad (93)$$

Note that Eq. (81) and $\dot{N}^\circ = 0$ can be used to calculate \dot{C}_o° as

$$\dot{C}_o^\circ = \dot{M}^\circ - p_E \dot{E}_s^\circ - R_\alpha^\circ \dot{C}_{cap}^\circ - \dot{C}_{OMd}^\circ . \quad (94)$$

Table B.4. Substitution Effect

Energy analysis

Financial analysis

$$\text{before } (*) \quad \dot{E}^* = \dot{E}_s^* + \dot{E}_{emb}^* + (\dot{C}_{OMd}^* + \dot{C}_o^*)I_E \quad (82)$$

$$\dot{M}^* = p_E \dot{E}_s^* + R_\alpha^* \dot{C}_{cap}^* + \dot{C}_{OMd}^* + \dot{C}_o^* + \dot{N}^* \quad (83)$$

$$\text{after } (\wedge) \quad \hat{E} = \hat{E}_s + \hat{E}_{emb} + (\hat{C}_{OMd} + \hat{C}_o)I_E \quad (95)$$

$$\hat{M} = p_E \hat{E}_s + \hat{R}_\alpha \hat{C}_{cap} + \hat{C}_{OMd} + \hat{C}_o + \hat{N} \quad (96)$$

Take differences to obtain the change in energy consumption,
 $\Delta \hat{E} \equiv \hat{E} - \dot{E}^*$.

Use the monetary constraint ($\dot{M}^* = \hat{M}$) to obtain

$$\Delta \hat{E} = \Delta \hat{E}_s + \overset{0}{\cancel{\Delta \hat{E}_{emb}}} + (\overset{0}{\cancel{\Delta \hat{C}_{OMd}}} + \Delta \hat{C}_o)I_E \quad (97)$$

$$\begin{aligned} p_E \dot{E}_s^* + \cancel{R_\alpha^* \dot{C}_{cap}^*} + \cancel{\dot{C}_{OMd}^*} + \dot{C}_o^* + \dot{N}^* \\ = p_E \hat{E}_s + \cancel{\hat{R}_\alpha \hat{C}_{cap}} + \cancel{\hat{C}_{OMd}} + \hat{C}_o + \hat{N} . \end{aligned} \quad (101)$$

Thus,

$$\Delta \hat{E} = \Delta \hat{E}_s + \Delta \hat{C}_o I_E . \quad (98)$$

For the substitution effect, there is no change in capital or operations, maintenance, and disposal costs ($R_\alpha^* \dot{C}_{cap}^* = \hat{R}_\alpha \hat{C}_{cap}$ and $\dot{C}_{OMd}^* = \hat{C}_{OMd}$). Solving for $\Delta \hat{N} \equiv \hat{N} - \dot{N}^*$ gives

All terms are energy takeback rates. Divide by \dot{S}_{dev} to create rebound terms.

$$\frac{\Delta \hat{E}}{\dot{S}_{dev}} = \frac{\Delta \hat{E}_s}{\dot{S}_{dev}} + \frac{\Delta \hat{C}_o I_E}{\dot{S}_{dev}} \quad (99)$$

$$\Delta \hat{N} = -p_E \Delta \hat{E}_s - \Delta \hat{C}_o . \quad (102)$$

Define $Re_{sub} \equiv \frac{\Delta \hat{E}}{\dot{S}_{dev}}$, $Re_{dsub} \equiv \frac{\Delta \hat{E}_s}{\dot{S}_{dev}}$, and $Re_{isub} \equiv \frac{\Delta \hat{C}_o I_E}{\dot{S}_{dev}}$, such that

The substitution effect adjusts net savings relative to \dot{N}^* by $\Delta \hat{N}$. Thus, $\hat{N} = \dot{N}^* + \Delta \hat{N}$. Substituting Eqs. (92), (93), and (102) yields

$$Re_{sub} = Re_{dsub} + Re_{isub} . \quad (100) \quad \hat{N} = \dot{N}^* - \Delta (R_\alpha \dot{C}_{cap})^* - \Delta \dot{C}_{OMd}^* - p_E \Delta \hat{E}_s - \Delta \hat{C}_o . \quad (103)$$

Table B.5. **Income Effect***Energy analysis**Financial analysis*

$$\text{before } (\wedge) \quad \hat{E} = \hat{E}_s + \hat{E}_{emb} + (\hat{C}_{OMd} + \hat{C}_o)I_E \quad (95)$$

$$\hat{M} = p_E \hat{E}_s + \hat{R}_\alpha \hat{C}_{cap} + \hat{C}_{OMd} + \hat{C}_o + \hat{N} \quad (96)$$

$$\text{after } (-) \quad \bar{E} = \bar{E}_s + \bar{E}_{emb} + (\bar{C}_{OMd} + \bar{C}_o)I_E \quad (104)$$

$$\bar{M} = p_E \bar{E}_s + \bar{R}_\alpha \bar{C}_{cap} + \bar{C}_{OMd} + \bar{C}_o + \bar{N} \quad (105)$$

Take differences to obtain the change in energy consumption,
 $\Delta \bar{E} \equiv \bar{E} - \hat{E}$.

Use the monetary constraint ($\hat{M} = \bar{M}$) to obtain

$$\Delta \bar{E} = \Delta \bar{E}_s + \cancel{\Delta \bar{E}_{emb}}^0 + (\cancel{\Delta \bar{C}_{OMd}}^0 + \Delta \bar{C}_o)I_E \quad (106)$$

$$\begin{aligned} p_E \hat{E}_s + \cancel{\hat{R}_\alpha \hat{C}_{cap}} + \cancel{\hat{C}_{OMd}} + \hat{C}_o + \hat{N} \\ = p_E \bar{E}_s + \cancel{\bar{R}_\alpha \bar{C}_{cap}} + \cancel{\bar{C}_{OMd}} + \bar{C}_o + \cancel{\bar{N}}^0. \end{aligned} \quad (110)$$

Thus,

$$\Delta \bar{E} = \Delta \bar{E}_s + \Delta \bar{C}_o I_E \quad (107)$$

All terms are energy takeback rates. Divide by \dot{S}_{dev} to create rebound terms.

$$\frac{\Delta \bar{E}}{\dot{S}_{dev}} = \frac{\Delta \bar{E}_s}{\dot{S}_{dev}} + \frac{\Delta \bar{C}_o I_E}{\dot{S}_{dev}} \quad (108)$$

Define $Re_{inc} \equiv \frac{\Delta \bar{E}}{\dot{S}_{dev}}$, $Re_{dinc} \equiv \frac{\Delta \bar{E}_s}{\dot{S}_{dev}}$, and $Re_{iinc} \equiv \frac{\Delta \bar{C}_o I_E}{\dot{S}_{dev}}$, such that

$$Re_{inc} = Re_{dinc} + Re_{iinc}. \quad (109)$$

For the income effect, there is no change in capital or maintainance, operations, and disposal costs ($\hat{R}_\alpha \hat{C}_{cap} = \bar{R}_\alpha \bar{C}_{cap}$ and $\hat{C}_{OMd} = \bar{C}_{OMd}$). Notably, $\hat{N} = 0$, because it is assumed that all net monetary savings after the substitution effect (\hat{N}) are spent on more energy service ($\hat{E}_s < \bar{E}_s$) and additional purchases in the economy ($\hat{C}_o < \bar{C}_o$). Solving for \hat{N} gives

$$\hat{N} = p_E \Delta \bar{E}_s + \Delta \bar{C}_o, \quad (111)$$

the budget constraint for the income effect. By construction, Eq. (111) ensures spending of net savings (\hat{N}) on (i) additional energy services ($\Delta \bar{E}_s$) and (ii) additional purchases of other goods in the economy ($\Delta \bar{C}_o$) only.

Table B.6. **Macro Effect**

Energy analysis

Financial analysis

$$\text{before } (-) \quad \bar{\dot{E}} \quad (112)$$

$$\text{after } (\sim) \quad \tilde{\dot{E}} \quad (113)$$

Take differences to obtain the change in energy consumption,

N/A

$$\Delta \tilde{\dot{E}} \equiv \tilde{\dot{E}} - \bar{\dot{E}} . \quad (114)$$

The energy change due to the macro effect ($\Delta \tilde{\dot{E}}$) is a scalar multiple (k) of net savings (\dot{N}^*), assumed to be spent at the energy intensity of the economy (I_E).

$$\Delta \tilde{\dot{E}} = k \dot{N}^* I_E \quad (115)$$

All terms are energy takeback rates. Divide by \dot{S}_{dev} to create rebound terms.

$$\frac{\Delta \tilde{\dot{E}}}{\dot{S}_{dev}} = \frac{k \dot{N}^* I_E}{\dot{S}_{dev}} \quad (116)$$

Define $Re_{macro} \equiv \frac{\Delta \tilde{\dot{E}}}{\dot{S}_{dev}}$, such that

$$Re_{macro} = \frac{k \dot{N}^* I_E}{\dot{S}_{dev}} . \quad (33)$$

B.4 Rebound expressions

All that remains is to determine expressions for each rebound effect. We begin with the device-level expected energy savings rate (\dot{S}_{dev}), which appears in the denominator of all rebound expressions.

B.4.1 Expected energy savings (\dot{S}_{dev})

\dot{S}_{dev} is the reduction of energy consumption rate by the device due to the EEU. No other effects are considered.

$$\dot{S}_{dev} \equiv \dot{E}_s^\circ - \dot{E}_s^* \quad (117)$$

The final energy consumption rates (\dot{E}_s° and \dot{E}_s^*) can be written as Eq. (6) in the forms $\dot{E}_s^\circ = \dot{q}_s^\circ / \eta^\circ$ and $\dot{E}_s^* = \dot{q}_s^* / \eta^*$.

$$\dot{S}_{dev} = \frac{\dot{q}_s^\circ}{\eta^\circ} - \frac{\dot{q}_s^*}{\eta^*} \quad (118)$$

With reference to Table B.1, we use $\dot{q}_s^* = \dot{q}_s^\circ$ and $\eta^* = \tilde{\eta}$ to obtain

$$\dot{S}_{dev} = \frac{\dot{q}_s^\circ}{\eta^\circ} - \frac{\dot{q}_s^\circ}{\tilde{\eta}}. \quad (119)$$

When the EEU increases efficiency such that $\eta^\circ < \tilde{\eta}$, expected energy savings grows ($\dot{S}_{dev} > 0$) as the rate of final energy consumption declines, as expected. As $\tilde{\eta} \rightarrow \infty$, all final energy consumption is eliminated ($\dot{E}_s^* \rightarrow 0$), and $\dot{S}_{dev} = \dot{q}_s^\circ / \eta^\circ = \dot{E}_s^\circ$. (Of course, $\tilde{\eta} \rightarrow \infty$ is impossible. See Paoli & Cullen (2020) for a recent discussion of upper limits to device efficiencies.)

After rearrangement and using $\dot{E}_s^\circ = \dot{q}_s^\circ / \eta^\circ$, we obtain a convenient form

$$\dot{S}_{dev} = \left(\frac{\tilde{\eta}}{\eta^\circ} - 1 \right) \frac{\eta^\circ}{\tilde{\eta}} \dot{E}_s^\circ. \quad (12)$$

B.4.2 **Emplacement effect**

The emplacement effect accounts for performance of the EEU only. No behavior changes occur. The direct emplacement effect of the EEU is device energy savings and energy cost savings. The indirect emplacement effects of the EEU produce changes in the embodied energy rate and the

888 maintenance and disposal expenditure rates. By definition, the direct emplacement effect has no
 889 rebound. However, indirect emplacement effects may cause energy rebound. Both direct and indirect
 890 emplacement effects are discussed below.

891 **Direct emplacement effect rebound expression (Re_{dempl})** As shown in Table B.3, the direct
 892 rebound from the emplacement effect is $Re_{dempl} \equiv 0$. This result is expected, because in the absence
 893 of embodied energy, maintenance and disposal cost, or behavioral changes, there is no takeback of
 894 energy savings at the upgraded device.

895 **Indirect emplacement effect rebound expression (Re_{iempl})** Indirect emplacement rebound
 896 effects can occur at any point in the life cycle of an energy conversion device, from manufacturing
 897 and distribution to the use phase (maintenance), and finally to disposal. For simplicity, we group
 898 maintenance with disposal to form two distinct indirect emplacement rebound effects: (i) an embodied
 899 energy effect (Re_{emb}) and (ii) a maintenance and disposal effect (Re_{md}).

900 **Embodied energy effect rebound expression (Re_{emb})** The first component of indirect em-
 901 placement effect rebound involves embodied energy. We define embodied energy consistent with the
 902 energy analysis literature to be the sum of all final energy consumed in the production of the energy
 903 conversion device. The EEU causes the embodied final energy of the device to change from \dot{E}_{emb}° to
 904 \dot{E}_{emb}^{*} .

905 Energy is embodied in the device within manufacturing and distribution supply chains prior to
 906 consumer acquisition of the device. For simplicity, we spread all embodied energy over the lifetime
 907 of the device, an equal amount assigned to each period.

908 Thus, we allocate embodied energy over the life of the original and upgraded devices (t_{life}° and t_{life}^{*} ,
 909 respectively) without discounting to obtain embodied energy rates, such that $\dot{E}_{emb}^{\circ} = E_{emb}^{\circ}/t_{life}^{\circ}$ and
 910 $\dot{E}_{emb}^{*} = E_{emb}^{*}/t_{life}^{*}$. The change in embodied final energy due to the EEU (expressed as a rate) is given
 911 by $\dot{E}_{emb}^{*} - \dot{E}_{emb}^{\circ}$. After substitution and algebraic rearrangement, the change in embodied energy
 912 rate due to the EEU can be expressed as $[(E_{emb}^{*}/E_{emb}^{\circ})(t_{life}^{\circ}/t_{life}^{*}) - 1]\dot{E}_{emb}^{\circ}$, a term that represents
 913 energy savings taken back due to embodied energy effects. Thus, Eq. (3) can be employed to write

embodied energy rebound as

$$Re_{emb} = \frac{\left(\frac{E_{emb}^*}{E_{emb}^\circ} \frac{t_{life}^\circ}{t_{life}^*} - 1 \right) \dot{E}_{emb}^\circ}{\dot{S}_{dev}}. \quad (14)$$

Embodied energy rebound can be either positive or negative, depending on the sign of the term $(E_{emb}^*/E_{emb}^\circ)(t_{life}^\circ/t_{life}^*) - 1$. Rising energy efficiency can be associated with increased device complexity and more embodied energy, such that $E_{emb}^* > E_{emb}^\circ$ and $Re_{emb} > 0$. However, if the upgraded device has longer life than the original device ($t_{life}^* > t_{life}^\circ$), $\dot{E}_{emb}^* - \dot{E}_{emb}^\circ$ can be negative, meaning that the upgraded device has a lower embodied energy rate than the original device.

Operations, maintenance, and disposal effect rebound expression (Re_{OMd}) In addition to embodied energy effects, indirect emplacement rebound can be associated with energy demanded by operations, maintenance, and disposal expenditures. We apply discounting to end-of-life disposal expenditures to form expenditure rates such that $\dot{C}_{OMd}^\circ = \dot{C}_{OM}^\circ + R_\omega \dot{C}_d^\circ$ and $\dot{C}_{OMd}^* = \dot{C}_{OM}^* + R_\omega \dot{C}_d^*$, with $\dot{C}_d \equiv C_d/t_{life}$. (For details, see Appendix B.1.)

We assume, for simplicity, that operations, maintenance, and disposal expenditures indicate energy consumption elsewhere in the economy at its energy intensity (I_E). Therefore, the change in energy consumption rate caused by a change in operations, maintenance, and disposal expenditures is given by $\Delta \dot{C}_{OMd}^* I_E$. This term is an energy takeback rate, so maintenance and disposal rebound is given by

$$Re_{OMd} = \frac{\Delta \dot{C}_{OMd}^* I_E}{\dot{S}_{dev}}, \quad (120)$$

as shown in Table B.3. Slight rearrangement gives

$$Re_{OMd} = \frac{\left(\frac{\dot{C}_{OMd}^*}{\dot{C}_{OMd}^\circ} - 1 \right) \dot{C}_{OMd}^\circ I_E}{\dot{S}_{dev}}. \quad (15)$$

Rebound from operations, maintenance, and disposal can be positive or negative, depending on the sign of the term $\dot{C}_{OMd}^*/\dot{C}_{OMd}^\circ - 1$.

B.4.3 Substitution effect

This section derives expressions for substitution effect rebound. Two terms comprise substitution effect rebound, direct substitution rebound (Re_{dsub}) and indirect substitution rebound (Re_{isub}). Assuming that conditions after the emplacement effect (*) are known, both the rate of energy service consumption (\hat{q}_s) and the rate of other goods consumption (\hat{C}_o) must be determined as a result of the substitution effect (the \wedge point).

The EEU's energy efficiency increase ($\eta^\circ < \tilde{\eta}$) causes the price of the energy service provided by the device to fall ($p_s^\circ > \tilde{p}_s$). The substitution effect quantifies the amount by which the device user, in response, increases the consumption rate of the energy service ($\dot{q}_s^* < \hat{q}_s$) and decreases the consumption rate of other goods ($\dot{q}_o^* > \hat{q}_o$).

The increase in consumption of the energy service substitutes for consumption of other goods in the economy, subject to a utility constraint. The reduction in spending on other goods in the economy is captured by indirect substitution rebound (Re_{isub}).

We begin by deriving an expression for direct and indirect substitution effect rebound (Re_{dsub} and Re_{isub} , respectively). Thereafter, we develop a constant price elasticity (CPE) utility model and a constant elasticity of substitution (CES) utility model for determining the post-substitution point (\hat{q}_s and \hat{C}_o).

Direct substitution effect rebound expression Direct substitution effect rebound (Re_{dsub}) is given by

$$Re_{dsub} = \frac{\Delta \hat{E}_s}{\dot{S}_{dev}} = \frac{\hat{E}_s - \dot{E}_s^*}{\dot{S}_{dev}}. \quad (17)$$

Substituting the typical relationship of Eq. (6) in the form $\dot{E}_s = \dot{q}_s/\eta$ gives

$$Re_{dsub} = \frac{\frac{\hat{q}_s}{\tilde{\eta}} - \frac{\dot{q}_s^*}{\tilde{\eta}}}{\dot{S}_{dev}}. \quad (121)$$

Rearranging produces

$$Re_{dsub} = \frac{\left(\frac{\hat{q}_s}{\hat{q}_s^\circ} - \frac{\dot{q}_s^*}{\dot{q}_s^\circ} \right) \frac{\dot{q}_s^\circ}{\tilde{\eta}}}{\dot{S}_{dev}}. \quad (122)$$

954 Recognizing that the rate of energy service consumption (\dot{q}_s) is unchanged across the emplacement
 955 effect leads to $\dot{q}_s^*/\dot{q}_s^\circ = 1$. Furthermore, $\dot{q}_s^\circ/\tilde{\eta} = (\dot{q}_s^\circ/\eta^\circ)(\eta^\circ/\tilde{\eta}) = \dot{E}_s^\circ(\eta^\circ/\tilde{\eta})$, such that

$$Re_{dsub} = \left(\frac{\hat{q}_s}{\dot{q}_s^\circ} - 1 \right) \frac{\dot{E}_s^\circ \frac{\eta^\circ}{\tilde{\eta}}}{\dot{S}_{dev}} . \quad (123)$$

956 Substituting Eq. (12) for \dot{S}_{dev} and rearranging gives

$$Re_{dsub} = \frac{\frac{\hat{q}_s}{\dot{q}_s^\circ} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \left(\frac{\cancel{\dot{E}_s^\circ} \frac{\eta^\circ}{\cancel{\tilde{\eta}}}}{\frac{\eta^\circ}{\cancel{\tilde{\eta}}} \cancel{\dot{E}_s^\circ}} \right) . \quad (124)$$

957 Canceling terms yields

$$Re_{dsub} = \frac{\frac{\hat{q}_s}{\dot{q}_s^\circ} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} . \quad (18)$$

958 Eq. (18) is the basis for developing expressions for Re_{dsub} under both the CPE and the CES utility
 959 models.

960 **Indirect substitution effect rebound expression** Indirect substitution effect rebound (Re_{isub})
 961 is given by

$$Re_{isub} = \frac{\Delta \hat{C}_o I_E}{\dot{S}_{dev}} = \frac{(\hat{C}_o - \dot{C}_o^*) I_E}{\dot{S}_{dev}} . \quad (19)$$

962 Rearranging gives

$$Re_{isub} = \frac{\left(\frac{\hat{C}_o}{\dot{C}_o^\circ} - \frac{\dot{C}_o^*}{\dot{C}_o^\circ} \right) \dot{C}_o^\circ I_E}{\dot{S}_{dev}} . \quad (125)$$

963 Recognizing that expenditures on other goods are constant across the emplacement effect gives
 964 $\dot{C}_o^*/\dot{C}_o^\circ = 1$ and

$$Re_{isub} = \left(\frac{\hat{C}_o}{\dot{C}_o^\circ} - 1 \right) \frac{\dot{C}_o^\circ I_E}{\dot{S}_{dev}} . \quad (126)$$

965 Substituting Eq. (12) for \dot{S}_{dev} and rearranging gives

$$Re_{isub} = \frac{\frac{\hat{C}_o}{\dot{C}_o^\circ} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \frac{\tilde{\eta}}{\eta^\circ} \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ} . \quad (20)$$

Eq. (20) is the basis for developing expressions for Re_{isub} under both the CPE and the CES utility models.

Determining the post-substitution effect conditions requires reference to a consumer utility model. We first show the CPE utility model, often used in the literature. Second, we use a constant elasticity of substitution (CES) utility model. The CES model is used for all calculations and graphs in this paper.

Constant price elasticity (CPE) utility model In the literature, a constant price elasticity (CPE) utility model is often used (Borenstein, 2015, p. 17, footnote 43). However, the CPE model does not produce precisely utility-preserving preferences, thus we do not recommend its use. We discuss the CPE utility model here for completeness only.

In the CPE utility model, the relationship between energy service price and energy service consumption rate is given by the compensated own price elasticity of energy service demand ($\varepsilon_{\dot{q}_s, p_{s,c}}$), such that

$$\frac{\hat{\dot{q}}_s}{\dot{q}_s^*} = \left(\frac{\tilde{p}_s}{p_s^\circ} \right)^{\varepsilon_{\dot{q}_s, p_{s,c}}}. \quad (127)$$

Note that the compensated own price elasticity of energy service demand ($\varepsilon_{\dot{q}_s, p_{s,c}}$) is assumed constant along an indifference curve in the CPE utility model. A negative value for the compensated own price elasticity of energy service demand is expected ($\varepsilon_{\dot{q}_s, p_{s,c}} < 0$), such that when the energy service price decreases ($p_s^\circ > \tilde{p}_s$), the rate of energy service consumption increases ($\dot{q}_s^* < \hat{\dot{q}}_s$).

Substituting Eq. (7) in the form $p_s^\circ = p_E^\circ/\eta^\circ$ and $\tilde{p}_s = p_E^\circ/\tilde{\eta}$ and noting that $\dot{q}_s^\circ = \dot{q}_s^*$ gives

$$\frac{\hat{\dot{q}}_s}{\dot{q}_s^\circ} = \left(\frac{\tilde{\eta}}{\eta^\circ} \right)^{-\varepsilon_{\dot{q}_s, p_{s,c}}}. \quad (128)$$

Again, note that the compensated own price elasticity of energy service demand is negative ($\varepsilon_{\dot{q}_s, p_{s,c}} < 0$), so that as energy service efficiency increases ($\eta^\circ < \tilde{\eta}$), the energy service consumption rate increases ($\dot{q}_s^\circ = \dot{q}_s^* < \hat{\dot{q}}_s$).

Substituting Eq. (128) into Eq. (18) yields the CPE model's expression for direct substitution rebound.

$$Re_{dsub} = \frac{\left(\frac{\tilde{\eta}}{\eta^\circ}\right)^{-\varepsilon_{\dot{q}_s, p_s, c}} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \quad (129)$$

such that, e.g., $\varepsilon_{\dot{q}_s, p_s, c} = -0.2$ and $\tilde{\eta}/\eta^\circ = 2$ yields $Re_{dsub} = 0.15$.

As long as $\varepsilon_{\dot{q}_s, p_s, c} \in (-1, 0)$, the CPE utility model indicates that direct substitution rebound will be below 1. I.e., the direct substitution effect alone will not cause backfire.

To quantify the substitution effect on other purchases in the CPE utility model, we use another elasticity, the compensated cross price elasticity of other goods demand ($\varepsilon_{\dot{q}_o, p_s, c}$), such that

$$\frac{\hat{\dot{q}}_o}{\dot{q}_o^*} = \left(\frac{\tilde{p}_s}{p_s^\circ}\right)^{\varepsilon_{\dot{q}_o, p_s, c}}. \quad (130)$$

For substitution to take place, the compensated cross price elasticity of other goods demand must be positive ($\varepsilon_{\dot{q}_o, p_s, c} > 0$). Thus, an energy service price decrease ($p_s^\circ > \tilde{p}_s$) implies a reduction in the rate of consumption of other goods ($\dot{q}_o^* > \hat{\dot{q}}_o$).

The energy service price is inversely proportional to efficiency, yielding

$$\frac{\hat{\dot{q}}_o}{\dot{q}_o^*} = \left(\frac{\tilde{\eta}}{\eta^\circ}\right)^{-\varepsilon_{\dot{q}_o, p_s, c}}. \quad (131)$$

Assuming that the average price is unchanged across the substitution effect such that $\hat{p}_o = \dot{p}_o^* = p_o^\circ$ (Appendix E), and noting that $\dot{q}_s^* = \dot{q}_s^\circ$ and $\dot{C}_o^* = \dot{C}_o^\circ$, we can write

$$\frac{\hat{\dot{C}}_o}{\dot{C}_o^\circ} = \frac{\hat{\dot{q}}_o}{\dot{q}_o^\circ} = \left(\frac{\tilde{\eta}}{\eta^\circ}\right)^{-\varepsilon_{\dot{q}_o, p_s, c}}. \quad (132)$$

Note that Eq. (132) can be used to determine the rate of expenditures on other goods in the economy ($\hat{\dot{C}}_o$) by

$$\hat{\dot{C}}_o = \dot{C}_o^\circ \left(\frac{\tilde{\eta}}{\eta^\circ}\right)^{-\varepsilon_{\dot{q}_o, p_s, c}}. \quad (133)$$

Substituting Eq. (133) into Eq. (20) gives the expression for indirect substitution rebound for the CPE utility model.

$$Re_{isub} = \frac{\left(\frac{\tilde{\eta}}{\eta^\circ}\right)^{-\varepsilon_{\dot{q}_o, p_s, c}} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \frac{\tilde{\eta}}{\eta^\circ} \frac{\dot{C}_o^\circ I_E}{\dot{E}_s} \quad (134)$$

Because the compensated cross price elasticity of other goods consumption is positive ($\varepsilon_{\dot{q}_o p_s, c} > 0$) and the energy service efficiency ratio is greater than 1 ($\eta^\circ < \tilde{\eta}$), indirect substitution rebound will be negative always ($Re_{isub} < 0$), as expected. Negative rebound indicates that indirect substitution effects reduce the energy takeback rate by direct substitution effects.

CES utility model The CPE utility model assumes that the compensated own price elasticity of energy service demand ($\varepsilon_{\dot{q}_s p_s, c}$) and the compensated cross price elasticity of other goods demand ($\varepsilon_{\dot{q}_o p_s, c}$) are constant along an indifference curve. These assumptions hold only for infinitesimally small energy service price changes ($\Delta p_s^* \equiv p_s^* - p_s^\circ \approx 0$). They also provide reasonable approximations for a 1–2% change. However, in the case of an energy efficiency upgrade (EEU), the energy service price change is neither infinitesimal nor confined to single-digit percentages. Rather, Δp_s^* is finite and may be very large in percentage terms.

To determine the new consumption bundle after the substitution effect (\hat{q}_s and \hat{C}_o) and, ultimately, to quantify the direct and indirect substitution rebound effects (Re_{dsub} and Re_{isub}) exactly, we remove the restriction that energy service price elasticities ($\varepsilon_{\dot{q}_s p_s, c}$ and $\varepsilon_{\dot{q}_o p_s, c}$) must be constant along an indifference curve (as in the CPE utility model). Instead, we require constancy of only the elasticity of substitution (σ) between the consumption rate of the energy service (\dot{q}_s) and the expenditure rate for other goods (\dot{C}_o) across the substitution effect. Thus, we employ a CES utility model in our framework. Figs. 4 and 7 in Part II (especially segments $* \text{---} c$ and $c \text{---} \wedge$) illustrates features of the CES utility model for determining the new consumption bundle.

Two equations are helpful for this analysis. First, the slope at any point on indifference curve (the $i^\circ \text{---} i^\circ$ curve in Figs. 4 and 7 of Part II) is given by Eq. (163) with $\dot{u}/\dot{u}^\circ = 1$ and the share parameter (a) replaced by $f_{\dot{C}_s}^\circ$, as discussed in Appendix C.

$$\begin{aligned} \frac{\partial(\dot{C}_o/\dot{C}_o^\circ)}{\partial(\dot{q}_s/\dot{q}_s^\circ)} &= - \frac{f_{\dot{C}_s}^\circ}{1 - f_{\dot{C}_s}^\circ} \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^{(\rho-1)} \\ &\quad \times \left[\left(\frac{1}{1 - f_{\dot{C}_s}^\circ} \right) - \left(\frac{f_{\dot{C}_s}^\circ}{1 - f_{\dot{C}_s}^\circ} \right) \left(\frac{\dot{q}}{\dot{q}_s^\circ} \right)^\rho \right]^{(1-\rho)/\rho}. \end{aligned} \quad (135)$$

Second, the equation of the pre-substitution-effect expenditure line ($* \text{---} *$ in Figs. 4 and 7 of Part II) is

$$\frac{\dot{C}_o}{\dot{C}_o^\circ} = -\frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right) + \frac{1}{\dot{C}_o^\circ} (\dot{M} - R_\alpha^\circ \dot{C}_{cap}^\circ - \dot{C}_{OMd}^\circ - \dot{G}) . \quad (136)$$

1028 To find the rate of energy service consumption after the substitution effect (\hat{q}_s), we set the slope
 1029 of the expenditure line (Eq. (136) and line *—* in Figs. 4 and 7 of Part II) equal to the slope of
 1030 the indifference curve (i° — i° in Figs. 4 and 7 of Part II) at the original utility rate of $\dot{u}/\dot{u}^\circ = 1$
 1031 (Eq. (135)).

$$-\frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} = -\frac{f_{\dot{C}_s}^\circ}{1 - f_{\dot{C}_s}^\circ} \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^{(\rho-1)} \left[\left(\frac{1}{1 - f_{\dot{C}_s}^\circ} \right) - \left(\frac{f_{\dot{C}_s}^\circ}{1 - f_{\dot{C}_s}^\circ} \right) \left(\frac{\dot{q}}{\dot{q}_s^\circ} \right)^\rho \right]^{(1-\rho)/\rho} \quad (137)$$

1032 Solving for $\dot{q}_s/\dot{q}_s^\circ$ gives $\hat{q}_s/\dot{q}_s^\circ$ as

$$\frac{\hat{q}_s}{\dot{q}_s^\circ} = \left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho} . \quad (21)$$

1033 Eq. (21) can be substituted directly into Eq. (18) to obtain an estimate for direct substitution
 1034 rebound (Re_{dsub}) via the CES utility model.

$$Re_{dsub} = \frac{\left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho} - 1}{\frac{\hat{\eta}}{\eta^\circ} - 1} \quad (23)$$

1035 The rate of other goods consumption after the substitution effect (\hat{C}_o) can be found by substituting
 1036 Eq. (21) and $\dot{u}/\dot{u}^\circ = 1$ into the functional form of the CES utility model (Eq. (162)) to obtain

$$\frac{\hat{C}_o}{\dot{C}_o^\circ} = \left(\left(\frac{1}{1 - f_{\dot{C}_s}^\circ} \right) - \left(\frac{f_{\dot{C}_s}^\circ}{1 - f_{\dot{C}_s}^\circ} \right) \left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\frac{\rho}{1-\rho}} \right\}^{-1} \right)^{1/\rho} . \quad (138)$$

1037 Simplifying gives

$$\frac{\hat{C}_o}{\dot{C}_o^\circ} = \left(1 + f_{\dot{C}_s}^\circ \left\{ \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho} . \quad (22)$$

1038 Eq. (22) can be substituted into Eq. (20) to obtain an expression for indirect substitution rebound
 1039 (Re_{isub}) via the CES utility model.

$$Re_{isub} = \frac{\left(1 + f_{\dot{C}_s}^\circ \left\{ \left[\left(\frac{1-f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\bar{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \frac{\tilde{\eta}}{\eta^\circ} \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ} \quad (24)$$

B.4.4 Income effect

Rebound from the income effect rebound quantifies the rate of additional energy demand that arises because the user of the energy conversion device spends net savings from the EEU. The income rate of the device user is \dot{M}° , which remains unchanged across the rebound effects, such that $\dot{M}^\circ = \dot{M}^* = \hat{\dot{M}} = \bar{\dot{M}} = \tilde{\dot{M}}$. Freed cash from the EEU is given by Eq. (93) as $\dot{G} = p_E \dot{S}_{dev}$. In combination, the emplacement effect and the substitution effect leave the device user with *net* savings ($\hat{\dot{N}}$) from the EEU, as shown in Eq. (103). Derivations of expressions for freed cash from the emplacement effect (\dot{G}) and net savings after the substitution effect ($\hat{\dot{N}}$) are presented in Tables B.3 and B.4.

In this framework, all net savings ($\hat{\dot{N}}$) are spent on either (i) additional energy service ($\hat{\dot{q}}_s < \bar{\dot{q}}_s$) or (ii) additional other goods ($\hat{\dot{q}}_o < \bar{\dot{q}}_o$). The income elasticity of energy service demand and the income elasticity of other goods demand ($\varepsilon_{\dot{q}_s, \dot{M}}$ and $\varepsilon_{\dot{q}_o, \dot{M}}$, respectively) quantify the income preferences of the device user according to the following expressions:

$$\frac{\bar{\dot{q}}_s}{\hat{\dot{q}}_s} = \left(1 + \frac{\hat{\dot{N}}}{\hat{\dot{M}}'} \right)^{\varepsilon_{\dot{q}_s, \dot{M}}} \quad (25)$$

and

$$\frac{\bar{\dot{q}}_o}{\hat{\dot{q}}_o} = \left(1 + \frac{\hat{\dot{N}}}{\hat{\dot{M}}'} \right)^{\varepsilon_{\dot{q}_o, \dot{M}}} , \quad (29)$$

where effective income ($\hat{\dot{M}}'$) is

$$\hat{\dot{M}}' \equiv \dot{M}^\circ - R_\alpha^* \dot{C}_{cap}^* - \dot{C}_{OMd}^* - \hat{\dot{N}} . \quad (26)$$

Homotheticity means that $\varepsilon_{\dot{q}_s, \dot{M}} = 1$ and $\varepsilon_{\dot{q}_o, \dot{M}} = 1$.

The budget constraint across the income effect (Eq. (111)) ensures that all net savings available after the substitution effect ($\hat{\dot{N}}$) is re-spent across the income effect, such that $\bar{\dot{N}} = 0$. Appendix D

1058 proves that the income preference equations (Eqs. (25) and (29)) satisfy the budget constraint
 1059 (Eq. (111)).

1060 The purpose of this section is derivation of expressions for (i) direct income rebound (Re_{dinc})
 1061 arising from increased consumption of the energy service ($\hat{q}_s < \bar{q}_s$) and (ii) indirect income re-
 1062 bound (Re_{iinc}) arising from increased consumption of other goods ($\hat{q}_o < \bar{q}_o$).

1063 But first, we derive an expression for device energy consumption rate prior to the income effect
 1064 (\hat{E}_s). This expression will be helpful later.

1065 **Derivation of expression for \hat{E}_s** An expression for \hat{E}_s that will be helpful later begins with

$$\hat{E}_s = \left(\frac{\hat{E}_s}{\dot{E}_s^*} \right) \left(\frac{\dot{E}_s^*}{\dot{E}_s^\circ} \right) \dot{E}_s^\circ. \quad (139)$$

1066 Substituting Eq. (6) and noting efficiency (η) equalities from Table B.1 gives

$$\hat{E}_s = \left(\frac{\hat{q}_s / \tilde{\eta}}{\dot{q}_s^* / \tilde{\eta}} \right) \left(\frac{\dot{q}_s^* / \tilde{\eta}}{\dot{q}_s^\circ / \eta^\circ} \right) \dot{E}_s^\circ. \quad (140)$$

1067 Canceling terms yields

$$\hat{E}_s = \left(\frac{\hat{q}_s}{\dot{q}_s^*} \right) \left(\frac{\dot{q}_s^*}{\dot{q}_s^\circ} \right) \left(\frac{\eta^\circ}{\tilde{\eta}} \right) \dot{E}_s^\circ. \quad (141)$$

1068 Noting energy service consumption rate equalities from Table B.1 ($\dot{q}_s^* = \dot{q}_s^\circ$) gives

$$\hat{E}_s = \frac{\hat{q}_s}{\dot{q}_s^*} \frac{\eta^\circ}{\tilde{\eta}} \dot{E}_s^\circ. \quad (142)$$

1069 The next step is to develop an expression for Re_{dinc} using the income preference for energy
 1070 service consumption.

1071 **Derivation of expression for Re_{dinc}** As shown in Table B.5, direct income rebound is defined as

$$Re_{dinc} \equiv \frac{\Delta \bar{E}_s}{\dot{S}_{dev}}. \quad (27)$$

1072 Expanding the difference and rearranging gives

$$Re_{dinc} = \frac{\bar{E}_s - \hat{E}_s}{\dot{S}_{dev}}, \quad (143)$$

1073 and

$$Re_{dinc} = \frac{\left(\frac{\bar{\bar{E}}_s}{\hat{E}_s} - 1\right) \hat{E}_s}{\dot{S}_{dev}}. \quad (144)$$

1074 Substituting Eq. (6) as $\bar{\bar{E}}_s = \frac{\bar{\bar{q}}_s}{\bar{\bar{\eta}}}$ and $\hat{E}_s = \frac{\hat{q}_s}{\hat{\eta}}$ gives

$$Re_{dinc} = \frac{\left(\frac{\bar{\bar{q}}_s/\bar{\bar{\eta}}}{\hat{q}_s/\hat{\eta}} - 1\right) \hat{E}_s}{\dot{S}_{dev}}. \quad (145)$$

1075 Eliminating terms and substituting Eq. (12) for \dot{S}_{dev} and Eq. (25) for $\bar{\bar{q}}_s/\bar{\bar{q}}_s$ gives

$$Re_{dinc} = \frac{\left[\left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_s, \hat{M}}} - 1\right] \hat{E}_s}{\left(\frac{\bar{\eta}}{\eta^\circ} - 1\right) \frac{\eta^\circ}{\bar{\eta}} \dot{E}_s^\circ}. \quad (146)$$

1076 Substituting Eq. (142) for \hat{E}_s gives

$$Re_{dinc} = \frac{\left[\left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_s, \hat{M}}} - 1\right] \frac{\hat{q}_s}{\hat{q}_s^*} \frac{\eta^\circ}{\bar{\eta}} \dot{E}_s^\circ}{\left(\frac{\bar{\eta}}{\eta^\circ} - 1\right) \frac{\eta^\circ}{\bar{\eta}} \dot{E}_s^\circ}. \quad (147)$$

1077 Eliminating terms, recognizing that $\hat{q}_s^\circ = \hat{q}_s^*$, and substituting Eq. (21), which assumes the CES
1078 utility model, gives

$$Re_{dinc} = \frac{\left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_s, \hat{M}}} - 1}{\frac{\bar{\eta}}{\eta^\circ} - 1} \left\{ f_{\hat{C}_s}^\circ + (1 - f_{\hat{C}_s}^\circ) \left[\left(\frac{1 - f_{\hat{C}_s}^\circ}{f_{\hat{C}_s}^\circ} \right) \frac{\tilde{p}_s \hat{q}_s^\circ}{\dot{C}_s^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho}. \quad (28)$$

1079 If there is no net savings ($\hat{N} = 0$), direct income effect rebound is zero ($Re_{dinc} = 0$), as expected.

1080 The next step is to develop an expression for Re_{iinc} using the income preference for other goods
1081 consumption.

1082 **Derivation of expression for Re_{iinc}** As shown in Table B.5, indirect income rebound is defined
1083 as

$$Re_{iinc} \equiv \frac{\Delta \bar{\bar{C}}_o I_E}{\dot{S}_{dev}}. \quad (31)$$

1084 Expanding the difference and rearranging gives

$$Re_{iinc} = \frac{(\bar{\dot{C}}_o - \hat{\dot{C}}_o)I_E}{\dot{S}_{dev}}, \quad (148)$$

1085 and

$$Re_{iinc} = \frac{\left(\frac{\bar{\dot{C}}_o}{\hat{\dot{C}}_o} - 1\right) \hat{\dot{C}}_o I_E}{\dot{S}_{dev}}. \quad (149)$$

1086 Substituting $\bar{\dot{C}}_o = p_o \bar{\dot{q}}_o$ and $\hat{\dot{C}}_o = p_o \hat{\dot{q}}_o$ and cancelling terms gives

$$Re_{iinc} = \frac{\left(\frac{\bar{\dot{q}}_o}{\hat{\dot{q}}_o} - 1\right) \hat{\dot{C}}_o I_E}{\dot{S}_{dev}}. \quad (150)$$

1087 Substituting the income preference equation for other goods consumption (Eq. (29) for $\bar{\dot{q}}_o/\hat{\dot{q}}_o$ and

1088 Eq. (12) for \dot{S}_{dev} yields

$$Re_{iinc} = \frac{\left[\left(1 + \frac{\hat{\dot{N}}}{\hat{\dot{M}}'}\right)^{\varepsilon_{\dot{q}_o, \dot{M}}} - 1\right] \hat{\dot{C}}_o I_E}{\left(\frac{\tilde{\eta}}{\eta^\circ} - 1\right) \frac{\eta^\circ}{\tilde{\eta}} \dot{E}_s^\circ}. \quad (151)$$

1089 Substituting $(\hat{\dot{C}}_o/\dot{C}_o^\circ)\dot{C}_o^\circ$ for $\hat{\dot{C}}_o$, recognizing that $\dot{C}_o^* = \dot{C}_o^\circ$, and simplifying gives

$$Re_{iinc} = \frac{\left(1 + \frac{\hat{\dot{N}}}{\hat{\dot{M}}'}\right)^{\varepsilon_{\dot{q}_o, \dot{M}}} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \left(\frac{\tilde{\eta}}{\eta^\circ}\right) \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ} \left(\frac{\hat{\dot{C}}_o}{\dot{C}_o^\circ}\right). \quad (152)$$

1090 Substituting Eq. (22) for $\hat{\dot{C}}_o/\dot{C}_o^\circ$, thereby assuming the CES utility model, gives the final form of

1091 the indirect income rebound expression:

$$Re_{iinc} = \frac{\left(1 + \frac{\hat{\dot{N}}}{\hat{\dot{M}}'}\right)^{\varepsilon_{\dot{q}_o, \dot{M}}} - 1}{\frac{\tilde{\eta}}{\eta^\circ} - 1} \left(\frac{\tilde{\eta}}{\eta^\circ}\right) \frac{\dot{C}_o^\circ I_E}{\dot{E}_s^\circ} \left(1 + f_{\dot{C}_s}^\circ \left\{ \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ}\right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho}. \quad (32)$$

1092 If there is no net savings ($\hat{\dot{N}} = 0$), indirect income effect rebound is zero ($Re_{iinc} = 0$), as expected.

1093 B.4.5 Macro effect

1094 Macro rebound (Re_{macro}) is given by Eq. (33). Substituting Eq. (92) for net savings (\dot{N}^*) gives

$$Re_{macro} = \frac{k(p_E \dot{S}_{dev} - \Delta(R_\alpha \dot{C}_{cap})^* - \Delta \dot{C}_{OMd}^*) I_E}{\dot{S}_{dev}}. \quad (153)$$

1095 Separating terms gives

$$Re_{macro} = \frac{k p_E \cancel{\dot{S}_{dev}} I_E}{\cancel{\dot{S}_{dev}}} - \frac{k \Delta (R_\alpha \dot{C}_{cap})^* I_E}{\dot{S}_{dev}} - \frac{k \Delta \dot{C}_{OMd}^* I_E}{\dot{S}_{dev}} . \quad (154)$$

1096 Canceling terms, substituting Eq. (120) to obtain Re_{OMd} , and defining Re_{cap} as

$$Re_{cap} \equiv \frac{\Delta (R_\alpha \dot{C}_{cap})^* I_E}{\dot{S}_{dev}} \quad (155)$$

1097 gives

$$Re_{macro} = k(p_E I_E - Re_{cap} - Re_{OMd}) . \quad (34)$$

1098 B.4.6 Rebound sum

1099 The sum of the four rebound effects is

$$Re_{tot} = Re_{empl} + Re_{sub} + Re_{inc} + Re_{macro} . \quad (156)$$

1100 Substituting Eqs. (88), (100), and (109) gives

$$\begin{aligned} Re_{tot} &= Re_{emb} + Re_{OMd} && \text{emplacement effect} \\ &+ Re_{dsub} + Re_{isub} && \text{substitution effect} \\ &+ Re_{dinc} + Re_{iinc} && \text{income effect} \\ &+ Re_{macro} && \text{macro effect} \end{aligned} \quad (157)$$

1101 Macro effect rebound (Re_{macro} , Eq. (34)) can be expressed in terms of other rebound effects.

1102 Substituting Eq. (34) gives

$$\begin{aligned} Re_{tot} &= Re_{emb} + Re_{OMd} && \text{emplacement effect} \\ &+ Re_{dsub} + Re_{isub} && \text{substitution effect} \\ &+ Re_{dinc} + Re_{iinc} && \text{income effect} \\ &+ k p_E I_E - k Re_{cap} - k Re_{OMd} . && \text{macro effect} \end{aligned} \quad (158)$$

1103 Rearranging distributes macro effect terms to emplacement and substitution effect terms. This last
 1104 rearrangement gives the final expression for total rebound.

$$Re_{tot} = Re_{emb} + k(p_E I_E - Re_{cap}) + (1 - k)Re_{OMd} + Re_{dsub} + Re_{isub} + Re_{dinc} + Re_{iinc} \quad (35)$$

1105 Eq. (35) shows that determining seven rebound values,

- 1106 • Re_{emb} (Eq. (14)),
- 1107 • Re_{cap} (Eq. (155)),
- 1108 • Re_{OMd} (Eq. (15)),
- 1109 • Re_{dsub} (Eq. (23)),
- 1110 • Re_{isub} (Eq. (24)),
- 1111 • Re_{dinc} (Eq. (28)), and
- 1112 • Re_{iinc} (Eq. (32)),

1113 is sufficient to calculate total rebound, provided that the macro factor (k), the price of energy (p_E),
 1114 and the energy intensity of the economy (I_E) are known.

1115 C Utility models and elasticities

1116 As discussed in Section 2.5.2 and Appendix B.4.3, the substitution effect requires a model for
 1117 device user behavior. Behavior is typically represented by a model of utility that is maximized with
 1118 arguments of consuming the energy service (\dot{q}_s) and other goods and services (\dot{q}_o) and subject to
 1119 income and price constraints. In this appendix, we describe two utility models. The first utility
 1120 model is a constant price elasticity (CPE) utility model, which allows an easy calculation of price-
 1121 demand relationships as Appendix B.4.3 illustrates. It gives a good approximation of the behavioral
 1122 response for very small changes in energy efficiency and energy service price, such that $\Delta\eta^* \approx 0$
 1123 and $\Delta p_s^* \approx 0$. The CPE utility model is discussed for continuity with the literature only. (See, for
 1124 example, Borenstein (2015, p. 17, footnote 43).)



We note that larger and non-marginal efficiency gains cause greater rebound (measured in joules) than small and marginal efficiency gains. Thus, rebound analysis framework needs to accommodate large, non-marginal efficiency changes. Since price elasticities are point-measures in analytical utility models, a version of the framework amenable to empirical applications should account for the changing price elasticity along an indifference curve.²³ The second utility model discussed in this appendix is the Constant Elasticity of Substitution (CES) utility model which does, in fact, accommodate large, non-marginal energy efficiency and energy service price changes. The CES utility model underlies the substitution effect in this framework. (See Section 2.5.2.) Furthermore, the CES utility model is needed for the example energy efficiency upgrades (EEUs) in Part II, which have large, non-marginal percentage increases in energy efficiency.

In addition to the substitution effect, the income effect requires income elasticities to describe consumer behavior. Elasticities for both the substitution effect and the income effect are discussed below, after we lay out the CPE and CES utility models.

Before proceeding with the utility models and elasticities, we note briefly that the rate of other goods consumption (\dot{q}_o) is not known independently from the prices of other goods (p_o). With the assumption that the prices of other goods do not change across rebound effects (i.e., p_o is exogenous), the ratio of other goods consumption is equal to the ratio of other goods spending, such that

$$\frac{\dot{q}_o}{\dot{q}_o^\circ} = \frac{\dot{C}_o/p_o}{\dot{C}_o^\circ/p_o^\circ} = \frac{\dot{C}_o}{\dot{C}_o^\circ} \quad (159)$$

at all rebound stages. (See Appendix E for details.)

C.1 Utility models for the substitution effect

A utility model gives the ratio of energy service consumption rate and other goods consumption rates across the substitution effect (\hat{q}_s/\hat{q}_s^* and \hat{q}_o/\hat{q}_o^* , respectively). In so doing, utility models quantify the decrease in other goods consumption ($\hat{q}_o/\hat{q}_o^* < 1$) caused by the increase of energy service consumption ($\hat{q}_s/\hat{q}_s^* > 1$) resulting from the decrease of the energy service price ($p_s^* < p_s^\circ$) under the

²³In principle, calculated arc elasticities could describe the relationship between price and quantity changes for any EEU by representing the percentage price and quantity changes between any two known consumption bundles (Allen & Lerner, 1934). However, we do not know the new consumption bundle and instead determine it with the CES utility function whose price elasticities vary along the indifference curve.

1148 constraint of constant device user utility. Across the substitution effect, the utility increase of the
 1149 larger energy service consumption rate must be exactly offset by the utility decrease of the smaller
 1150 other goods consumption rate.

1151 C.1.1 Constant price elasticity (CPE) utility model

1152 The constant price elasticity (CPE) utility model is given by Eqs. (128) and (132). The equations
 1153 for the approximate utility model are repeated here for convenience.

$$\frac{\hat{q}_s}{\dot{q}_s^\circ} = \left(\frac{\tilde{\eta}}{\eta^\circ} \right)^{-\varepsilon_{\hat{q}_s, p_{s,c}}} \quad (128)$$

$$\frac{\hat{C}_o}{\dot{C}_o^\circ} = \frac{\hat{q}_o}{\dot{q}_o^\circ} = \left(\frac{\tilde{\eta}}{\eta^\circ} \right)^{-\varepsilon_{\hat{q}_o, p_{s,c}}} \quad (132)$$

1154 C.1.2 CES utility model

1155 The CES utility model is given by Eq. (16). Here, its derivation is shown. Throughout the derivation,
 1156 references to Part II are provided for visual representations of several important concepts. Those
 1157 concepts (equilibrium tangency requirements, e.g.) are best visualized in rebound planes that are
 1158 introduced in Section 2.2 of Part II.

1159 The CES utility model is normalized by (indexed to) conditions prior to emplacement:

$$\frac{\dot{u}}{\dot{u}^\circ} = \left[a \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^\rho + (1-a) \left(\frac{\dot{q}_o}{\dot{q}_o^\circ} \right)^\rho \right]^{(1/\rho)}, \quad (160)$$

1160 where $\rho \equiv (\sigma - 1)/\sigma$, a is a share parameter (determined below), and σ is the elasticity of substitution
 1161 between the normalized consumption rate of the energy service (\dot{q}_s) and the normalized consumption
 1162 rate of other goods (\dot{q}_o).²⁴ By definition, σ is assumed constant such that $\sigma^\circ = \sigma^* = \hat{\sigma} = \bar{\sigma} = \tilde{\sigma} = \sigma$.

1163 With the assumption of exogenous other goods prices in Eq. (159), we find

$$\frac{\dot{u}}{\dot{u}^\circ} = \left[a \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^\rho + (1-a) \left(\frac{\dot{C}_o}{\dot{C}_o^\circ} \right)^\rho \right]^{(1/\rho)}. \quad (161)$$

²⁴In the international trade literature, where the CES utility model is often used, the elasticity of substitution is also called the Armington elasticity (Feenstra et al., 2018).

Eq. (161) is the functional form of the CES utility model, whose share parameter (a) is yet to be determined. The correct expression for the share parameter (a) is found from the equilibrium requirement, namely that the expenditure curve is tangent to the indifference curve in the $\dot{C}_o/\dot{C}_o^\circ$ vs. $\dot{q}_s/\dot{q}_s^\circ$ plane (the “consumption plane” in Part II) prior to the EEU. For example, the $\circ\text{---}\circ$ line is tangent to the constant-utility indifference curve $i^\circ\text{---}i^\circ$ at point \circ in Figs. 4 and 7 of Part II.

To find the slope at any point on the indifference curve ($i^\circ\text{---}i^\circ$ in Figs. 4 and 7 of Part II), Eq. (161) can be rearranged to give the normalized consumption rate of other goods ($\dot{C}_o/\dot{C}_o^\circ$) as a function of the normalized consumption rate of the energy service ($\dot{q}_s/\dot{q}_s^\circ$) and the normalized utility rate (\dot{u}/\dot{u}°):

$$\frac{\dot{C}_o}{\dot{C}_o^\circ} = \left[\frac{1}{1-a} \left(\frac{\dot{u}}{\dot{u}^\circ} \right)^\rho - \frac{a}{1-a} \left(\frac{\dot{q}}{\dot{q}_s^\circ} \right)^\rho \right]^{(1/\rho)}, \quad (162)$$

a form convenient for drawing constant utility rate (\dot{u}/\dot{u}°) indifference curves on a graph of $\dot{C}_o/\dot{C}_o^\circ$ vs. $\dot{q}_s/\dot{q}_s^\circ$ (the consumption plane of Figs. 4 and 7 in Part II). In the consumption plane, the slope of an indifference curve is found by taking the first partial derivative of $\dot{C}_o/\dot{C}_o^\circ$ with respect to $\dot{q}_s/\dot{q}_s^\circ$, starting from Eq. (162) and using the chain rule repeatedly. The result is

$$\begin{aligned} \frac{\partial(\dot{C}_o/\dot{C}_o^\circ)}{\partial(\dot{q}_s/\dot{q}_s^\circ)} &= - \frac{a}{1-a} \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^{(\rho-1)} \\ &\times \left[\left(\frac{1}{1-a} \right) \left(\frac{\dot{u}}{\dot{u}^\circ} \right)^\rho - \left(\frac{a}{1-a} \right) \left(\frac{\dot{q}}{\dot{q}_s^\circ} \right)^\rho \right]^{(1-\rho)/\rho}. \end{aligned} \quad (163)$$

The budget constraint is the starting point for finding the slope of an expenditure line in the consumption plane. (Example expenditure lines include the $\circ\text{---}\circ$, $\ast\text{---}\ast$, $\wedge\text{---}\wedge$, and $\text{---}\text{---}\text{---}$ lines in Figs. 4 and 7 of Part II.) The following equation is a generic version of Eqs. (81), (83), (96), and (105) with $p_s\dot{q}_s$ substituted for $p_E\dot{E}_s$.

$$\dot{M} = p_s\dot{q}_s + R_\alpha\dot{C}_{cap} + \dot{C}_{OMd} + \dot{C}_o + \dot{N} \quad (164)$$

In a manner similar to derivations in Appendix B.3.1 of Part II, we solve for \dot{C}_o and judiciously multiply by $\dot{C}_o^\circ/\dot{C}_o$ and $\dot{q}_s^\circ/\dot{q}_s$ to obtain

$$\frac{\dot{C}_o}{\dot{C}_o^\circ} \dot{C}_o^\circ = -p_s \frac{\dot{q}_s}{\dot{q}_s^\circ} \dot{q}_s^\circ + \dot{M} - R_\alpha\dot{C}_{cap} - \dot{C}_{OMd} - \dot{N}. \quad (165)$$

1183 Solving for $\dot{C}_o/\dot{C}_s^\circ$ and rearranging gives

$$\frac{\dot{C}_o}{\dot{C}_s^\circ} = -\frac{p_s \dot{q}_s^\circ}{\dot{C}_s^\circ} \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right) + \frac{1}{\dot{C}_s^\circ} (\dot{M} - R_\alpha \dot{C}_{cap} - \dot{C}_{OMd} - \dot{N}) , \quad (166)$$

1184 from which the slope of the indifference curve in the consumption plane is taken by inspection to be

$$\frac{\partial(\dot{C}_o/\dot{C}_s^\circ)}{\partial(\dot{q}_s/\dot{q}_s^\circ)} = -\frac{p_s \dot{q}_s^\circ}{\dot{C}_s^\circ} . \quad (167)$$

1185 At any equilibrium point, the expenditure line must be tangent to its indifference curve, or, as
 1186 economists say, the ratio of prices must be equal to the marginal rate of substitution. Applying the
 1187 tangency requirement before emplacement enables solving for the correct expression for a , the share
 1188 parameter in the CES utility model. Setting the slope of the expenditure line (Eq. (167)) equal to
 1189 the slope of the indifference curve (Eq. (163)) gives

$$\begin{aligned} -\frac{p_s \dot{q}_s^\circ}{\dot{C}_s^\circ} &= -\frac{a}{1-a} \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^{(\rho-1)} \\ &\times \left[\left(\frac{1}{1-a} \right) \left(\frac{\dot{u}}{\dot{u}^\circ} \right)^\rho - \left(\frac{a}{1-a} \right) \left(\frac{\dot{q}}{\dot{q}_s^\circ} \right)^\rho \right]^{(1-\rho)/\rho} . \end{aligned} \quad (168)$$

1190 For the equilibrium point prior to emplacement (point \circ in Figs. 4 and 7 of Part II), $\dot{q}_s/\dot{q}_s^\circ = 1$,
 1191 $\dot{u}/\dot{u}^\circ = 1$, and $p_s = p_s^\circ$, which reduces Eq. (168) to

$$-\frac{p_s^\circ \dot{q}_s^\circ}{\dot{C}_s^\circ} = -\frac{a}{1-a} (1)^{(\rho-1)} \left[\left(\frac{1}{1-a} \right) (1)^\rho - \left(\frac{a}{1-a} \right) (1)^\rho \right]^{(1-\rho)/\rho} . \quad (169)$$

1192 Simplifying gives

$$\frac{p_s^\circ \dot{q}_s^\circ}{\dot{C}_s^\circ} = \frac{a}{1-a} . \quad (170)$$

1193 Recognizing that $p_s^\circ \dot{q}_s^\circ = \dot{C}_s^\circ$ and solving for a gives

$$a = \frac{\dot{C}_s^\circ}{\dot{C}_s^\circ + \dot{C}_o^\circ} , \quad (171)$$

1194 which is called $f_{\dot{C}_s^\circ}^\circ$, the share of energy service expenditure (\dot{C}_s°) relative to the sum of energy service
 1195 and other goods expenditures ($\dot{C}_s^\circ + \dot{C}_o^\circ$) before emplacement of the EEU. Thus, the CES utility
 1196 equation (Eq. (161)) becomes

$$\frac{\dot{u}}{\dot{u}^\circ} = \left[f_{\dot{C}_s}^\circ \left(\frac{\dot{q}_s}{\dot{q}_s^\circ} \right)^\rho + (1 - f_{\dot{C}_s}^\circ) \left(\frac{\dot{C}_o}{\dot{C}_o^\circ} \right)^\rho \right]^{(1/\rho)}, \quad (16)$$

1197 with

$$f_{\dot{C}_s}^\circ \equiv \frac{\dot{C}_s^\circ}{\dot{C}_s^\circ + \dot{C}_o^\circ}. \quad (172)$$

1198 C.2 Elasticities for the substitution effect

1199 Calculating the change in consumer preferences across the substitution effect requires a utility model,
 1200 two of which are described in the section above: the constant price elasticity (CPE) model and
 1201 the constant elasticity of substitution (CES) model. Within those utility models, price (ε) and
 1202 substitution (σ) elasticities describe consumer preferences.

1203 Own and cross price elasticities describe consumer preferences for consumption of the energy
 1204 service (\dot{q}_s) and other goods (\dot{q}_o) as the price of the energy service (p_s) changes due to the EEU.
 1205 Thus, there are four price elasticities: (i) the uncompensated own price elasticity of energy service
 1206 consumption ($\varepsilon_{\dot{q}_s, p_s}$), (ii) the uncompensated cross price elasticity of other goods consumption
 1207 ($\varepsilon_{\dot{q}_o, p_s}$), (iii) the compensated own price elasticity of energy service consumption ($\varepsilon_{\dot{q}_s, p_s, c}$), and (iv) the
 1208 compensated cross price elasticity of other goods consumption ($\varepsilon_{\dot{q}_o, p_s, c}$).

1209 The elasticity of substitution (σ) describes the willingness of consumers to substitute one good
 1210 for another. In the context of rebound from an EEU, substitution is considered between consumption
 1211 of the energy service (\dot{q}_s) and consumption of the basket of other goods (\dot{q}_o).

1212 C.2.1 Original, pre-EEU (\circ) elasticities

1213 Economists use surveys, statistical data, and other means to estimate values for the uncompensated
 1214 own price elasticity of energy service consumption ($\varepsilon_{\dot{q}_s, p_s}^\circ$) prior to the EEU. With $\varepsilon_{\dot{q}_s, p_s}^\circ$ in hand,
 1215 calculation of all other elasticities is possible.

1216 **Elasticity of substitution (σ)** For the constant price elasticity (CPE) utility model, there is
 1217 no analytical expression for the elasticity of substitution (σ) and values are most likely taken from
 1218 estimation, if they are obtained at all. As we show in Tables 13 and 14 of Part II, not all rebounds

are typically calculated, so not all elasticities are needed.

For the constant elasticity of substitution (CES) utility model, Gørtz (1977) shows that the elasticity of substitution prior to the EEU (σ°) can be computed by

$$\sigma^\circ = \frac{f_{\dot{C}_s}^\circ + \varepsilon_{\dot{q}_s, p_s}^\circ}{f_{\dot{C}_s}^\circ - 1} . \quad (173)$$

Thus, the original elasticity of substitution (σ°) can be determined from two pieces of readily available information: (i) the original uncompensated own price elasticity ($\varepsilon_{\dot{q}_s, p_s}^\circ$) and (ii) the share of income spent on the energy service prior to the EEU ($f_{\dot{C}_s}^\circ$ from Eq. (172)). In the CES utility model, σ° is assumed invariant and given the undecorated symbol σ to indicate that it applies across all rebound effects.

For the rest of the pre-EEU elasticities ($\varepsilon_{\dot{q}_\alpha, p_s}^\circ$, $\varepsilon_{\dot{q}_s, p_{s,c}}^\circ$, and $\varepsilon_{\dot{q}_\alpha, p_{s,c}}^\circ$), there is no difference for the CPE utility model or the CES utility model.

Uncompensated cross price elasticity ($\varepsilon_{\dot{q}_\alpha, p_s}^\circ$) From Hicks & Allen (1934), we note that the pre-EEU uncompensated cross price elasticity ($\varepsilon_{\dot{q}_\alpha, p_s}^\circ$) can be expressed as

$$\varepsilon_{\dot{q}_\alpha, p_s}^\circ = f_{\dot{C}_s}^\circ (\sigma - \varepsilon_{\dot{q}_\alpha, \dot{M}}) . \quad (174)$$

Compensated own price elasticity ($\varepsilon_{\dot{q}_s, p_{s,c}}^\circ$) An expression for the pre-EEU compensated own price elasticity ($\varepsilon_{\dot{q}_s, p_{s,c}}^\circ$) can be derived using the Slutsky equation, whereby the uncompensated own price elasticity of the energy service ($\varepsilon_{\dot{q}_s, p_s}^\circ$) is decomposed into the compensated own price elasticity ($\varepsilon_{\dot{q}_s, p_{s,c}}^\circ$) and the income elasticity ($\varepsilon_{\dot{q}_s, \dot{M}}$) as follows:

$$\varepsilon_{\dot{q}_s, p_s}^\circ = \varepsilon_{\dot{q}_s, p_{s,c}}^\circ - f_{\dot{C}_s}^\circ \varepsilon_{\dot{q}_s, \dot{M}} , \quad (175)$$

where $f_{\dot{C}_s}^\circ$ is given by Eq. (172), and the income elasticity ($\varepsilon_{\dot{q}_s, \dot{M}}$) is given in Section C.3. Solving for the compensated price elasticity prior to the EEU ($\varepsilon_{\dot{q}_s, p_{s,c}}^\circ$) gives

$$\varepsilon_{\dot{q}_s, p_{s,c}}^\circ = \varepsilon_{\dot{q}_s, p_s}^\circ + f_{\dot{C}_s}^\circ \varepsilon_{\dot{q}_s, \dot{M}} . \quad (176)$$

Compensated cross price elasticity ($\varepsilon_{\dot{q}_\alpha, p_{s,c}}^\circ$) The cross price version of the Slutsky equation is the starting point for deriving the pre-EEU compensated cross price elasticity ($\varepsilon_{\dot{q}_\alpha, p_{s,c}}^\circ$):

$$\varepsilon_{\dot{q}_\alpha p_s}^\circ = \varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ - f_{\dot{C}_s}^\circ \varepsilon_{\dot{q}_\alpha \dot{M}} . \quad (177)$$

1239 The income elasticity of other goods consumption ($\varepsilon_{\dot{q}_\alpha \dot{M}}$) is given in Section C.3. Solving for $\varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ$
 1240 gives

$$\varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ = \varepsilon_{\dot{q}_\alpha p_s}^\circ + f_{\dot{C}_s}^\circ \varepsilon_{\dot{q}_\alpha \dot{M}} . \quad (178)$$

1241 An alternative formulation can be derived by setting Eq. (174) equal to Eq. (177) to obtain

$$f_{\dot{C}_s}^\circ (\sigma - \varepsilon_{\dot{q}_\alpha \dot{M}}) = \varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ - f_{\dot{C}_s}^\circ \varepsilon_{\dot{q}_\alpha \dot{M}} . \quad (179)$$

1242 Solving for $\varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ$ gives

$$\varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ = f_{\dot{C}_s}^\circ \sigma . \quad (180)$$

1243 Substituting σ from Eq. (173) gives

$$\varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ = \frac{f_{\dot{C}_s}^\circ (f_{\dot{C}_s}^\circ + \varepsilon_{\dot{q}_s p_s}^\circ)}{f_{\dot{C}_s}^\circ - 1} . \quad (181)$$

1244 Assuming a known value for the original uncompensated own price elasticity ($\varepsilon_{\dot{q}_s p_s}^\circ$), all other
 1245 pre-EEU elasticities can be calculated from Eqs. (173), (174), (176), and (178) or (181).

1246 Note that the rebound framework in this paper uses the CES utility model and needs only the
 1247 uncompensated own price elasticity ($\varepsilon_{\dot{q}_s p_s}^\circ$) and the derived elasticity of substitution (σ) to calculate
 1248 rebound values. The other price elasticities ($\varepsilon_{\dot{q}_s p_s}^\circ$, $\varepsilon_{\dot{q}_s p_{s,c}}^\circ$, and $\varepsilon_{\dot{q}_\alpha p_{s,c}}^\circ$) are not necessary for the model.
 1249 However, they are helpful for elucidating results derived from the framework, a task left for Part II.

1250 C.2.2 Post substitution effect (\wedge) elasticities

1251 The stage after the substitution effect (\wedge) represents utility-maximizing behavior after the energy
 1252 service price drop caused by the EEU and the compensating variation. Post-EEU, elasticities may
 1253 be different from the original condition, because the consumption bundle has changed (due to a
 1254 move along the indifference curve). This section derives expressions for elasticities at the \wedge stage.
 1255 Elasticities at the \wedge stage are different for the CPE utility model and the CES utility model.

1256 **CPE utility model** By definition, all price elasticities are assumed unchanged from their original
 1257 values across the substitution effect in the constant price elasticity (CPE) utility model. Thus,

$$\varepsilon_{\dot{q}_s, p_s}^{\circ} = \hat{\varepsilon}_{\dot{q}_s, p_s} , \quad (182)$$

$$\varepsilon_{\dot{q}_{\sigma}, p_s}^{\circ} = \hat{\varepsilon}_{\dot{q}_{\sigma}, p_s} , \quad (183)$$

$$\varepsilon_{\dot{q}_s, p_{s,c}}^{\circ} = \hat{\varepsilon}_{\dot{q}_s, p_{s,c}} , \text{ and} \quad (184)$$

$$\varepsilon_{\dot{q}_{\sigma}, p_{s,c}}^{\circ} = \hat{\varepsilon}_{\dot{q}_{\sigma}, p_{s,c}} . \quad (185)$$

1258 Under the CPE approximation, the post-EEU elasticity of substitution will be different from its
 1259 original value ($\sigma^{\circ} \neq \hat{\sigma}$). However, there is no analytical expression for σ and values are most likely
 1260 taken from estimation, if they are found at all.

1261 **CES utility model** The CES utility model is rather different to the CPE model with respect to
 1262 the behavior of elasticities across the substitution effect. In the CES utility model, price elasticities
 1263 (ε) are different after the substitution effect (\wedge) compared to the original (\circ).

1264 **Elasticity of substitution (σ)** Be definition, the elasticity of substitution (σ) is constant
 1265 across the substitution effect for the CES utility model. Thus,

$$\sigma^{\circ} = \hat{\sigma} . \quad (186)$$

1266 Because the elasticity of substitution is unchanged, we refer to σ without decoration for the CES
 1267 utility model. The constancy of σ means that the price elasticities (ε) will vary with the energy
 1268 service price (\tilde{p}_s) across the substitution effect.

1269 **Compensated own price elasticity ($\hat{\varepsilon}_{\dot{q}_s, p_{s,c}}$)** The compensated own price elasticity of energy
 1270 service demand ($\hat{\varepsilon}_{\dot{q}_s, p_{s,c}}$) gives the percentage change of the consumption rate of the energy service
 1271 (\dot{q}_s) across the substitution effect due to a unit percentage change in the energy service price (\tilde{p}_s)
 1272 resulting from the EEU under the constraint that utility is unchanged ($\dot{u}^* = \hat{u}$). In contrast to the
 1273 CPE utility model above, the compensated own price elasticity of energy service demand ($\hat{\varepsilon}_{\dot{q}_s, p_{s,c}}$) is

not constant in the CES utility model. Rather, $\hat{\varepsilon}_{\dot{q}_s, p_s, c}$ is a function of the post-EEU energy service price (\tilde{p}_s). The definition of $\hat{\varepsilon}_{\dot{q}_s, p_s, c}$ is

$$\hat{\varepsilon}_{\dot{q}_s, p_s, c} \equiv \frac{\tilde{p}_s}{\hat{q}_s} \frac{\partial \hat{q}_s}{\partial \tilde{p}_s} \bigg|_{\dot{u} = \dot{u}^* = \hat{\dot{u}}} . \quad (187)$$

To find an expression for $\hat{\varepsilon}_{\dot{q}_s, p_s, c}$ for the CES utility function, we need to first find the partial derivative of the rate of energy service consumption (\hat{q}_s) with respect to the post-EEU energy service price \tilde{p}_s at constant utility ($\dot{u} = \dot{u}^* = \hat{\dot{u}}$) across the substitution effect. This derivation of an expression for $\hat{\varepsilon}_{\dot{q}_s, p_s, c}$ for the CES utility model commences with Eq. (21), which was derived for constant utility across the substitution effect.

$$\frac{\hat{q}_s}{\dot{q}_s^\circ} = \left\{ f_{\dot{C}_s}^\circ + (1 - f_{\dot{C}_s}^\circ) \left[\left(\frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \right) \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)} \right\}^{-1/\rho} \quad (21)$$

In Eq. (21), all terms on the right side except \tilde{p}_s are constant for the purposes of the partial derivative. Finding the partial derivative of \hat{q}_s with respect to \tilde{p}_s amounts to applying the chain rule repeatedly. To simplify the derivation, we can define the following constants

$$f \equiv f_{\dot{C}_s}^\circ , \quad (188)$$

$$g \equiv 1 - f_{\dot{C}_s}^\circ , \quad (189)$$

$$h \equiv \frac{\dot{q}_s^\circ}{\dot{C}_o^\circ} , \quad (190)$$

$$m_s \equiv \rho/(1 - \rho) , \quad (191)$$

$$n \equiv -1/\rho , \text{ and} \quad (192)$$

$$z \equiv \frac{g}{f} h = \frac{1 - f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \frac{\dot{q}_s^\circ}{\dot{C}_o^\circ} \quad (193)$$

and rearrange slightly to obtain

$$\hat{q}_s = \dot{q}_s^\circ [f + g (z \tilde{p}_s)^{m_s}]^n . \quad (194)$$

Taking the partial derivative of \hat{q}_s with respect to \tilde{p}_s , via repeated application of the chain rule, gives

$$\frac{\partial \hat{q}_s}{\partial \tilde{p}_s} = \dot{q}_s^\circ m_s n g z^{m_s} \tilde{p}_s^{m_s-1} \left\{ [f + g(z\tilde{p}_s)^{m_s}]^{n-1} \right\} . \quad (195)$$

Forming the elasticity via its definition (Eq. (187)) gives

$$\hat{\varepsilon}_{\dot{q}_s, p_s, c} \equiv \frac{\tilde{p}_s}{\hat{q}_s} \frac{\partial \hat{q}_s}{\partial \tilde{p}_s} \bigg|_{\dot{u} = \dot{u}^* = \hat{u}} = \frac{\tilde{p}_s}{\dot{q}_s^\circ [f + g(z\tilde{p}_s)^{m_s}]^n} \dot{q}_s^\circ m_s n g z^{m_s} \tilde{p}_s^{m_s-1} \left\{ [f + g(z\tilde{p}_s)^{m_s}]^{n-1} \right\} . \quad (196)$$

Cancelling terms and combining \tilde{p}_s and $[f + g(z\tilde{p}_s)^{m_s}]$ terms with different exponents gives

$$\hat{\varepsilon}_{\dot{q}_s, p_s, c} = \frac{m_s n g (z\tilde{p}_s)^{m_s}}{f + g(z\tilde{p}_s)^{m_s}} . \quad (197)$$

Back-substituting the constants and simplifying where possible yields

$$\hat{\varepsilon}_{\dot{q}_s, p_s, c} = - \frac{\frac{1}{1-\rho} \left(1 - f_{\dot{C}_s}^\circ \right) \left[\frac{1-f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)}}{f_{\dot{C}_s}^\circ + \left(1 - f_{\dot{C}_s}^\circ \right) \left[\frac{1-f_{\dot{C}_s}^\circ}{f_{\dot{C}_s}^\circ} \frac{\tilde{p}_s \dot{q}_s^\circ}{\dot{C}_o^\circ} \right]^{\rho/(1-\rho)}} . \quad (198)$$

Eq. (198) shows that the compensated energy service price elasticity of energy service consumption ($\hat{\varepsilon}_{\dot{q}_s, p_s, c}$) under the CES utility model is a function of the energy service price after the EEU (\tilde{p}_s). It is negative, as it should be, because all terms are positive, with ρ and $f_{\dot{C}_s}^\circ$ being bounded above by 1.

Of interest is how the elasticity changes as \tilde{p}_s changes. Taking the derivative of Eq. (197) and simplifying gives

$$\frac{\partial \hat{\varepsilon}_{\dot{q}_s, p_s, c}}{\partial \tilde{p}_s} = \frac{m_s^2 n g (z\tilde{p}_s)^{m_s}}{\tilde{p}_s (f + g(z\tilde{p}_s)^{m_s})^2} . \quad (199)$$

All terms taken to their power are positive with the exception of n . For $\sigma < 1$, n is positive; for $\sigma > 1$, n is negative. Since we expect $\sigma < 1$ (otherwise we have backfire rebound conditions), the derivative is positive: the compensated own price elasticity becomes less negative as \tilde{p}_s increases.²⁵ Since the share of income spent on the energy service declines for $\sigma < 1$, it is not immediately clear in which direction $\hat{\varepsilon}_{\dot{q}_s, p_s}$ moves according to equation 174. See Fig. C.8 in Appendix C.7 of Part II for a graph of the sensitivity of price elasticities ($\hat{\varepsilon}$) to energy service price (\tilde{p}_s) for concrete examples.

²⁵For $\sigma = 1$, $m_s = 0$ and the derivative is zero: the Cobb-Douglas special case.

Compensated cross price elasticity ($\hat{\varepsilon}_{\dot{q}_o, p_s, c}$)

The compensated cross price elasticity of other goods demand ($\hat{\varepsilon}_{\dot{q}_o, p_s, c}$) gives the percentage change of the consumption rate of other goods (\dot{q}_o) across the substitution effect due to a unit percentage change in the energy service price (\tilde{p}_s) resulting from the EEU under the constraint that utility is unchanged ($\dot{u}^* = \hat{u}$). To find the compensated cross price elasticity of other goods consumption ($\hat{\varepsilon}_{\dot{q}_o, p_s, c}$), we follow a similar procedure as for deriving the own price elasticity of energy service consumption ($\hat{\varepsilon}_{\dot{q}_s, p_s, c}$), with two differences being (i) the elasticity definition and (ii) the equation from which the partial derivative is derived.

The first difference is the definition of the compensated cross price elasticity of other goods consumption ($\hat{\varepsilon}_{\dot{q}_o, p_s, c}$).

$$\hat{\varepsilon}_{\dot{q}_o, p_s, c} \equiv \frac{\tilde{p}_s}{\hat{q}_o} \frac{\partial \hat{q}_o}{\partial \tilde{p}_s} \bigg|_{\dot{u} = \dot{u}^* = \hat{u}} \quad (200)$$

Again, we need to find the partial derivative of the rate of other goods consumption (\dot{q}_o) with respect to the energy service price (\tilde{p}_s) at constant utility ($\dot{u}^* = \hat{u}$) across the substitution effect. The second difference is the starting point for this derivation, Eq. (22) (instead of Eq. (21)).

$$\frac{\hat{C}_o}{\dot{C}_o} = \left(1 + f_{\dot{C}_s}^{\circ} \left\{ \left[\left(\frac{1 - f_{\dot{C}_s}^{\circ}}{f_{\dot{C}_s}^{\circ}} \right) \frac{\tilde{p}_s \dot{q}_s^{\circ}}{\dot{C}_o} \right]^{\rho/(\rho-1)} - 1 \right\} \right)^{-1/\rho}. \quad (22)$$

In Eq. (22), all terms on the right side except \tilde{p}_s are constant for the purposes of the partial derivative. So finding the derivative amounts to applying the chain rule repeatedly. To simplify the derivation, we can define

$$m_o \equiv \rho/(\rho - 1), \quad (201)$$

invoke the constancy of other prices ($p_o^{\circ} = \hat{p}_o$) from Appendix E, and rearrange slightly to obtain

$$\hat{q}_o = \dot{q}_o^{\circ} \{1 + f[(z\tilde{p}_s)^{m_o} - 1]\}^n, \quad (202)$$

with f , n , and z being constants defined in the derivation of $\hat{\varepsilon}_{\dot{q}_s, p_s, c}$ above.

Taking the partial derivative of \hat{q}_o with respect to \tilde{p}_s , via repeated application of the chain rule, gives

$$\frac{\partial \hat{q}_o}{\partial \tilde{p}_s} = \dot{q}_o^o m_o n f z^{m_o} \tilde{p}_s^{m_o-1} \{1 + [f(z\tilde{p}_s)^{m_o} - 1]\}^{n-1} . \quad (203)$$

Forming the elasticity via its definition (Eq. (200)) gives

$$\begin{aligned} \hat{\varepsilon}_{\dot{q}_o p_s, c} &\equiv \frac{\tilde{p}_s}{\hat{q}_o} \frac{\partial \hat{q}_o}{\partial \tilde{p}_s} \bigg|_{\dot{u} = \dot{u}^* = \hat{u}} \\ &= \frac{\tilde{p}_s}{\dot{q}_o^o \{1 + f[(z\tilde{p}_s)^{m_o} - 1]\}^n} \dot{q}_o^o m_o n f z^{m_o} \tilde{p}_s^{m_o-1} \{1 + f[(z\tilde{p}_s)^{m_o} - 1]\}^{n-1} . \end{aligned} \quad (204)$$

Cancelling terms and combining \tilde{p}_s and $\{1 + f[(z\tilde{p}_s)^{m_o} - 1]\}$ terms with different exponents gives

$$\hat{\varepsilon}_{\dot{q}_o p_s, c} = \frac{m_o n f (z\tilde{p}_s)^{m_o}}{1 + f[(z\tilde{p}_s)^{m_o} - 1]} . \quad (205)$$

Back-substituting the constants and simplifying where possible yields

$$\hat{\varepsilon}_{\dot{q}_o p_s, c} = - \frac{\frac{1}{\rho-1} f_{\dot{C}_s}^o \left(\frac{1-f_{\dot{C}_s}^o}{f_{\dot{C}_s}^o} \frac{\tilde{p}_s \dot{q}_s^o}{\dot{C}_o^o} \right)^{\rho/(\rho-1)}}{1 + f_{\dot{C}_s}^o \left[\left(\frac{1-f_{\dot{C}_s}^o}{f_{\dot{C}_s}^o} \frac{\tilde{p}_s \dot{q}_s^o}{\dot{C}_o^o} \right)^{\rho/(\rho-1)} - 1 \right]} . \quad (206)$$

Eq. (206) shows that the compensated energy service price elasticity of other goods consumption ($\hat{\varepsilon}_{\dot{q}_o p_s, c}$) under the CES utility model is a function of the energy service price after the EEU (\tilde{p}_s). It is positive, because all terms except $\frac{1}{\rho-1}$ are positive, with ρ and $f_{\dot{C}_s}^o$ being bounded above by 1.

Of interest is how the elasticity changes as \tilde{p}_s changes. Taking the derivative of 205 and simplifying gives

$$\frac{\partial \hat{\varepsilon}_{\dot{q}_o p_s, c}}{\partial \tilde{p}_s} = \frac{m_o^2 n f (z\tilde{p}_s)^{m_o}}{\tilde{p}_s (1 + f[(z\tilde{p}_s)^{m_o} - 1])^2} . \quad (207)$$

All terms taken to their power are positive with the exception of n , analogous to the derivative of the own price elasticity in equation 199. Thus, with $\sigma < 1$ and n positive, the compensated cross price elasticity becomes more positive as \tilde{p}_s increases.

See Fig. C.8 of Appendix C.7 of Part II for a graph of the sensitivity of price elasticities ($\hat{\varepsilon}$) to energy service price (\tilde{p}_s) for concrete examples.

Uncompensated own price elasticity ($\hat{\varepsilon}_{\dot{q}_s p_s}$) After finding the compensated own price elasticity ($\hat{\varepsilon}_{\dot{q}_s p_s, c}$), the Slutsky equation can be used directly to find the uncompensated own price

1335 elasticity ($\hat{\varepsilon}_{\dot{q}_s, p_s}$) after the substitution effect for the CES utility model.

$$\hat{\varepsilon}_{\dot{q}_s, p_s} = \hat{\varepsilon}_{\dot{q}_s, p_s, c} - \hat{f}_{\dot{C}_s} \varepsilon_{\dot{q}_s, \dot{M}} \quad (208)$$

1336 **Uncompensated cross price elasticity** ($\hat{\varepsilon}_{\dot{q}_o, p_s}$) The result from Hicks & Allen (1934) can be
 1337 used to calculate the uncompensated cross price elasticity ($\hat{\varepsilon}_{\dot{q}_o, p_s}$) for the CES utility model.

$$\hat{\varepsilon}_{\dot{q}_o, p_s} = \hat{f}_{\dot{C}_s} (\sigma - \varepsilon_{\dot{q}_o, \dot{M}}) . \quad (209)$$

1338 **C.3 Elasticities for the income effect** ($\varepsilon_{\dot{q}_s, \dot{M}}$ and $\varepsilon_{\dot{q}_o, \dot{M}}$)

1339 The income effect requires two elasticities to estimate the spending of net savings: the income
 1340 elasticity of energy service consumption ($\varepsilon_{\dot{q}_s, \dot{M}}$) and the income elasticity of other goods consumption
 1341 ($\varepsilon_{\dot{q}_o, \dot{M}}$). Due to the homotheticity assumption, both income elasticities are unitary. Thus,

$$\varepsilon_{\dot{q}_s, \dot{M}} = 1 , \quad (210)$$

1342 and

$$\varepsilon_{\dot{q}_o, \dot{M}} = 1 . \quad (211)$$

1343 **D Proof: Income preference equations satisfy the budget** 1344 **constraint**

1345 After the substitution effect, a rate of net savings is available (\hat{N}), all of which is spent on additional
 1346 energy service ($\Delta \bar{\dot{q}}_s, \Delta \bar{\dot{C}}_s = p_E \Delta \bar{\dot{E}}_s$) or additional other goods ($\Delta \bar{\dot{q}}_o, \Delta \bar{\dot{C}}_o$). The income effect must
 1347 satisfy the budget constraint such that net savings is zero afterward ($\bar{\dot{N}} = 0$). The budget constraint
 1348 across the income effect is represented by Eq. (111):

$$\hat{N} = p_E \Delta \bar{\dot{E}}_s + \Delta \bar{\dot{C}}_o . \quad (111)$$

1349 The additional spending due to the income effect is given by income preference equations

$$\frac{\bar{q}_s}{\hat{q}_s} = \left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_s, \hat{M}}} \quad (25)$$

1350 and

$$\frac{\bar{q}_o}{\hat{q}_o} = \left(1 + \frac{\hat{N}}{\hat{M}'}\right)^{\varepsilon_{\hat{q}_o, \hat{M}}}, \quad (29)$$

1351 where

$$\hat{M}' \equiv \dot{M}^\circ - R_\alpha^* \dot{C}_{cap}^* - \dot{C}_{OMd}^* - \hat{N}. \quad (26)$$

1352 This appendix proves that the income preference equations (Eqs. (25) and (29)) satisfy the budget
1353 constraint (Eq. (111)).

1354 The first step in the proof is to convert the income preference equations to \dot{C}_s° and \dot{C}_o° ratios.
1355 For the energy service income preference equation (Eq. (25)), multiply numerator and denominator
1356 of the left-hand side by $\tilde{p}_s = p_E/\tilde{\eta}$ (Eq. (7)) to obtain \bar{C}_s/\hat{C}_s . For the other goods income preference
1357 equation (Eq. (29)), multiply numerator and denominator of the left-hand side by p_o to obtain
1358 \bar{C}_o/\hat{C}_o . Then, invoke homotheticity to set $\varepsilon_{\hat{q}_s, \hat{M}} = 1$ and $\varepsilon_{\hat{q}_o, \hat{M}} = 1$ to obtain

$$\frac{\bar{C}_s}{\hat{C}_s} = 1 + \frac{\hat{N}}{\hat{M}'} \quad (212)$$

1359 and

$$\frac{\bar{C}_o}{\hat{C}_o} = 1 + \frac{\hat{N}}{\hat{M}'} . \quad (213)$$

1360 The second step in the proof is to obtain expressions for $\Delta\bar{C}_s$ and $\Delta\bar{C}_o$. Multiply the income
1361 preference equations above by $\Delta\hat{C}_s$ and $\Delta\hat{C}_o$, respectively. Then, subtract $\Delta\hat{C}_s$ and $\Delta\hat{C}_o$, respectively,
1362 to obtain

$$\Delta\bar{C}_s = \frac{\hat{C}_s}{\hat{M}'} \hat{N} \quad (214)$$

1363 and

$$\Delta\bar{C}_o = \frac{\hat{C}_o}{\hat{M}'} \hat{N} . \quad (215)$$

1364 The above versions of the income preference equations can be substituted into the budget
1365 constraint (Eq. (111)) to obtain

$$\hat{N} \stackrel{?}{=} \frac{\hat{C}_s}{\hat{M}'} \hat{N} + \frac{\hat{C}_o}{\hat{M}'} \hat{N}. \quad (216)$$

1366 If equality is demonstrated, the income preference equations satisfy the budget constraint. The
1367 remainder of the proof shows the equality of Eq. (216).

1368 Dividing by \hat{N} and multiplying by \hat{M}' gives

$$\hat{C}_s + \hat{C}_o \stackrel{?}{=} \hat{M}'. \quad (217)$$

1369 Substituting Eq. (26) for \hat{M}' gives

$$\hat{C}_s + \hat{C}_o \stackrel{?}{=} \dot{M}^\circ - R_\alpha^* \dot{C}_{cap}^* - \dot{C}_{OMd}^* - \hat{N}. \quad (218)$$

1370 Substituting Eq. (96) for \dot{M}° , because $\dot{M}^\circ = \hat{M}$, gives

$$\hat{C}_s + \hat{C}_o \stackrel{?}{=} p_E \hat{E}_s + \hat{R}_\alpha \hat{C}_{cap} + \hat{C}_{OMd} + \hat{C}_o + \cancel{\hat{N}} - R_\alpha^* \dot{C}_{cap}^* - \dot{C}_{OMd}^* - \cancel{\hat{N}}. \quad (219)$$

1371 Cancelling terms and recognizing that $R_\alpha^* \dot{C}_{cap}^* = \hat{R}_\alpha \hat{C}_{cap}$, $\dot{C}_{OMd}^* = \hat{C}_{OMd}$, and $\hat{C}_s = p_E \hat{E}_s$ gives

$$\hat{C}_s + \hat{C}_o \stackrel{?}{=} \hat{C}_s + \cancel{\hat{R}_\alpha \hat{C}_{cap}} + \cancel{\hat{C}_{OMd}} + \hat{C}_o - \cancel{\hat{R}_\alpha \hat{C}_{cap}} - \cancel{\hat{C}_{OMd}}. \quad (220)$$

1372 Cancelling terms gives

$$\hat{C}_s + \hat{C}_o \stackrel{\checkmark}{=} \hat{C}_s + \hat{C}_o, \quad (221)$$

1373 thereby completing the proof that the income preference equations (Eqs. (25) and (29)) satisfy the
1374 budget constraint (Eq. (111)).

1375 E Other goods expenditures and constant p_o

1376 This framework utilizes a partial equilibrium analysis (at the microeconomic level) in which we
1377 account for the change of the energy service price due to the EEU ($p_s^\circ \neq p_s^*$), but we do not track

1378 the effect of the EEU on prices of other goods. These assumptions have important implications for
 1379 the relationship between the rate of consumption of other goods (\dot{q}_o) and the rate of expenditure on
 1380 other goods (\dot{C}_o).

1381 We assume a basket of other goods (besides the energy service) purchased in the economy, each
 1382 (i) with its own price ($p_{o,i}$) and rate of consumption ($\dot{q}_{o,i}$), such that the average price of all other
 1383 goods purchased in the economy prior to the EEU (p_o°) is given by

$$p_o^\circ = \frac{\sum_i p_{o,i}^\circ q_{o,i}^\circ}{\sum_i q_{o,i}^\circ} . \quad (222)$$

1384 Then, the expenditure rate of other purchases in the economy can be given as

$$\dot{C}_o^\circ = p_o^\circ \dot{q}_o^\circ \quad (223)$$

1385 before the EEU and

$$\hat{C}_o = \hat{p}_o \hat{q}_o \quad (224)$$

1386 after the substitution effect, for example.

1387 We assume that any microeconomic effects (emplacement, substitution, or income) for a single
 1388 device are not so large that they cause a measurable change in prices of other goods. Thus,

$$p_o^\circ = p_o^* = \hat{p}_o = \bar{p}_o = \tilde{p}_o . \quad (225)$$

1389 In the partial equilibrium analysis, any two other goods prices can be equated across any rebound
 1390 effect to obtain (for the example of the original conditions (\circ) and the post-substitution state (\wedge))

$$\frac{\hat{C}_o}{\dot{C}_o^\circ} = \frac{\hat{q}_o}{\dot{q}_o^\circ} . \quad (226)$$

1391 Thus, a ratio of other goods expenditure rates is always equal to a ratio of other goods consumption
 1392 rates.

1393 F Energy price effect

1394 Energy price effect rebound (Re_{E_p}) is caused by a reduction in energy price (p_E) that can occur
 1395 when widespread implementation of an energy efficiency upgrade (EEU) leads to an economy-wide
 1396 reduction in energy demand. Reduced demand leads, via demand-supply rebalancing, to a lower
 1397 energy price (p_E). Thus, the device owner spends less on energy purchases to operate the upgraded
 1398 device and all other devices that use the same energy type. For simplicity, we assume the device
 1399 owner's additional freed cash is spent on other goods and services with energy implications at the
 1400 energy intensity of the economy (I_E). This appendix derives an expression for an energy price effect
 1401 rebound (Eq. (36)) shown in Section 3.2. This derivation and our assessment of the magnitude of
 1402 energy price effect rebound in Part II illustrate the flexibility and extensibility of the framework
 1403 presented in these papers.

1404 The derivation begins with an equation for the new economy-wide demand for energy (\bar{Q}_E) after
 1405 the EEU:

$$\bar{Q}_E = \dot{Q}_E^\circ - f_{EEU} N_{dev} \dot{E}_s^\circ \left(1 - \frac{\bar{E}_s}{\dot{E}_s^\circ} \right), \quad (227)$$

1406 where \dot{Q}_E is the rate of economy-wide demand for energy in MJ/year, f_{EEU} is the fraction of devices
 1407 upgraded across the economy (i.e., the penetration of the EEU), N_{dev} is the number of devices
 1408 in service, and \dot{E}_s is the rate of energy consumption by a single device in MJ/device-year. The
 1409 decorations “ \circ ” and “ $-$ ” have the usual meanings provided in Fig. 1, namely that “ \circ ” indicates
 1410 the original, pre-EEU device and “ $-$ ” indicates conditions for the device owner after emplacement,
 1411 substitution, and income adjustments. The ratio between new (\bar{Q}_E) and pre-EEU (\dot{Q}_E°) energy
 1412 demand is given by

$$\frac{\bar{Q}_E}{\dot{Q}_E^\circ} = \frac{\dot{Q}_E^\circ - f_{EEU} N_{dev} \dot{E}_s^\circ \left(1 - \frac{\bar{E}_s}{\dot{E}_s^\circ} \right)}{\dot{Q}_E^\circ}. \quad (228)$$

1413 Simplifying gives

$$\frac{\bar{Q}_E}{\dot{Q}_E^\circ} = 1 - f_{EEU} \frac{N_{dev} \dot{E}_s^\circ}{\dot{Q}_E^\circ} \left(1 - \frac{\bar{E}_s}{\dot{E}_s^\circ} \right). \quad (229)$$

1414 Note that the group $\frac{N_{dev}\dot{E}_s^\circ}{\dot{Q}_E^\circ}$ is the original (pre-EEU) fraction of all energy production (of the kind
 1415 used by the device) consumed by all such devices throughout the economy.

1416 The relationship between energy price (p_E) and economy-wide energy supply (\dot{Q}_E) can be given
 1417 by an elasticity relationship

$$\frac{\bar{\dot{Q}}_E}{\dot{Q}_E^\circ} = \left(\frac{\bar{p}_E}{p_E^\circ} \right)^{\varepsilon_{\dot{Q}_E, p_E}}, \quad (230)$$

1418 where $\varepsilon_{\dot{Q}_E, p_E}$ is the energy price (p_e) elasticity of economy-wide energy supply (\dot{Q}_E) and is expected
 1419 to be positive. To assess the effect on price ($p_E^\circ > \bar{p}_E$) of demand reduction due to widespread
 1420 adoption of the EEU ($\dot{Q}_E^\circ > \bar{\dot{Q}}_E$), we solve for $\frac{\bar{p}_E}{p_E^\circ}$ to obtain

$$\frac{\bar{p}_E}{p_E^\circ} = \left(\frac{\bar{\dot{Q}}_E}{\dot{Q}_E^\circ} \right)^{\frac{1}{\varepsilon_{\dot{Q}_E, p_E}}}. \quad (231)$$

1421 Substituting Eq. (229) gives

$$\frac{\bar{p}_E}{p_E^\circ} = \left[1 - f_{EEU} \frac{N_{dev}\dot{E}_s^\circ}{\dot{Q}_E^\circ} \left(1 - \frac{\bar{\dot{E}}_s}{\dot{E}_s^\circ} \right) \right]^{\frac{1}{\varepsilon_{\dot{Q}_E, p_E}}}. \quad (232)$$

1422 The energy price reduction ($p_E^\circ > \bar{p}_E$) leads to additional freed cash (\dot{G}_{p_E}) for the device owner
 1423 at a rate of

$$\dot{G}_{p_E} = \left[\dot{E}^\circ - (\dot{E}_s^\circ - \bar{\dot{E}}_s) \right] (p_E^\circ - \bar{p}_E), \quad (233)$$

1424 where \dot{E}° is the rate at which the device owner consumes the final energy carrier that supplies the
 1425 energy service (gasoline for a car and electricity for an electric lamp) prior to the EEU in all devices
 1426 (the upgraded devices and others), $(\dot{E}_s^\circ - \bar{\dot{E}}_s)$ reduces \dot{E}° by the energy savings after the income
 1427 adjustment such that $\dot{E}^\circ - (\dot{E}_s^\circ - \bar{\dot{E}}_s)$ is the total rate of energy consumption by all of the consumer's
 1428 devices after the income effect and the energy price adjustment, and $(p_E^\circ - \bar{p}_E)$ is the energy price
 1429 reduction caused by reduced demand for energy across the whole economy estimated by Eq. (232).

1430 Rearrangement of terms gives

$$\dot{G}_{p_E} = \left[\dot{E}^\circ - (\dot{E}_s^\circ - \bar{\dot{E}}_s) \right] \left(1 - \frac{\bar{p}_E}{p_E^\circ} \right) p_E^\circ, \quad (234)$$

1431 into which Eq. (232) can be substituted easily.

1432 The energy implications of spending the additional freed cash (\dot{G}_{p_E}) on other goods and services
1433 is $\dot{G}_{p_E} I_E$, another energy takeback rate. By Eq. (3), rebound associated with this energy price effect
1434 takeback can be written as

$$Re_{p_E} = \frac{\dot{G}_{p_E} I_E}{\dot{S}_{dev}}, \quad (36)$$

1435 as shown in Section 3.2, thus completing the derivation.