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Is rebound effect 'a cost' or 'a benefit'? Evidence from China's urban households

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ABSTRACT

Rebound effect is recognized as a loss ratio of energy savings or environmental emission reductions. But, this research suggests a positive side of rebound effect to consumers – welfare effect. We define the welfare effect using a dual form to rebound effect, explain its mechanism in the same economic framework with rebound effect, and give its estimation formula using Taylor expansion. Four consumer types are classified according to the sizes of rebound effect and welfare effect, and the determinants of the classification are discussed. We then conduct empirical research on both rebound effect and welfare effect for urban residents in China. We find backfire and large welfare effect, revealing that the urban residents in China are likely to remain 'the insufficient in demand' for a long period. Besides, rebound effect tends to decline and welfare effect to increase when energy efficiency measures are enhanced.

Keywords: Rebound effect, welfare effect, loss ratio of emission reduction, gain ratio of welfare benefits, LA-AIDS, EEIO-LCA

INTRODUCTION

Energy efficiency improvement policy is generally considered as an effective measure for reducing energy consumption and controlling environmental pollution, while the policy is likely to be partially or completely ineffective as a result of rebound effect (RE). Research shows that on one hand, the expected target of energy conservation or emission reduction might not be fully achieved because of the RE (Sorrell, 2007). But on the other hand, it may bring gains in welfare benefits by optimizing consumption portfolio (basket) with lower price and higher real income. In other words, the existence of residential RE would impede energy conservation and emission reduction, and affect residential welfare simultaneously (Borenstein, 2013; Chan and Gillingham, 2015). Thus, it would be interesting to consider both RE and the welfare effect (WE), yet studies seldom do so. The goals of this research are twofold. First, to provide the definition of WE, its mechanism, estimation methodology, and enlightenment for consumer-type classification. Second, to conduct empirical research of RE and WE for China's urban residents.

1. BASIC THEORY

1.1 Rebound effect

When the energy efficiency measures have been implemented, the cost of energy service falls with it, which often makes people tend to consume more energy services and other consumer commodities than before. Generally, the RE is expressed as a proportion of the lost energy savings to potential (or expected) energy savings, where the lost energy savings refer to the difference between actual energy savings and those initially expected from engineering calculations (Khazzoom, 1980; Musters, 1995; Haas and Biermayr, 2000; Wang et al., 2019a). Thus, the loss ratio of energy savings (or environmental emission reduction) is the RE in a general form. For environmental emission reduction (e.g., CO_2, SO_2, NO_X, Soot and dust), RE can be specified as Eq. 1.

$$rebound\ effect = \frac{lost\ emission\ reduction}{potential\ emission\ reduction} = \frac{potential\ emission\ reduction - actual\ emission\ reduction}{potential\ emission\ reduction} \quad (1)$$

The mechanism of RE for *n*-commodities is illustrated with a 'four-in-one' graph in the consumer demand framework by Wang et al. (2019a). As shown in Fig. 1, holding disposal income y and price of the *i*th commodity $P_{X_i}^0$ constant *(i*=1,…,*n*-1), the optimal consumption portfolio under the maximum utility would change from $M_0(S_0, X_{i,0})$ to $M_1(S_1, X_{i,1})$ when energy service price P_S^0 reduces to P_S^1 (equally, energy efficiency is improved from ε_0 to ε_1)[1]. The price effect in absolute form is represented by the energy demand change from S_0 to S_1 (or own-price effect), and the *i*th commodity demand change from $X_{i,0}$ to $X_{i,1}$ (or cross-price effect). The uncompensated demand for each commodity with respect to energy service price can be obtained if all possible levels of P_S^1 are considered.

While for its dual problem, expenditure minimization, which holds original utility U^0 and price vector of other commodities $\mathbf{P}_\mathbf{X}^0$ constant, optimal consumption portfolio would move from $M_0(S_0, X_{i,0})$ to $M^*(S_1^c, X_{i,1}^c)$ when energy service price falls to P_S^1. Also, the compensated price demand for each commodity with respect to energy service price can be obtained accordingly.

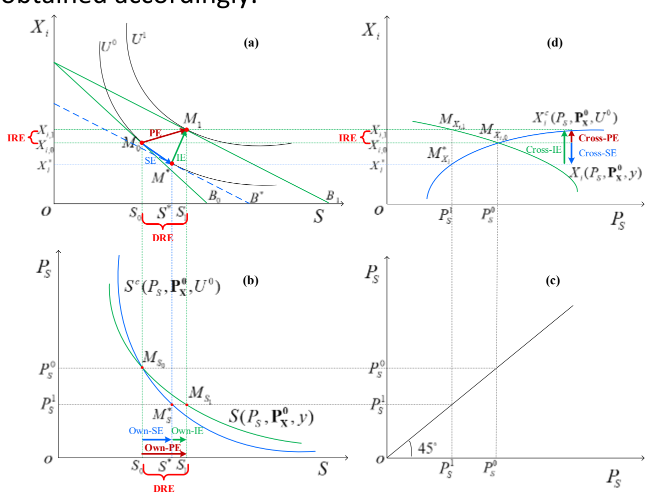

Fig. 1. (a) Price effect and RE; (b) Own-price effect and DRE; (c) Conversion graph; (d) Cross-price effect and IRE
Reference: Wang et al. (2019a)

Generally, RE can be decomposed into direct RE (DRE) and indirect RE (IRE), where the DRE relates with the demand change of energy service because of the own-price effect, while IRE relates with the demand change of other commodities because of the cross-price effect.

Let $EE_S(\,)$ and $EE_S^{'}(\,)$ indicate the environmental emission functions of energy service demand before and after energy efficiency improvement, respectively, the RE can be expressed as Eq. 2.

$$RE = DRE + IRE = \frac{\textit{lost emission reduction}}{\textit{potential emission reduction}} = \frac{\left(EE_S^{'}(S_1) - EE_S^{'}(S_0)\right) + \sum_{i=1}^{n-1}\left(EE_{X_i}(X_{i,1}) - EE_{X_i}(X_{i,0})\right)}{EE_S(S_0) - EE_{S'}(S_0)} \tag{2}$$

1.2 Welfare effect corresponding to RE

When RE happens, it may bring gains in welfare benefits by optimizing consumption basket with lower price and higher real income after energy efficiency improvement. Intuitively, we consider the expenditure saved in the efficiency case compared with the basic case as the potential (or expected) welfare benefits, and consider the change of welfare benefits after the energy efficiency improvement as actual welfare benefits. Thus analogously, we formulate the WE corresponding to RE as a proportion of the gained welfare benefits to potential welfare benefits, where the gained welfare benefits denote the difference between potential welfare benefits and those actually calculated taking into account the re-spending effect. This gain ratio of welfare benefits is taken as an indicator to estimate the WE corresponding to RE (see Eq. 3).

$$\textit{welfare effect} = \frac{\textit{gained welfare benefits}}{\textit{potential welfare benefits}} = \frac{\textit{actual welfare benefits} - \textit{potential welfare benefits}}{\textit{potential welfare benefits}} \tag{3}$$

To denote WE, Marshallian consumer surplus change (CS; Marshall, 1920) and Hicksian compensating variation (CV; Hicks, 1942.) are employed as welfare measures[2]. Based on the 'four-in-one' graph of Fig. 1, CS and CV for each commodity are illustrated in Fig. 2. For energy service consumption itself, CS and CV are the geometric areas $P_S^0 M_{S_0} M_{S_1} P_S^1$ (blue and green area) and $P_S^0 M_{S_0} M_S^* P_S^1$ (blue only), respectively. Besides, for the consumption of the *i*th commodity, CS and CV are the geometric areas $P_S^0 M_{X_{i,0}} M_{X_{i,1}} P_S^1$ and $P_S^0 M_{X_{i,0}} M_{X_i}^* P_S^1$, respectively. However, when only energy service price changes, we develop the WE corresponding to RE measurement using CV, as a unique measure of CS relies

[1] To distinguish own- and cross-price demand, the *i*th commodity in this paper represents the *i*th other commodity other than energy service (or energy).

[2] Marshallian consumer surplus is measured by the area under an uncompensated demand curve, while the Hicksian consumer surplus by the area under a compensated demand curve.

on restrictive consumptions about the constancy of marginal utility of income (Hassan, 1995).

The CV measures the reduction in income needed to restore him to the original utility level after a price decrease. When energy service price decreases, it can be written in terms of expenditure function from the dual problem mentioned in section 1 and Wang et al. (2019a).

$$CV(P_S^0 \to P_S^1) = e(P_S^1, \mathbf{P_X^0}, U^0) - e(P_S^0, \mathbf{P_X^0}, U^0) \quad (4)$$

where $CV(P_S^0 \to P_S^1)$ denotes the compensation variation, representing the amount of money an individual hypothetically gives up to remain at the indifference curve U^0.

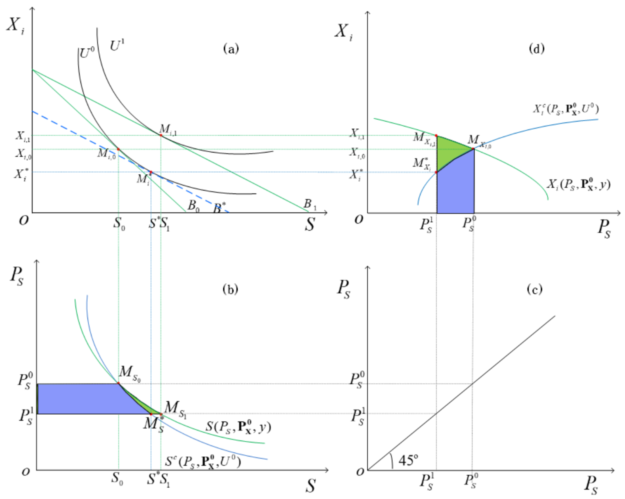

Fig. 2. Welfare benefits corresponding to the rebound effect

For finite changes of the energy service price, CV is derived to be the definite integral of the own- and cross-compensation demand function with respect to P_S from P_S^0 to P_S^1.

$$CV(P_S^0 \to P_S^1) = \int_{P_S^1}^{P_S^0} S^c(P_S, \mathbf{P_X^0}, U^0)dP_S + \sum_{i=1}^{n-1}\int_{P_S^1}^{P_S^0} X_i^c(P_S, \mathbf{P_X^0}, U^0)dP_S \quad (5)$$

Then, the WE can be decomposed into direct WE (DWE) and indirect WE (IWE) similarly, and expressed as Eq. 4[3].

$$WE = DWE + IWE = \frac{CV(P_S^0 \to P_S^1) - \tau y_S^0}{\tau y_S^0} \quad (6)$$

where $\tau = (P_S^0 - P_S^1)/P_S^0$ ($\tau > 0$) indicates the percentage of energy service price decline.

1.3 Four distinct consumer types

As mentioned above, we know that the larger the RE, the higher the loss ratio of lost environmental emission reduction; while the larger the WE, the greater the proportion of the gained welfare benefit. In Fig.3, the horizontal axis of this coordinate system is the RE and the vertical axis represents the WE. And if we make a simple distinction between 'small' and 'large' RE, as well as WE, and consider the lower and higher segments of each axis, four distinct scenarios emerge that correspond to the four distinct consumer types: Type I, 'the insufficient in demand' with large RE and large WE; Type II, 'the economical and environmentally friendly' with small RE and large WE; Type III, 'the satisfied' with small RE and small WE; Type IV, 'the low efficiency in consumption' with large RE and small WE. These might imply more benefit than the cost for consumers of Type II, on the contrary, more cost than benefit for Type IV.

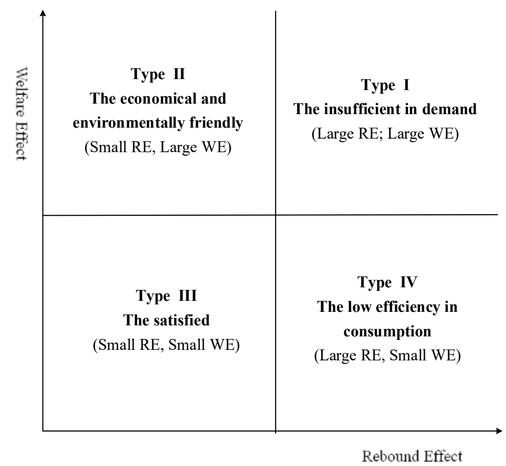

Fig. 3. Four distinct consumer types

2. METHODOLOGY

2.1 Hybrid methodology for RE estimation

The hybrid methodology, which integrates the econometric model, re-spending framework and environmentally-extended input–output analysis, is employed to estimate RE (Thomas and Azevedo, 2013; Chitnis and Sorrell, 2015; Wang et al. 2019a). In simplicity, we assume all the disposable income is spent. Following Wang et al. (2019a), the final formula to estimate RE is obtained as follows.

$$RE = DRE + IRE = -(1-\tau)\eta_{P_S}(S) - \sum_{i=1}^{n-1} \frac{F_{X_i}^{cum}}{F_S^{cum}} \frac{w_{X_i}^0}{w_S^0} \eta_{P_S}(X_i) \quad (7)$$

where $\eta_{P_S}(S)$ and $\eta_{P_S}(X_i)$ denote uncompensated own- and cross-price elasticities with respect to energy service price, respectively. F_S^{cum} and $F_{X_i}^{cum}$ denote the cumulative environmental emission intensity of energy and the *i*th commodity, respectively. And both of the demand elasticity and emission intensity parameters above are to be estimated.

[3] Since CV is of the most popular welfare effect indicator, we use CV to represent the welfare effect corresponding to RE.

2.1.1 LA-AIDS method for estimation of demand elasticity parameters

For the parameters of own and cross-price elasticities of energy demand, they can be investigated using the almost ideal demand system (AIDS; Deaton and Muellbauer, 1980). AIDS is recognized to be one of the most popular methods for doing demand analysis. And the linearized approximation of the almost ideal demand system (LA-AIDS) is adopted (see Eq. 8).

$$w_t^{(k)} = \alpha^{(k)} + \sum_{l=1}^{n} \gamma^{(k)(l)} \ln P_t^{(l)} + \beta^{(k)} \ln\left(x_t / P_t\right) + \lambda^{(k)} w_{t-1}^{(k)} + u_t^{(k)} \quad (8)$$

$$u_t^{(k)} \sim N(0,\Sigma),\ k,l = 1,\ldots,n$$

where for observation t, $w_t^{(k)}$ and $w_{t\text{-}1}^{(k)}$ represent the budget share and the budget share lagged one period of the kth commodity, respectively. $P_t^{(l)}$ represents the consumer price index of the l th commodity. x_t represents the total nominal expenditure. P_t represents the Stone's price index defined by $\ln P_t = \sum_{k=1}^{n} w_t^{(k)} \ln P_t^{(k)}$. In order to estimate Eq. 8, 'adding-up' ($\sum_{k=1}^{n} \alpha^{(k)} = 1;\ \sum_{k=1}^{n} \beta^{(k)} = 0;\ \sum_{l=1}^{n} \lambda^{(k)}=0;\ \sum_{k=1}^{n} \gamma^{(k)(l)} = 0,\ \forall l$), 'homogeneity' ($\sum_{l=1}^{m} \gamma^{(k)(l)} = 0,\ \forall k$) and 'symmetry' ($\gamma^{(k)(l)}=\gamma^{(l)(k)},\ \forall k,l$) constraints are imposed.

2.1.2 EEIO-LCA method for estimation of emission intensity parameters

For the parameters of cumulative environmental emission intensity of each final demand item, they can be obtained using the Environmentally-extended Input-Output Life Cycle Assessment (EEIO-LCA) method (Hendrickson et al., 2006; Lenzen et al., 2004, 2006; Wang et al., 2019b). This intensity contains two parts, the embodied and the direct environmental emission for every unit of currency spent on final demand. Following Wang et al. (2019b), Let character code v is used to represent different environmental emissions, i. e., $v = CO_2, SO_2, NO_X, SD$ denotes CO_2, SO_2, NO_X, and Soot and dust emissions, respectively. According to the EEIO-LCA model, the cumulative for the vth emission is written as Eq. 9 (Wang et al., 2019b).

$$\mathbf{F}_v^{cum} = \mathbf{D}_v \hat{\mathbf{q}}^{-1} (\mathbf{I} - \mathbf{A})^{-1} + \mathbf{F}_v^{hh} \quad (9)$$

where $\mathbf{D}_v$ is a vector ($1 \times m$) of environmental load discharged directly in each industry sector. $\hat{\mathbf{q}}$ is a diagonal matrix representing the total output of industry sectors. $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse matrix or the total requirements matrix. $\mathbf{F}_v^{hh}$ represents direct environmental emission of a monetary unit expenditure on final demand, and its elements $\mathbf{F}_{v\_j}^{hh}$ is specified as

$$\mathbf{F}_{v\_j}^{hh} = \begin{cases} \pi_v^{hh} / Y_j^{hh} & j = 2 \\ 0 & j \neq 2 \end{cases} \quad (10)$$

where π^{hh} denotes the direct environmental emission of the urban household sector. Y_j^{hh} represents the urban household consumption on energy in integrated input-output table of the j th industry sector (j=1,…,m), where m denotes the number of industrial (or product) categories. In this paper, m=6 and j=1,2,3,4,5,6 represents the category of 'food', 'energy', 'housing, appliances, and consumables', 'transportation and communication', 'others' and 'approximately non-consumer product', respectively[4].

2.2 Taylor expansion method for WE estimation

Taylor expansion is used to approximate CV by existing research (Hicks, 1942; Deaton and Muellbauer, 1980; LaFrance, 1991; Irvine and Simis, 1998; Friedman and Levinsohn, 2002). Based on the second-order Taylor expansion of CV, WE that is represented by Eq. (6) could be estimated through algebra changes (Wang, 2018)[5].

$$WE_{CV} = -\frac{\tau}{2} \eta_{P_S}^{c}(S) \quad (11)$$

where $\eta_{P_S}^{c}(S)$ denotes compensated own-price elasticity with respect to energy service price.

In comparison with the integral form of CV (see Eq. 5), one can see that the CV which relates to cross-price demand has been overlooked by Taylor expression approximation. Thus, the indirect WE is not estimated in this paper.

2.3 Determinants of rebound effect and welfare effect

The percentage of energy service price decline (or the proportion of improvement in energy efficiency ζ)[6], τ , plays an important role both in estimation equations for RE and WE (See Eqs. 7 and 11). Eq. 7 denotes that IRE is related to three factors: uncompensated cross-price

[4] According to Lenzen et al. (2004 and 2006), Y_j^{hh} represents the currency spent on commodity j during the reference year. But Wang (2018) and Wang et al. (2019b) inappropriately used the total urban household consumption instead.

[5] Taylar expansion for CV measure is not used in the right way by Wang (2018), but the algebra changes for WE estimation are worth learning.

[6] According to Thomas and Azevedo (2013), the percentage change in the price of energy service $\tau = \zeta / (1 + \zeta)$, where ζ represents the proportion of improvement in energy efficiency ($\zeta = (\varepsilon_1 - \varepsilon_0) / \varepsilon_0$).

elasticity of demands for each commodity $\eta_{P_S}(X_i)$, the relative size of cumulative emission intensity of expenditure on each commodity with respect to energy service $F_{X_i}^{cum} / F_S^{cum}$, and the relative size of the budget share of each commodity with respect to energy service $w_{X_i}^0 / w_S^0$. In general, however, cross-price elasticity of other commodities often shows less elastic than the own-price elasticity of energy service; the relative size of cumulative emission intensity is also small, since the energy industry is of high emission-intensive, and direct environmental emission of household is considered for the energy sector as well. As a result, whereas the relative size of budget share might be bigger than one, the IRE as a whole would contribute to RE relatively less than DRE.

Then, given a certain value of τ (e.g., τ =5%, 10%, 20%, 30%, 50%, and 70%), the sizes of DRE and WE will depend on the uncompensated ($\eta_{P_S}(S)$) and compensated ($\eta_{P_S}^c(S)$) own-price elasticities of energy service demand respectively[7]. The more the price elastic of energy service demand, the more that DRE and WE are likely to be large. This could be attributed to the high own-price elasticity, which indicates that energy service demand is not yet met. Thus, individuals desire to consume more when energy service efficiency is improved.

And on the other hand, given the own-price elasticity of energy service demand, the higher the energy service efficiency raised, the smaller the DRE, but the larger the WE. This may be due to the fact that energy in need for the same energy service activity would be significantly decreased after the efficiency improvement.

3. DATA SOURCES AND ADJUSTMENTS

The data mainly includes consumption expenditure and consumer price indices, energy consumption by industry, total Output and environmental emission by sector, and product price indices. And they are derived from the following resources: *China Statistical Yearbooks* (1996-2019); *China Yearbook of Household Survey* (2014-2019); DRCNET Statistical Database System; *China Price and Urban Household Income and Expenditure Survey Statistical Yearbooks* (1996-2005); *China Urban Life and Price Yearbooks* (2006-2012); *China Price Statistical Yearbooks* (2013-2019); Chinese Environmentally-extended Input-Output (CEEIO) Database[8].

The consumer commodities are integrated into five categories and mapped to corresponding products categories (Wang et al., 2019b). In addition, the year 2010 is chosen as the base year both for demand analysis and environmental emission intensity estimation. And the integrated CEEIO table with six sectors is adjusted to be non-competitive.

4. RESULTS

The uncompensated and compensated own-price elasticity of energy are estimated to be -1.286 and -1.158 according to the LA-AIDS method. This indicated a high level of RE and WE. As shown in Tab. 1, given that energy service price declined by 10% (or energy efficiency has been improved by 11.1%), the sizes of RE for CO_2, SO_2, NO_X, and Soot and dust are estimated to be 114.41%, 114.27%, 105.01%, and 116.33%, respectively, which indicates backfire effect. Tab. 1 also shows that DRE is dominated, indicating that RE is mainly contributed by the demand change of energy service itself. The size of WE is about 5.79%, which implies that RE brings more than 6% of consumers' expectations for welfare benefits.

Tab. 1. Results of rebound effect and welfare effect (tau=10%; unit: %)

	DRE	IRE_{Fo}	IRE_{HAC}	IRE_{TC}	IRE_{Ot}	RE	WE
CO_2	115.7	-2.68	8.92	-10.45	2.84	114.41	5.79
SO_2	115.7	-1.05	2.35	-3.82	1.00	114.27	5.79
NO_X	115.7	-3.34	9.69	-20.78	3.66	105.01	5.79
SD	115.7	-3.16	6.66	-4.73	1.79	116.33	5.79

As expected, the size of RE and WE change with the level of energy service decline. Taking RE for carbon emission as an example, Fig. 4 shows RE is close to WE when energy service price declined by about 70%, and WE is larger than RE beyond that.

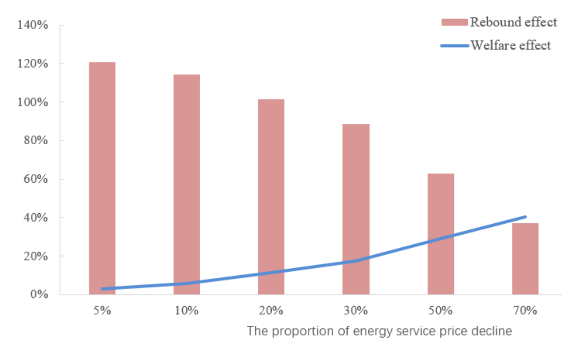

Fig. 4. RE and WE for different percentages of energy service price decline

[7] In practice, sizes of uncompensated and compensated own-price elasticity are often close to each other.

[8] http://www.ceeio.com

5. INSIGHTS

The large rebound and welfare effects indicate that although the reallocation after end-use efficiency improvement has drained all expected environmental reduction, it benefits residents considerably. This finding suggests that there are inadequate demands for energy services. Urban residents in China are likely to remain 'the insufficient in demand' type for a longer period. The downtrend of RE and uptrend of WE along with the percentage increase of energy service price decline suggest that powerful energy efficiency measures are helpful to reduce the RE while improving the WE. In addition, the results suggest residents should strive to be 'the economical and environmentally friendly' and avoid to be 'the low efficiency in consumption.'

This paper developed a practical way to consider both RE and WE together. The work might be helpful for research both on the environment (or energy) management and welfare economics.

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