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Abstract

The rebound effect is a well-known behavioral response whereby potential energy savings from efficiency improvements are partially offset by increased consumption of energy services, as the marginal cost of energy services is reduced. This paper characterizes a similar rebound effect related to installation and operation of a residential photovoltaic (PV) system. This solar rebound effect is different from traditionally studied rebound effects, primarily because it is due not to an improvement in the energy efficiency of a household's appliances, but to the supply of a zero-marginal-cost perfect substitute for grid electricity. The solar rebound effect is first derived in the absence of any subsidization mechanism. We then modify the model to account for two commonly implemented incentives: installation rebates and net metering. Rebates are shown to increase the rebound effect, whereas the effect of net metering depends on the per-unit compensation rate.

JEL-Codes: Q410, Q420, Q480.

Keywords: rebound effect, solar energy, residential photovoltaic systems, net metering, investment tax credit.

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1. Introduction

Subsidization of residential solar photovoltaic (PV) systems is increasingly pervasive, as policy makers around the world seek ways to reduce consumers' reliance on conventional, carbon-intensive energy technologies. A key policy question is whether the reduction in grid electricity demand resulting from the induced adoption of PV systems justifies the cost of providing economic support for this substitute technology. In this spirit, this paper explores the possibility that the installation of residential PV systems will result in a "rebound effect" that erodes the expected reduction in electricity demand.

The rebound effect is a widely studied behavioral response through which potential energy savings from efficiency improvements are partially offset by increased consumption of energy services, as the marginal cost of energy services is reduced (Berhkout et al. 2000; Sorrell et al. 2009; Borenstein 2015; Chan and Gillingham 2015). This paper characterizes the rebound effect related to installation of a residential PV system using a simple neoclassical model similar to that of Chan and Gillingham (2015). This work is distinct from the existing literature in two ways. First, the rebound effect in this case is due not to an improvement in the energy efficiency of a household's appliances, but to the supply of a zero-marginal-cost perfect substitute for grid electricity. Second, although we derive the direct rebound effect (DRE) in a manner consistent with the existing literature, we also introduce a new rebound concept for residential PV, which we refer to as the *solar rebound*. The DRE for PV is the elasticity of total electricity consumption with respect to an increase in PV output. The solar rebound, on the other hand, is defined as the increase in total electricity consumption as a percentage of the change in PV output. One advantage of this characterization is that, while the DRE characterizes a marginal change only (*e.g.*, resulting from an exogenous increase in solar irradiation), the solar rebound can be defined both for a marginal change and for a discrete change (*e.g.*, resulting from the decision to adopt a PV system). The analytical convenience of this solar rebound concept becomes especially apparent when viewed through the lens of a standard indifference map; the solar rebound is essentially equivalent to the effect of an increase in household income.

A secondary goal of this research is to understand the relationship between household income and the rebound effect, which has implications for subsidies designed to stimulate adoption of residential PV systems.[1] Two of the most common subsidization schemes for residential PV are (i) a partial rebate of the fixed installation cost (or, equivalently, an income tax credit), and (ii) net metering. After establishing the baseline characteristics of the two rebound concepts, in which we assume zero fixed installation cost (equivalent to a full rebate) and no net metering scheme, we extend the model to account for partial rebate and net metering. We then examine how the DRE and solar rebound relate to household income, and discuss the implications for the implementation of subsidization schemes targeted toward low-income households.

Results indicate that, all else equal, the DRE increases as the fraction of fixed installation cost recovered via the rebate decreases. Conversely, the solar rebound for a discrete change in PV output (and thus fixed cost) increases as the rebate fraction increases, but is unaffected at the margin because no change in fixed cost is incurred. All else equal, full retail price net metering has no effect on the DRE or the solar rebound. By contrast, partial retail price net metering potentially results in a negative rebound effect—that is, the consumer reduces electricity consumption by more than the increase in PV generation. In addition, theory indicates that, all else equal, an increase in household income increases the DRE. The solar rebound is constant across

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[1] The baseline model presented here is also utilized in Toroghi and Oliver (2019). The intent of the modeling exercise in this paper is to incorporate and explore the implications of residential PV subsidization policies.

income levels under the restriction that households all have structurally identical utility functions; although empirically, the solar rebound has been shown to be declining as income increases.

This implies that rebate schemes targeted to incentivize adoption by lower-income households are unlikely to yield as much “bang for the buck” in terms of reducing grid electricity consumption as would result from offering the same incentive on the same PV system to a richer household. Preferential treatment of richer households, however, is unlikely to be politically popular. One solution might be to augment the rebate subsidy to low-income households with an additional incentive to reduce total electricity consumption. An obvious way to do this would be to set a joint subsidy policy such that the higher the rebate the household receives upon installation, the lower the compensation level per unit via net-metering. A higher rebate for low-income households implies a higher solar rebound (due to both the income and the rebate relationships described above), but this could be partially offset by a lower net metering compensation level.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on rebound effects, both as traditionally defined for energy efficiency improvements and the emerging literature on the rebound effect related to residential solar. Section 3 presents the model. Section 4 discusses some alternative explanations for the rebound and other considerations regarding its empirically observed magnitude. Section 5 concludes.

2. Review of Related Literature

Almost every review of the rebound effect literature begins with Jevons (1865), who first hypothesized the phenomenon as a likely result of improving system efficiency in industries with respect to electricity usage. Resurgent interest has emerged recently, as energy economists and policy makers have sought to understand and characterize consumer responses to policies to spur improvements in the energy efficiency of durable goods like electrical appliances and automobiles.

Two broad types of rebound effect are described in the modern literature—termed the *direct* and *indirect* rebound effects. The DRE, generally attributed to Khazoom (1980), is defined as the result of substitution and income effects on the demand for energy services provided by appliances with differing energy efficiency attributes. By contrast, the indirect rebound effect constitutes three *macroeconomic* factors: economy-wide changes in income, changes in embodied energy, and substitution (Brookes 1978; Dimitropoulos 2007; Azevedo 2014). This formulation of the rebound analyzes the impact of energy efficiency improvements in one sector on the demand for all other goods and services, including the resulting changes in energy use patterns (Bentzen 2004; Barker et al. 2009; Gillingham et al. 2016; Yu et al. 2015). While indirect rebound effects related to widespread PV adoption are likely to occur, the focus of the remainder of this paper is on the DRE associated with residential PV systems.

The DRE is typically modeled by economists as the elasticity of energy demand with respect to a change in energy efficiency (Binswanger 2001; Sorrell and Dimitropoulos 2008; Chan and Gillingham 2015). For example, researchers have found a DRE resulting from improvements in fuel efficiency in both passenger vehicles (Greene et al. 1999; Wang et al. 2012; Linn 2013) and freight vehicles (Matos and Silva 2011; Winebrake et al. 2012; Wang and Lu 2014). Saunders (2013) studies energy efficiency improvements across the US economy, finding significant rebound effects in 30 industrial sectors. Household-level DRE's have been estimated for efficiency improvements across multiple energy-use vectors in Sweden (Nässén and Holmberg 2009) and China (Ouyang et al. 2010; Lin and Liu 2015). Others have measured DREs from efficiency improvements in specific household energy-use vectors, including space heating (Haas and

Biermayr 2000; Guerra Santin 2013) and air conditioning and refrigeration (Jin 2007). Some researchers have even found rebound effects in not just energy use but greenhouse gas emissions (Brännlund et al. 2007; Druckman et al. 2011).

In addition to the traditionally studied rebound effect that occurs as a result of energy efficiency improvements, recent studies have found evidence that the installation of PV systems also results in a rebound. A study in Australia found an average rebound effect of 15% for early PV adopters, measured as the percentage of PV energy generated (Havas et al., 2015). Another empirical study of nearly 2 million homes across Australia found an average rebound effect of between 16% and 21% per kWh of solar power generated (Deng and Newton, 2017). Similarly, Beppler (2019) estimated a rebound effect of roughly 15% for PV adopters in the PJM service area. Among PV owners in Texas, Spiller et al (2017) found a rebound of 8.5-10%, estimated at the margin and based on daily fluctuations in solar radiation, where the point estimate varied depending on ownership of an electric vehicle.

To date, the existing research on the solar rebound has been entirely empirical in nature. This paper fills a gap in the literature by laying out the microeconomic foundations for the solar rebound effect, taking a similar approach to that of Chan and Gillingham (2015) in modeling the microeconomics of the energy efficiency rebound. The other key contribution of this paper is to explicitly model the effect of widely used subsidy schemes on the solar rebound, which will aid policy makers in understanding how solar subsidies and rebound effects are related.

3. The Model

The goal of this section is to derive the direct rebound effect (DRE) of installing a residential solar PV system. Thomas and Azevedo (2013) analytically derive the DRE using a demand function for “fuel” (*e.g.*, electricity, gasoline), which is consumed by an appliance of a given efficiency. These authors assume households do not derive utility from energy directly, “but from the useful energy services that a fuel or energy carrier provides when used with an appliance, *i.e.* the demand for energy is derived from the demand for energy services.” For the present purpose, we are concerned with one specific type of energy consumption—electricity use. We simplify the problem by assuming a direct mapping of electricity consumption, e, into household utility, where this mapping reflects the fixed energy efficiency attributes of the household’s set of appliances.[2] The household also consumes a composite normal good, x, which serves as the numeraire. A critical assumption is that x is comprised of consumptive goods and services that do not fundamentally require electricity in order to yield utility, such that e and x are imperfect substitutes.

We adapt the basic neoclassical framework of Chan and Gillingham (2015), starting with the household utility function:

$$U = U(e, x), \tag{1}$$

where

$$U_e \equiv \frac{\partial U}{\partial e} > 0; \quad U_x \equiv \frac{\partial U}{\partial x} > 0.$$

For simplicity we assume a static model based on monthly income and electricity consumption levels.

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[2] Alternatively, our model could be interpreted as normalizing the energy efficiency attributes of the household’s appliances to 1. That is, following Chan and Gillingham (2015), denote consumption of energy services as $s = \omega e$, where ω is an efficiency parameter normalized to 1. The remainder of the model thus proceeds unchanged.

Assume a rebate program is implemented that will cover some fraction, γ, of the fixed cost to the household of installing a solar PV system.[3] Denote the fixed cost as $\bar{C}$, which we assume to be exogenous and constant. That is, $\bar{C}$ represents the monthly payment toward a principal balance plus interest. The rational household's decision to adopt a PV system depends on the utility level with the system versus without it. That is, given the post-rebate fixed cost, $(1-\gamma)\bar{C}$, relative to household income, the household will choose to install the PV system if $U^{PV} > U^{no\ PV}$. We explore later the sensitivity of the adoption decision to these parameters.

Once the household has installed a PV system, electricity may be supplied either from the system, denoted e_{pv}, or from the grid, denoted e_g. The total amount of electricity supplied to the household is thus

$$e = e_{pv} + e_g. \tag{2}$$

To the household, e_{pv} and e_g are perfect substitutes at the point of consumption. In other words, holding x constant, the household is indifferent (in marginal utility terms) between consuming an additional unit of electricity as supplied by the PV system versus an additional unit supplied by the grid. The key difference is that the household has no control over e_{pv}, which is therefore taken as given. As an additional simplification, assume the PV system size is such that $e > e_{pv}$ at the household's optimal level of electricity consumption.[4]

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[3] A tax credit would function in a similar manner—some portion of the fixed cost would be recoverable via the credit, adding to post-installation disposable income.

[4] Relaxing this assumption allows for the possibility that the PV system generates more electricity that the household consumes over the course of the monthly billing cycle. While technically possible—and although PV generation may exceed consumption at any point in time—based on previous studies' findings PV generation exceeding total consumption at the monthly level appears to be rare.

The price of x is normalized to one, and denote the price of electricity purchased from the grid as p. Electricity supplied by the PV system incurs zero marginal cost to the household. Denoting household income as M, the budget constraint is

$$pe_g + x = M - (1-\gamma)\bar{C}. \tag{3}$$

For ease of exposition, we assume for now that $\gamma = 1$, but relax this assumption later. We also later analyze the inclusion of a net-metering program.

The household's objective is thus to choose e_g and x to maximize (1) subject to both (2) and (3), taking p and e_{pv} as given. After substituting (2) directly into the utility function, the Lagrangian is

$$\mathcal{L} = U\left(e_{pv} + e_g, x\right) + \lambda\left(M - pe_g - x\right), \tag{4}$$

where λ is the Lagrangian multiplier. The first-order conditions are:

$$U_e - \lambda p = 0, \tag{5}$$

$$U_x - \lambda = 0, \tag{6}$$

$$M - pe_g - x = 0. \tag{7}$$

These can be solved for the Marshallian demands for e_g and x, given e_{pv}, p, and M:

$$e_g^* = e_g\left(p, M, e_{pv}\right), \tag{8}$$

$$x^* = x\left(p, M, e_{pv}\right), \tag{9}$$

$$\lambda^* = \lambda\left(p, M, e_{pv}\right). \tag{10}$$

Equation (8) represents the household's demand for grid electricity under the assumption that PV generation perfectly displaces grid electricity consumption. This would be the case, for example, if the household has also installed (sufficient) on-site electricity storage capacity such that any differences in the temporal consumption and PV generation profiles can be reconciled via storage. The market for residential electricity storage systems is growing rapidly, and the installation of such systems increasingly accompanies the installation of PV systems. In the absence of on-site storage, however, grid electricity may not be perfectly displaced by PV resulting in ‘load shifting’ behavior, complicating the problem. In such cases a fraction of e_{pv} would likely be fed back into the grid at zero marginal benefit to the household. Denoting as θ the fraction of e_{pv} actually consumed by the household, total electricity consumption is then $e = e_g + \theta e_{pv}$. We implicitly assume $\theta = 1$ here. Later, we show that under net-metering on-site storage is redundant, because net metering allows the household to treat the grid as substitute for storage.

For the purpose of facilitating a simple and intuitive exposition, we henceforth assume a Cobb-Douglass form for $U(e, x)$:

$$U = U(e, x) = e^{\alpha} x^{\beta}, \tag{11}$$

where $\alpha + \beta = 1$. Despite the rather strict assumptions of the Cobb-Douglass form—*e.g.*, that it gives rise to constant consumption shares that do not vary with changes in income—we feel it is sufficient for our present goal.[5] For an individually rational household with a given income facing a given grid electricity price, the Cobb-Douglass utility function is likely to be approximately representative of preferences, so as to adequately describe the associated normative short-run behavior.

Given (11), the Marshallian demand function for e_g has the following explicit form:

$$e_g^* = \frac{\alpha M}{p} - \beta e_{pv}, \tag{12}$$

where the effect on e_g^* of a marginal change in e_{pv} is

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[5] One could easily choose a different functional form, provided it maintains some basic properties (*e.g.*, concavity, monotonicity) to ensure that it reflects rational preferences. Irrespective of the functional form used, the qualitative, intuitive characteristics of the solar rebound should be unaffected.

$$\frac{\partial e_g^*}{\partial e_{pv}} = -\beta. \tag{13}$$

Clearly this marginal effect lies between -1 and 0, meaning a one-unit increase in e_{pv} does not lead to a full one-unit reduction in e_g.

The standard approach throughout the literature, as explained by Chan and Gillingham (2015), has been to define the DRE as an elasticity. A key elasticity in the current model is that of grid electricity demand with respect to e_{pv}, denoted η. From (13), it follows that

$$\eta \equiv \frac{e_{pv}}{e_g} \cdot \frac{\partial e_g}{\partial e_{pv}} = -\beta \frac{e_{pv}}{e_g}. \tag{14}$$

The DRE is defined as the elasticity of *total* electricity consumption with respect to e_{pv}, denoted ε. By substituting (12) into (2) and deriving ε, after performing a few minor algebraic manipulations it is easily shown that the DRE is equal to the income share spent on electricity (in the absence of a PV system) multiplied by the fraction of e_{pv} in total electricity consumption:

$$\varepsilon = \frac{\alpha e_{pv}}{e}. \tag{15}$$

Further manipulation yields the relationship between ε and η,

$$\varepsilon = \frac{1}{e}\left(\eta e_g + e_{pv}\right), \tag{16}$$

which differs significantly from the more traditional formulation in Chan and Gillingham.

The intuition of these expressions is as follows. If $\varepsilon = 0$, the DRE is zero; there is no change in total electricity consumption following an increase in e_{pv}. This is only possible if an increase in PV generation results in a one-for-one decrease in consumption of grid electricity. By (15), this would require $\alpha = 0$, in which case the household spends its entire income on the numeraire good—which we rule out as trivial. Conversely, if $\varepsilon = 1$, the DRE is 100 percent, implying no reduction in grid electricity consumption. By (16) this would require $\eta = 1$, which cannot occur because η is strictly non-positive. The implication here is that the two extremes—zero rebound and full rebound—are each impossible. The DRE is always between 0 and 1. This is both good and bad; an increase in PV generation will always result in a reduction in grid electricity consumption, but it will never be a full one-for-one reduction.

3.1. The Solar Rebound

Although the DRE as defined by the elasticities ε and η is informative, we wish to introduce an alternative characterization of the rebound with regard to PV electricity generation, which we will henceforth refer to as the *solar rebound*, using the notation Θ. Our characterization of Θ relates directly to the standard formulation of the DRE. To see this, let

$$\Theta = \frac{\Delta e_g}{\Delta e_{pv}} + 1. \tag{17}$$

That is, the solar rebound is expressed in terms of the ratio of the absolute reduction in grid electricity consumption to the increase in PV electricity production.

The intuitive appeal of this structure is straightforward. Consider a marginal increase in e_{pv}. At the margin, $\frac{\Delta e_g}{\Delta e_{pv}} = \frac{\partial e_g}{\partial e_{pv}} = -\beta$, which implies

$$\Theta = -\beta + 1 = \alpha. \tag{18}$$

The solar rebound is constant and precisely equal to the income share that would be spent on electricity if no PV electricity were available. While this result holds for any marginal increase in e_{pv}, it is straightforward to show that for a discrete change from $e_{pv} = 0$ to $e_{pv} > 0$ with fixed cost $\bar{C}$, the solar rebound is

$$\Theta_\Delta = \alpha\left[1 - \frac{(1-\gamma)\bar{C}}{pe_{pv}}\right], \tag{19}$$

where the second term inside the brackets is the monetary cost-to-benefit ratio of installing the PV system. To distinguish the marginal solar rebound from the discrete, we henceforth use the subscript Δ to denote the latter. For the remainder of this initial exercise, we maintain the assumptions of (i) no net metering and (ii) a full installation rebate ($\gamma = 1$) , where each will be relaxed in the next section. The implication of the latter is that even the discrete-change solar rebound will be equal to α.

A standard indifference map, depicted in Figure 1, is instructive in establishing the underlying economic intuition of the solar rebound. As this exercise is illustrative only, we have adopted simple but arbitrary parameters. Specifically, we set M equal to one, the price of grid electricity, p_e, equal to 0.2, and the Cobb-Douglas exponents, α and β, to 0.1 and 0.9, respectively.[6] Note that, given the unevenness of the income shares implied by these values of α and β, in Figure 1 we have adjusted the scales of the vertical and horizontal axes so as to render the indifference map more visually perspicuous.

We start with the 'baseline' case in which $e_{pv} = 0$, such that total electricity consumption must be procured entirely from the grid. Given p_e and M, the budget line is L_0, for which the tangency point with indifference curve I_0, labeled point A, yields the optimal bundle $x_0 = 0.9$ and $e_0 = 0.5$. Now consider the 'comparison' case in which $e_{pv} = 0.25$, or exactly half the household's baseline electricity consumption; total electricity consumption is now the sum of grid and PV electricity. Here, the optimal bundle of the numeraire good and grid electricity, computed from their respective Marshallian demand functions, is $x_1 = 0.945$ and $e_g' = 0.275$, labeled point B. The household's total electricity consumption with PV is $e_1 = e_g' + e_{pv} = 0.525$, which, with x_1, yields a utility

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[6] In reality α is typically less than 0.1 for most households, but such values would make an indifference map exceedingly difficult to illustrate due to the sharply skewed indifference curves.

level along indifference curve I_1. This is labeled point C. Note that because the household's realized utility is greater with the PV system than without it, the household would rationally choose to adopt.

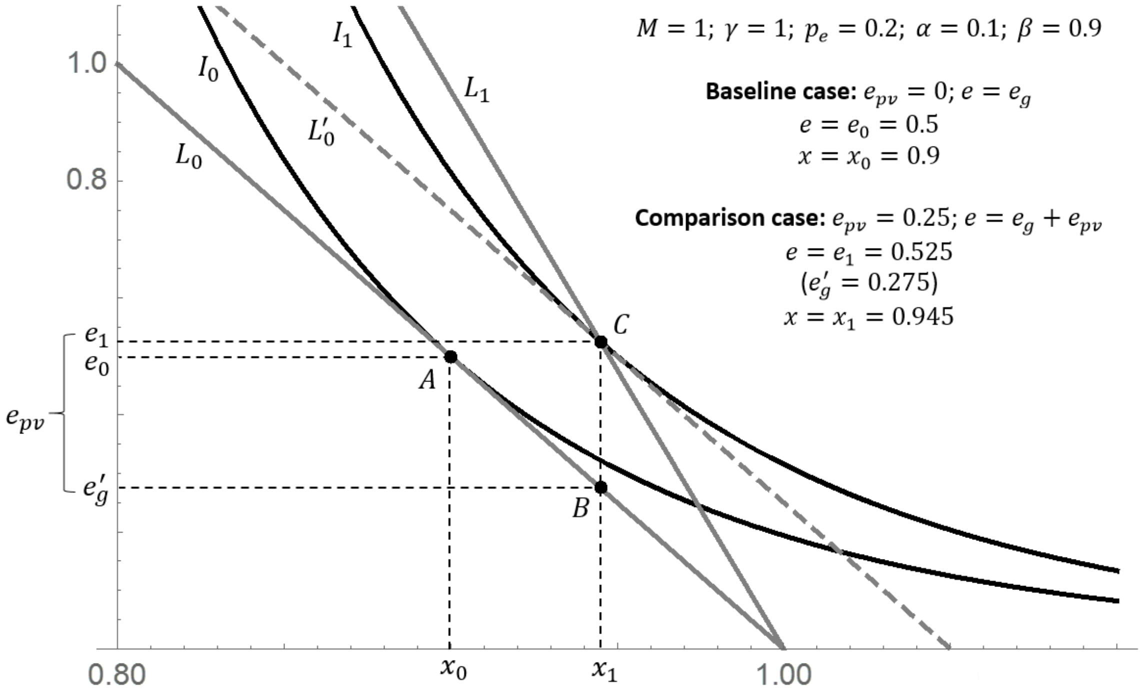

Figure 1. Indifference map depiction of the solar rebound.

We see that point B lies on the original budget line, because the price of grid electricity has not changed. However, because the cost per unit of total electricity is reduced due to the availability of e_{pv}, the *implicit* budget line is L_1. Given the new relative price of electricity, the household would prefer a consumption bundle somewhere on L_1 above and to the left of point C, as defined by a tangency point with a higher indifference curve. Any such point would be infeasible given the household's true budget constraint, because e_{pv} is fixed at 0.25. Point C, while not a tangency point between the implicit budget L_1 and curve I_1, represents the highest utility the household can achieve while remaining on its true budget line, L_0.

Now consider the intuition that becomes apparent by shifting the true budget line, L_0, outward until it is tangent to the higher indifference curve, I_1. This is illustrated as the dashed gray line, L_0'. We find that the point of tangency between L_0' and I_1 is precisely point C. The fundamental implication is that *the availability of* e_{pv} *is economically equivalent to an increase in household income*; the solar rebound is essentially a pure income effect.

It therefore *must be* the case that $\Theta_\Delta = \alpha$. We can confirm this by computing the solar rebound resulting from the discrete change in PV generation from $e_{pv} = 0$ to $e_{pv} = 0.25$. With no PV, grid electricity consumption is 0.5. When $e_{pv} = 0.25$, grid electricity consumption falls to 0.275. Thus, the solar rebound is $\Theta_\Delta = \frac{-0.225}{0.25} + 1 = 0.1 = \alpha$; the introduction of $e_{pv} = 0.25$ resulted in an increase in total electricity consumption equal to 10 percent of the PV system's output, which is precisely equal to the income share spent on electricity when $e_{pv} = 0$.[7] It is straightforward to show that the solar rebound is always equal to α for all combinations of e_g and e_{pv} that satisfy the grid electricity demand function, (12).

So far we have made two rather strong assumptions regarding the subsidies available to the household—that the fixed cost of system installation is fully recoverable via the rebate and that no net-metering system is in place. It is far more realistic to assume that only a portion of the full fixed cost would be recoverable via rebates. Many retail markets—both in the U.S. and elsewhere—offer net metering schemes. How might these policies affect the rebound?

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[7] At point C, the DRE, as calculated using (15), is $\varepsilon = 0.0476$.

3.2. Partial Rebate

Consider first the case of a partial rebate (or, equivalently, a partial investment tax credit) of the fixed cost of installation, $(1-\gamma)\bar{C}$,[8] with $0<\gamma<1$, while maintaining the assumption of no net metering. Let $\bar{M} \equiv M-(1-\gamma)\bar{C}$. It is clear that grid electricity demand under a partial rebate offer is

$$\bar{e}_g = \frac{\alpha\bar{M}}{p} - \beta e_{pv} < e_g^*. \tag{20}$$

where e_g^* is the household's grid electricity demand when $\gamma = 1$.

Structurally, the elasticity of grid electricity consumption with respect to e_{pv} is the same as in (14), but because $\bar{e}_g < e_g^*$, it follows that η is larger (in absolute value) when $\gamma<1$, implying a greater reduction in grid electricity consumption for the same marginal increase in e_{pv}. The DRE can then be expressed as

$$\bar{\varepsilon} = \frac{\alpha e_{pv}}{\bar{e}}, \tag{21}$$

where $\bar{e} = \bar{e}_g + e_{pv}$, implying—perhaps counterintuitively—that the DRE is larger when $\gamma<1$, and increases as $\gamma \to 0$.[9]

A key question regards how much of the fixed cost the rebate must cover to induce the household to adopt a PV system. We stated earlier that the rational household will adopt if $U^{PV} > U^{no\ PV}$, given $\bar{M}$. Derivation of the critical value of γ as a function of C, M, p, α, and β is difficult to the point of being uninformative. Rather, we define $c = (1-\gamma)\bar{C}/M$, which is the post-rebate fixed cost as a percentage of household income. Using the parameter values from Figure 1, we can

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[8] We are implicitly assuming the fixed installation cost is truly fixed—that is, constant and independent of system size, and thus output. This is a reasonable assumption for a marginal change in e_{pv}, but perhaps not for a large, discrete change. One might plausibly imagine installation cost as a step-wise increasing function of output.

[9] We noted earlier that when $\gamma = 1$, the DRE in our numerical example with $e_{pv} = 0.25$ is $\varepsilon = 0.0476$. Alternatively, setting $\gamma = 1/3$, by (23) and (24) we get $\bar{\varepsilon} = 0.0485$.

numerically compute the critical value of c below which the household would rationally choose to adopt a PV system. Figure 2 plots U^{PV} as a (decreasing) function of c, and $U^{no\ PV}$, which is constant with respect to c. If the fixed cost net of the rebate is less than 4 percent of household income, adoption will occur. It follows that, provided adoption occurs, the DRE will be positive and increasing as γ increases.

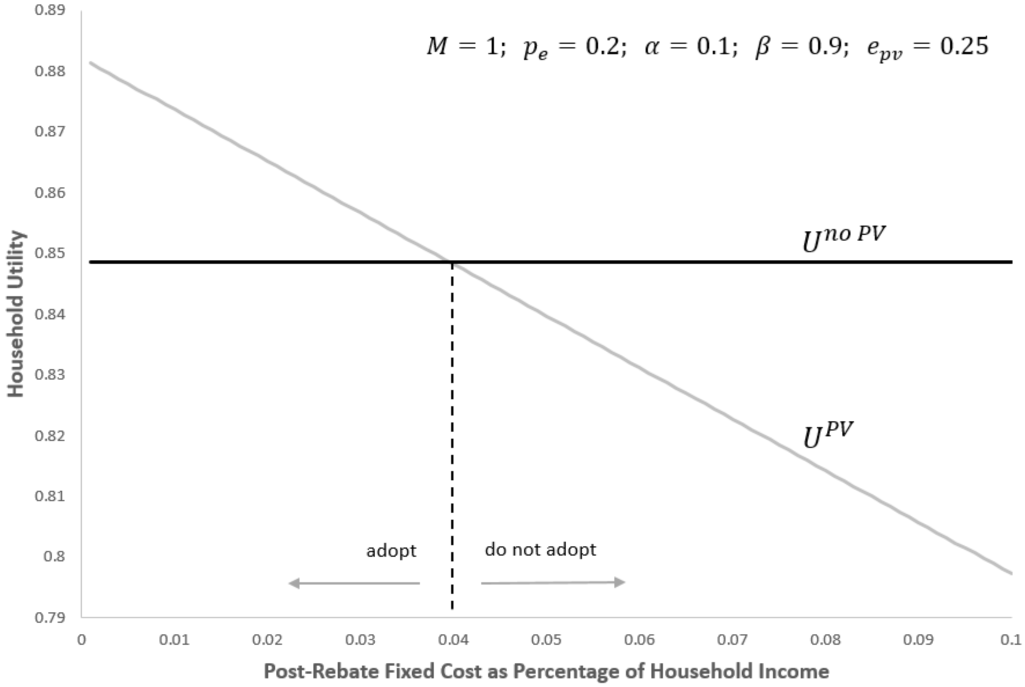

Figure 2. Partial rebate and the adoption decision (without net metering).

We now examine the *solar rebound*, Θ, under a partial rebate scheme. At the margin, the solar rebound is still precisely equal to α, irrespective of the values of $\bar{C}$ or γ. This is because $(1-\gamma)\bar{C}$

is fixed; the benefit of the marginal increase in e_{pv} is not offset by an increase in cost, and can be fully realized as an income effect on the household's utility.[10]

Returning to our numerical example, now consider the *discrete* solar rebound, Θ_Δ, resulting from the change from $e_{pv} = 0$ to $e_{pv} = 0.25$ at a net cost after rebate of $(1 - \gamma)\bar{C}$. Let us assume that $\bar{C} = 0.03$—*i.e.*, 3 percent of household income—and that 1/3 of the installation cost is recovered via rebate. We know by Figure 2 that the rational household would choose to adopt the PV system given these parameters. Upon doing so, by (19) the solar rebound would be $\Theta_\Delta = 0.06$; the increase in total electricity consumption would equal 6 percent of the output of the PV system. Moreover, an increase in γ increases the discrete solar rebound. As γ approaches full rebate, Θ_Δ approaches α (from below).

3.3. Net Metering

We now explore the implications of a net-metering program on the DRE and solar rebound. For simplicity, we return to the baseline rebate case of $\gamma = 1$, such that the household bears no fixed installation cost.

Considerable variation exists among state-level net-metering programs in the U.S., especially with respect to net-metering caps (typically expressed as a percentage of forecast peak customer demand), system size eligibility limits, monthly rollover of kWh credits, and compensation rates.[11] We abstract away from most of these complexities, assuming no cap, a non-binding system size limit, and no inter-period rollover (which at the annual level is consistent with many state policies).

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[10] One might consider this to be representative of the solar rebound resulting from increased PV output from a given system as the result of, for example, a sunnier-than-average year.

[11] For net metering program features by state, see: http://programs.dsireusa.org/system/program.

We do, however, explore the implications of retail rate versus partial retail-rate (*e.g.*, 'avoided cost') compensation.

In its most basic form—and setting aside engineering details—a net metering program is administered such that the household is billed for its total electricity consumption, but receives retail rate compensation per unit of e_{pv} generated. A key assumption is that the household does not actively choose how much e_{pv} to consume versus sell back to the grid; the retail provider simply bills the household for its total consumption net of the value of its total PV generation. These features are easily captured by a simple modification to the household budget constraint:

$$pe + x = M + pe_{pv}. \tag{22}$$

However, because $e = e_g + e_{pv}$, it is easy to see that pe_{pv} cancels out from both sides and the budget constraint is effectively identical to Eq. (3). Under the realistic assumption that total electricity consumption exceeds PV system output, $e > e_{pv}$, the household pays only for electricity consumption in excess of e_{pv}, or e_g.[12] With a Cobb-Douglas utility function, grid electricity demand is identical to (12), and the associated DRE and solar rebound are identical to (15) and (18), respectively. Note also that net metering with retail-rate compensation effectively allows the household to use the grid as a storage system, rendering on-site storage redundant.

In many cases, however, states implement 'utility buy-back' programs, which are similar to net metering but specify that the household is compensated per unit of PV output at a fraction of the retail electricity rate. This avoids the retailer effectively subsidizing the consumer's usage of the grid infrastructure as a storage system. In other words, because the retail rate of electricity includes the capital cost of the grid infrastructure, which is not inherently incurred in the

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[12] A more complex result obtains when PV output exceeds the household's total electricity consumption, as this would imply a corner solution in which grid electricity consumption is zero. In practice, such cases appear to be sufficiently rare so as to be safely ignored here.

consumption of on-site PV generation, retailers compensate the household only for the *avoided cost* of the power generation itself.

To incorporate this idea into the present modeling exercise, we assume simply that the household receives a per-unit compensation for its PV generation that is a fraction, $\phi \in (0,1)$, of the retail price of electricity. After collecting terms (22) now becomes

$$pe_g + x = M - (1 - \phi)pe_{pv}. \tag{23}$$

The household is effectively paying the retailer for the use of the grid as a storage system. After simplification, the grid electricity demand function with an avoided cost buy-back program is thus

$$\tilde{e}_g = \frac{\alpha M}{p} - [\beta + (1 - \phi)]e_{pv}. \tag{24}$$

It is clear that $\tilde{e}_g < e_g^*$, meaning the consumer's grid electricity consumption—and thus total electricity consumption, given e_{pv}—is less than it would be with full retail-rate compensation.

An interesting and perhaps counter-intuitive result, however, is that with avoided cost utility buy-back it is possible—likely, even—that the rebound is *negative*, meaning the household decreases its grid electricity consumption by more than the increase in PV output. The DRE is

$$\tilde{\varepsilon} = (\phi - \beta)\frac{e_{pv}}{\tilde{e}}, \tag{25}$$

where $\tilde{e} = \tilde{e}_g + e_{pv}$. Likewise, given $\gamma = 1$, the (discrete) solar rebound is

$$\widetilde{\Theta}_\Delta = \phi - \beta. \tag{25}$$

Note that if $\phi = 1$, corresponding to full retail rate compensation, then (25) and (26) are equivalent to (15) and (18), respectively. By contrast, both expressions are negative if $\phi < \beta$. In other words, the rebound will be negative if the fraction of the per-unit retail rate of electricity compensated via the net metering program is smaller than the share of household income spent on the numeraire, which we consider to be a highly likely scenario. The intuition underlying this result is that the marginal cost of consumption and marginal benefit of generation of e_{pv} are in this case decoupled; the household pays the full retail price per unit of consumption but receives only a fraction of that in return for PV generation. That is, in addition to paying full price for its total consumption, as in the no PV case, the household is also paying an implicit surcharge per unit of e_{pv} for effectively storing it in the grid. As a result, the household reduces its grid—and thus total—electricity consumption to compensate for this extra cost.

Our numerical example is again illustrative. Recall that with $e_{pv} = 0$, total electricity consumption was $e_0 = 0.5$. With $e_{pv} = 0.25, \gamma = 1$, and a partial retail rate net-metering program in which the compensation rate is 40 percent of the retail rate ($\phi = 0.4$), by (24) grid electricity consumption is $\tilde{e}_g = 0.125$. Total electricity consumption is therefore $\tilde{e} = 0.375$, a reduction of 0.125, or precisely one-half of e_{pv}; grid electricity consumption is reduced by 150 percent of the increase in PV generation. Likewise, given $\beta = 0.9$, by (25) we have a negative solar rebound of $\widetilde{\Theta}_\Delta = -0.5$.

3.4. Relationship to Household Income

We now explore some additional characteristics of the DRE and solar rebound, in particular their relationships to household income. For simplicity, we again return to our baseline case of full rebate ($\gamma = 1$) and no net-metering, keeping in mind below that the same intuitive results apply as before when such restrictions are relaxed.

First, although the marginal effect in (13) is independent of income, M, we can show that η depends on M. Combining (12) and (14), we get

$$\eta = -\beta e_{pv} \left[\frac{\alpha M}{p} - \beta e_{pv}\right]^{-1}. \qquad (26)$$

Clearly, given α, β, p, and e_{pv}, as M increases the absolute value of η decreases. In other words, the percentage reduction in grid electricity demand following a one-percent increase in electricity supplied from the PV system diminishes as income increases. The DRE, interestingly, is also negatively related to household income—the richer the household, the smaller the rebound. This is made clearer by substituting (12) and (2) into (15), which yields

$$\varepsilon = \alpha e_{pv}\left[\frac{\alpha M}{p} + \alpha e_{pv}\right]^{-1}. \tag{27}$$

This result follows because grid electricity is a normal good, greater income implies greater consumption of grid electricity, all else equal. Thus, the increase in total electricity consumption resulting from a marginal increase in e_{pv} is smaller *in percentage terms* the greater is e_g.

By contrast, the solar rebound is always equal to α. To the extent that α is independent of income—as is the standard Cobb-Douglass assumption—we can say that the solar rebound is as well. Empirically, however, the income share spent on electricity appears generally to be negatively related to income.[13] This is intuitive; a richer household spends a smaller share of its income on grid electricity (in the absence of a PV system). Thus, whether we look at the DRE for a given household with a constant income share spent on electricity, or the solar rebound across households with heterogeneous income shares spent on electricity, the effect is likely to be diminishing as income increases.

It remains to examine how the rebound relates to income under each subsidy policy. With $\gamma < 1$, then (with or without net metering) the higher DRE for low-income households can be offset by an increase in γ, but this is deceptive. Because higher γ implies more net income to spend on grid electricity, total electricity consumption is higher, so the elasticity (*i.e.*, ratio of percentage

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[13] See, for example, Toroghi and Oliver (2019), who find such a result using data for the Atlanta region.

changes) with respect to a marginal increase in PV output is lower. This is where the distinction of the solar rebound becomes especially informative. When we look at the solar rebound, increasing or decreasing γ has no effect at the margin; the increase in grid electricity is always the same percentage of the increase in PV output.

Moreover, when considering the inducement of adoption, an increase in γ *increases* the discrete solar rebound. In other words, if the policy maker sets γ higher for low-income households as a way to incentivize adoption, this yields a smaller "bang for the buck" (in terms of reducing grid electricity consumption) as would be achieved by offering the same incentive to a richer household. Preferential treatment of richer households, however, is not likely to be politically popular. One potential solution is to augment the rebate subsidy to low-income households with some additional incentive to reduce total electricity consumption if they are to receive the rebate. One obvious way to do this (since most markets have net metering) might be to require that the greater the rebate a household receives upon installation, the lower the compensation level it receives via net-metering. Combining Equations (19) and (25), it is straightforward to show that with both a partial rebate scheme and partial retail rate net metering, the discrete solar rebound is

$$\Theta_{\Delta} = (\phi - \beta)\left[1 - \frac{(1-\gamma)\bar{C}}{pe_{pv}}\right]. \tag{28}$$

If the net metering policy is such that ϕ, the fraction of the retail rate at which the household is compensated per unit of PV generation, is equal to β, the share of its income spent on electricity in the absence of a PV system, the rebound would be zero regardless of either income level or the level of the rebate.

4. Further Discussion

The above modeling exercise provides a point of departure for thinking about the basic microeconomics of the rebound effect for residential PV systems, but has several limitations (aside from those already noted) that bear further exploration in future research.

The first is that our model does not account for the intertemporal variation of electricity production and consumption. Over a billing cycle, e_g and e_{pv} are, in reality, imperfect substitutes unless storage is available or net-metering serves as a proxy for storage. The assumption that all electricity produced by the panels offsets grid consumption, even without storage, in the base model would require perfectly shiftable loads. In reality, electricity consumption is temporally dependent with a significant share occurring in the morning and evening hours when panels are not producing electricity. As a result, without storage or net-metering the rebound is likely to be even larger than modeled in the baseline case. That said, the baseline model result can be thought of as a lower bound for the rebound in the absence of net-metering and provides a reference point for the scale of the effect with which to compare results from empirical studies.

Accounting for behavioral drivers of electricity consumption patterns may also generate alternative hypotheses about the magnitude and direction of the solar rebound effect. Ours is a static model of the idealized normative behavior of a perfectly rational household decision maker. Economists are increasingly aware, however, that in many complex decision environments, consumers display bounded rationality, in that they are unable to process all the information needed to make rational choices (Simon 1955). Electricity prices are not always salient to the average consumer (Jessoe and Rapson 2012; Gilbert and Graff Zivin 2014), such that consumers may be more responsive to non-price signals and framing (Delmas et al. 2013; Asensio and Delmas 2016). Evidence has shown that electricity demand is much more sensitive to average price than to marginal price. Customers tend to react to the total amount on their monthly bill, where lagged average price is a stronger predictor of current electricity consumption than current prices (Ito 2014). Thus, although any income adjustment from net-metered solar is likely to be small compared to total income, it represents a significant percentage of a household's monthly electricity bill. Consumers may react to dramatically lower net energy expenditures by increasing electricity consumption in excess of rational economic predictions.

Other behavioral economic concepts may also help explain empirically observed rebound effects. First, evidence suggests that individuals regularly violate the economic principle of fungibility and instead engage in *mental accounting*, assigning different expenditures to specific categories (*e.g.*, utilities) when determining budgets (Thaler 1999). If households practice mental accounting they may be more likely to spend energy expenditure savings in the from which category they originated (Antonides et al. 2011). This may lead to a larger solar rebound following electricity bill savings than would be predicted by the neoclassical model. Second, households have demonstrated a tendency to evaluate information about their current bills by revisiting previous bills (Buchanan et al. 2015). That is, prior billing amounts may serve as an *anchor* (Tversky and Kahneman 1974), priming consumers to previous expenditures and causing an adjustment in consumption levels to align with previous information provision and expectations. That the new bills represent net as opposed to total electricity consumption may drive up total electricity consumption and lead to a solar rebound.

The psychology literature offers additional justification for a rebound. *Moral licensing* is an effect in which engaging in a good deed can liberate individuals to engage in behaviors that are immoral, anti-social welfare, or otherwise problematic which they would ordinarily avoid (Merritt et al. 2010). Evidence of moral licensing has been found across a wide variety of domains, including having been used as an explanation for the rebound effect in energy consumption (Dütschke et al. 2018). The decision to install solar panels may give consumers the perception that they can use more electricity since they have completed a good deed and are generating green electricity (Peters and Dütschke 2016). Importantly, moral licensing can be prospective. The anticipation of engagement in moral behavior has been shown to negatively influence current behavior (Cascio and Plant 2015). If moral licensing is a driver of the rebound effect we might see evidence of increased consumption between when the consumer makes the decision to install (the application date) and the panels starting to generate electricity (the installation date).

By contrast, the change of an energy product or service constitutes an intervention that interrupts previous routines, potentially leading to behavioral change in how the relevant product or service is used. This has led to the development of a 'double dividend' argument for distributed generation. Adopters not only generate energy, but may also engage in conservation (Truelove et al 2014) or 'sufficiency' behavior (Seidl et al 2017), reducing consumption upon installation. Adoption of PV may increase the salience of environmental impacts of energy use (Kierstad 2007). The visible presence of solar panels may remind or encourage people to make other green choices, serving as a 'green cue' for consumers to form habits or make capital stock changes that cause persistent effects (Allcott and Rogers 2014). Moreover, PV installation is routinely accompanied by an in-home display or mobile application for tracking PV output. The use of in home displays has been shown to extend conservation behaviors through habit formation and learning (Jessoe and Rapson 2012). Hondo and Baba (2010) test this hypothesis by measuring household awareness of solar installations and the effects of awareness. Households who more frequently engaged in "PV-checking behavior"—*e.g.*, examination of the panels themselves and checking their output—were more likely to increase pro-environmental behavior post-installation.

There may also be a financial justification for reducing electricity consumption post-installation. Rai and McAndrews (2012) find that customers consider their electricity price and usage in determining whether distributed generation is a sound financial investment. They report results of a survey of PV adopters in Texas. 87% of the respondents used a payback period approach to calculate the financial attractiveness of a PV system. Consumers under a net metering scheme discover that the payback period for their panels shrinks if they use less electricity. Rai and McAndrews note, “Over 70% of the sample reports that their awareness regarding their electricity use (amount used, bill paid, and purpose of use) is ‘higher or much higher’ as a result of installing solar.” Any such behaviors are likely to impact empirically observed rebound effects resulting from the adoption of residential solar PV.

5. Conclusion

This paper has formulated the neoclassical microeconomic foundations of the rebound effect associated with residential solar photovoltaic (PV) systems, in the spirit of Chan and Gillingham (2015). The solar rebound is fundamentally different from rebound effects traditionally studied in the literature, in that it arises not from an improvement in consumptive energy efficiency, but from the availability of a zero-marginal-cost supply of power to the household. We show using our model that the solar rebound works through a pure income effect channel. Our second goal with this modeling exercise has been to analyze the effects of two popular subsidization instruments—installation cost rebates and net metering—on the magnitude of the rebound effect. The model thus serves as a normative baseline for energy economists and policy makers studying the impacts of distributed solar.

Governments around the world are aggressively pursuing policies to stimulate the adoption of this technology, making it a core strategy in most energy decarbonization programs. As the market for residential PV systems expands, any associated rebound effect in total electricity consumption will be an important determinant of the realized reductions in conventional, centralized—especially fossil fuel—power generation, and thus ultimately for reductions in CO_2 emissions from the electricity sector.

References

Allcott, H., & Rogers, T. (2014). The short-run and long-run effects of behavioral interventions: Experimental evidence from energy conservation. *The American Economic Review* 104, 3003-3037.

Antonides, G., De Groot, I.M., & Van Raaij, W.F. (2011). Mental budgeting and the management of household finance. *Journal of Economic Psychology* 32, 546-555.

Asensio, O.I., & Delmas, M.A. (2016). The dynamics of behavior change: Evidence from energy conservation. *Journal of Economic Behavior & Organization* 126, 196-212.

Azevedo, I.M.L. (2014). Consumer End-Use Efficiency and Rebound Effects. *Annual Review of Environment and Resources* 39, 393-418.

Barker, T., Eakins, P., & Foxon, T. (2009). The macro-economic rebound effect and the UK economy. *Energy Policy* 35, 4935-4946.

Bentzen, J. (2004). Estimating the Rebound Effect in US manufacturing energy consumption. *Energy Economics* 26, 123-134.

Beppler, R.C. (2019). *The Effects of Distributed Solar on Utilities and their Customers*. Doctoral Dissertation.

Berkhout, P.H.G., Muskens, J.C., & Velthuijsen, J.W. (2000). Defining the rebound effect. *Energy Policy* 28, 425-432.

Binswanger, M. (2001). Technological Progress and sustainable development: what about the rebound effect? *Ecological Economics* 36, 119-132.

Borenstein, S. (2015). A Microeconomic Framework for Evaluating Energy Efficiency Rebound and Some Implications. *The Energy Journal* 36, 1-21.

Brännlund, R., Ghalwash, T., & Nordström, J. (2007). Increased energy efficiency and the rebound effect: Effects on consumption and emissions. *Energy Economics* 29, 1-17.

Brookes, L.G. (1978). Energy policy, the energy price fallacy and the role of nuclear energy in the UK. *Energy Policy* 6, 94-106.

Buchanan, K., Russo, R., & Anderson, B., (2015). The question of energy reduction: The problem(s) with feedback. *Energy Policy* 77, 89-96.

Cascio, J. & Plant, E.A. (2015). Prospective moral licensing: Does anticipating doing good later allow you to be bad now? *Journal of Experimental Social Psychology* 56, 110-116.

Chan, N.W., & Gillingham, K. (2015). The Microeconomic Theory of the Rebound Effect and Its Welfare Implications. *Journal of the Association of Environmental and Resource Economists* 2, 133-159.

Delmas, M.A., Fischlein, M., & Asensio, O.I. (2013). Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975-2012. *Energy Policy* 61, 729-739.

Deng, G., & Newton, P. (2017). Assessing the impact of solar PV on domestic electricity consumption: Exploring the prospect of rebound effects. *Energy Policy* 110, 313-324.

Dimitropoulos, J. (2007). Energy productivity improvements and the rebound effect: An overview of the state of knowledge. Energy Policy 35, 6354-6363.

Druckman, A., Chitnis, M., Sorrell, S., & Jackson, T. (2011). Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy* 39, 3572-3581.

Dütschke, E., Frondel, M., Schleich, J., & Vance, C. (2018). Moral licensing: Another source of Rebound? *Frontiers in Energy Research* 6, 38.

Gilbert, B. & Graff Zivin, J. (2014). Dynamic salience with intermittent billing: Evidence from smart electricity meters. *Journal of Economic Behavior & Organization* 107, 176-190.

Gillingham, K., Rapson, D., & Wagner, G. (2016). The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy* 10, 68-88.

Greene, D.L., Kahn, J.R., & Gibson, R.C. (1999). Fuel Economy Rebound Effect for U.S. Household Vehicles. *The Energy Journal* 20, 1-31.

Guerra Santin, O. (2013). Occupant behaviour in energy efficient dwellings: Evidence of a rebound effect. *Journal of Housing and the Built Environment* 28, 311-327.

Haas, R., & Biermayr, P. (2000). The rebound effect for space heating: Empirical evidence from Austria. *Energy Policy* 28, 403-410.

Havas, L., Ballweg, J., Penna, C., & Race, D. (2015). Power to change: Analysis of household participation in a renewable energy and energy efficiency programme in Central Australia. *Energy Policy* 87, 325-333.

Hondo, H., & Baba, K. (2010). Socio-psychological impacts of the introduction of energy technologies: Change in environmental behavior of households with photovoltaic systems. *Applied Energy* 87, 229-235.

Ito, K. (2014). Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing. *The American Economic Review* 104, 537-563.

Jessoe, K., & Rapson, D. (2014). Knowledge is (less) power: Experimental evidence from residential energy use. *The American Economic Review* 104, 1417-1438.

Jevons, W. S. (1865). *The coal question; an enquiry concerning the progress of the Nation, and the probable exhaustion of our coal-mines.* 2d ed. London: Macmillan.

Jin, S.H. (2007). The effectiveness of energy efficiency improvement in a developing country: Rebound effect of residential energy use in South Korea. *Energy Policy* 35, 5622-5629.

Khazoom, J.D. (1980). Economic implications of mandated efficiency in standards for household appliances. *The Energy Journal* 1, 21-40.

Kierstad, J. (2007). Behavioural responses to photovoltaic systems in the UK domestic sector. *Energy Policy* 35, 4128-4141.

Lin, B.,& Liu, H. (2015). A study on the energy rebound effect of China's residential building energy efficiency. *Energy & Buildings* 86, 608-618.

Linn, J. (2013). The Rebound Effect for Passenger Vehicles. *The Energy Journal* 37, 257-288.

Matos, F.J.F., & Silva, F.J.F. (2011). The rebound effect on road freight transport: Empirical evidence from Portugal. *Energy Policy* 39, 2833-2841.

Merritt, A.C., Effron, D.A., & Monin, B. (2010). Moral self-licensing: When being good frees us to be bad. *Social and Personality Psychology Compass* 4, 344-357.

Nässén, J., & Holmberg, J. (2009). Quantifying the rebound effects of energy efficiency improvements and energy conserving behaviour in Sweden. *Energy Efficiency* 2, 221-231.

Ouyang, J., Long, E., & Hokao, K. (2010). Rebound effect in Chinese household energy efficiency and solution for mitigating it. *Energy* 35, 5269-5276.

Peters, A., & Dütschke, E. (2016). Exploring rebound effects from a psychological perspective. *Rethinking Climate and Energy Policies,* 89-105. Springer, Cham.

Rai, V., & McAndrews, K. (2012). Decision-making and behavior change in residential adopters of solar PV. In *Proceedings of the World Renewable Energy Forum* (May 2012).

Saunders, H.D. (2013). Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. *Technological Forecasting & Social Change* 80, 1317-1330.

Seidl, R., Moser, C., & Blumer, Y. (2017). Navigating behavioral energy sufficiency: Results from a survey in Swiss cities on potential behavior change. *PloS one* 12, e0185963.

Simon, H.A. (1955). A behavioral model of rational choice. *The Quarterly Journal of Economics* 69, 99-118.

Sorrell, S., & Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics* 65, 636-649.

Sorrell, S., Dimitropoulos, J., & Somerville, M. (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy* 37, 1356-1371.

Spiller, E., Sopher, P., Martin, N., Mirzatuny, M., & Zhang, X. (2017). The environmental impacts of green technologies in TX. *Energy Economics* 68, 199-214.

Thaler, R. (1999). Mental accounting matters. *Journal of Behavioral Decision Making* 12, 183-206.

Thomas, B. & Azevedo, I.L. (2013). Estimating direct and indirect rebound effects for U.S. households with input-output analysis. Part 1: Theoretical framework. *Ecological Economics* 86, 199-210.

Toroghi, S.H., & Oliver, M.E. (2019). Framework for estimation of the direct rebound effect for residential photovoltaic systems. Working paper.

Truelove, H.B., Carrico, A.R., Weber, E.U., Raimi, K.T., & Vandenbergh, M.P. (2014). Positive and negative spillover of pro-environmental behavior: An integrative review and theoretical framework. *Global Environmental Change* 29, 127-138.

Tversky, A., & Kahneman, D., (1974). Judgment under uncertainty: Heuristics and biases. *Science* 185, 1124-1131.

Wang, Z., & Lu, M. (2014). An empirical study of direct rebound effect for road freight transport in China. *Applied Energy* 133, 274-281.

Wang, Z., Zhou, D.Q., Zhou, P., & Zha, D.L. (2012). Direct rebound effect for passenger transport: Empirical evidence from Hong Kong. *Applied Energy* 92, 162-167.

Winebrake, J.J., Green, E.H., Comer, B., Corbett, J.J., & Froman, S. (2012). Estimating the direct rebound effect for on-road freight transportation. *Energy Policy* 48, 252-259.

Yu, X., Moreno-Cruz, J., & Crittenden, J.C. (2015). Regional energy rebound effect: The impact of economy-wide and sector level energy efficiency improvement in Georgia, USA. *Energy Policy* 87, 250-259.