Welfare Effects of Nonlinear Electricity Pricing

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ABSTRACT

Block pricing is widespread among electricity and water utilities to protect low-income households and to encourage energy conservation through higher marginal prices. However, whether a block pricing system achieves those objectives is controversial. In this article, we analyze the impact of alternative electricity pricing systems on the welfare of consumers for the case of residential electricity block pricing in Korea. To do this, we first develop a theoretical model to compute each household's welfare change under alternative pricing systems. Then, we estimate the residential electricity demand function and compute every household's electricity consumption and expenses under alternative pricing systems. Finally, we compute each household's welfare change and social welfare to draw policy implications.

Keywords: Blocking pricing, Electricity demand estimation, Welfare change, Equivalent variation, Price regulation

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1. INTRODUCTION

Electricity in South Korea is provided by a monopolistic state-owned entity, Korea Electric Power Corporation. This market is heavily regulated: electricity prices are set by agreement between the entity and the government. Particularly, residential electricity pricing in Korea follows a complicated block pricing system. The pricing structure consists of six blocks, each with its own usage fee and fixed fee. The amount of electricity a household consumes determines the block it is put in, and both the usage fee and the fixed fee increase for higher electricity usage blocks. Prices also depend on whether a household resides in a single-family home supplied with low voltage or in an apartment with high voltage. The block pricing system generates a non-convex budget set due to different fixed fees for blocks, and the ratio of the largest usage fee to the smallest usage fee (hereafter, progressivity) is at least eleven times.

The original purpose of implementing this complex residential electricity pricing was to encourage energy conservation and to redistribute income, and thereby to increase welfare. However, whether the current block pricing system has achieved those objectives is controversial. As domestic consumers heavily cross-subsidize industrial consumers, block pricing as a progressive tariff is perceived as unfair. This perception is intensified when domestic consumers experience drastic increases in their electricity bill after a small increase in their electricity consumption. Large differences in prices between blocks makes electricity bills unpredictable. As the block pricing

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system appears to fail the goal of redistribution, policy makers and NGOs suggest reducing the number of blocks and the progressivity between blocks to simplify the price system. However, we are unaware of research that helps to assess the impact on consumer welfare of possible changes in the electricity pricing system.

In this article, we analyze the impact of alternative pricing systems on residential electricity demand, expense, and welfare of consumers by performing scenario analyses. To do this, we first develop a theoretical model to compute each household's welfare change due to alternative pricing systems when it faces a non-convex budget set. Our measurement of welfare change is equivalent variation. Hausman (1981) shows how to compute equivalent variation when a Marshallian market demand curve is known and a budget curve is linear. We modify Hausman (1981)'s method to construct the formula of equivalent variation for the case of the non-convex electricity pricing that applies to the general convex pricing. Then, we estimate the Marshallian demand function of residential electricity in Korea and predict every household's electricity consumption and expenses under different scenarios.[1] The estimated demand function and consumption levels under alternative scenarios are used to compute every household's equivalent variation. We then use these equivalent variations to calculate social welfare according to Atkinson's inequality aversion indices.

Our results indicate that consumer welfare would be higher under alternative scenarios. Additionally, the large price difference between the first block and the last block under the current pricing system suppresses demand increase. Electricity demand and welfare increase for all income groups under alternative pricing systems. Moreover, when a society wants to protect low-income households, three-tier systems with progressitivity value of three achieve greater social welfare than six-tier pricing systems or flat charges. This suggests that a tier system should be maintained to protect low-income households, but that the number of blocks and the price difference between blocks should be reduced from the current level.

Only a few studies estimate individual household welfare changes based on the practice of block pricing. Our analysis is closest to Ruijs (2009) and Reiss and White (2006). Ruijs (2009) analyzes the consumer welfare effect of water pricing system under possible price changes. His analysis adopts an equivalent variation computation as we do in this paper. However, Ruijs (2009) shows how to compute equivalent variation, only when the block thresholds of an initial price system are fixed under the new scenarios. Unlike Ruijs (2009), we provide the formula for equivalent variation and show how to find the value when the number of blocks, block thresholds and prices vary. Thus, our analysis covers the general convex budget set, and also applies to the case of non-convex budget sets.[2] Reiss and White (2006) evaluate welfare changes under nonlinear prices applied to wireless phone service. However, their metric to measure welfare-change is compensating variation, which may not result in a correct ranking of multiple pricing systems.[3] In addition, Reiss and White (2006) perform a Monte Carlo integration to overcome the lack of micro-level data. They randomly sample individual preference parameters and incomes after they estimate distribution of these parameters with aggregate data. On the other hand, our analysis uses both aggregate and micro-level household data.

1. Few studies have been done on the residential electricity demand in Korea. Using a survey data of households in Seoul, the capital of Korea, Yoo et al. (2007) use the cross-sectional data to estimate the residential electricity demand function.

2. Yatchew (1980) provides a general treatment of modeling in nonlinear pricing frameworks (both convex and non-convex).

3. From a survey of over 1000 households in Medellin, Colombia, Maddock and Castano (1991) compute compensating variation to evaluate redistribution impact of block pricing in electricity when flat charge is removed.

Related work computes residential electricity demand and bill changes when switching from a block pricing to the flat rate. Borenstein (2012) computes consumer surplus for each income bracket when a five-tier block pricing system changes to a flat rate. His alternative price is computed to maintain profit neutrality for a utility, given a range of elasticity and marginal costs of production. Using a representative sample of Barbadian households, Carter et al. (2012) perform simulation exercises to examine the impact of a proposed electricity pricing system on residential electricity demand and expenses.[4] In regard to the existing literature, our work demonstrates a concrete welfare analysis of a complicated non-convex block pricing system.

The paper proceeds as follows. Section 2 explains how to compute equivalent variation under a non-convex block pricing system and introduces our measure of social welfare. Section 3 estimates the residential electricity demand function for South Korea and explains how to compute price elasticity of demand in the case of block pricing. Section 4 performs scenario analysis, providing household electricity consumption, expense, welfare change and social welfare changes under alternative pricing systems. The section draws policy implications for the various pricing systems discussed. Finally, Section 5 lists our conclusions. In the Appendix, we provide robustness checks.

2. BLOCK PRICING SYSTEM AND EQUIVALENT VARIATION

Applied works usually employ consumer surplus or sometimes compensating variation to measure welfare effects of price changes. However, Hicks' *equivalent variation* is the correct measure to evaluate welfare effects of price changes.[5] Equivalent variation (EV) measures the amount the consumer would be indifferent to accept in lieu of the price change (Mas-Colell et al., 1995).

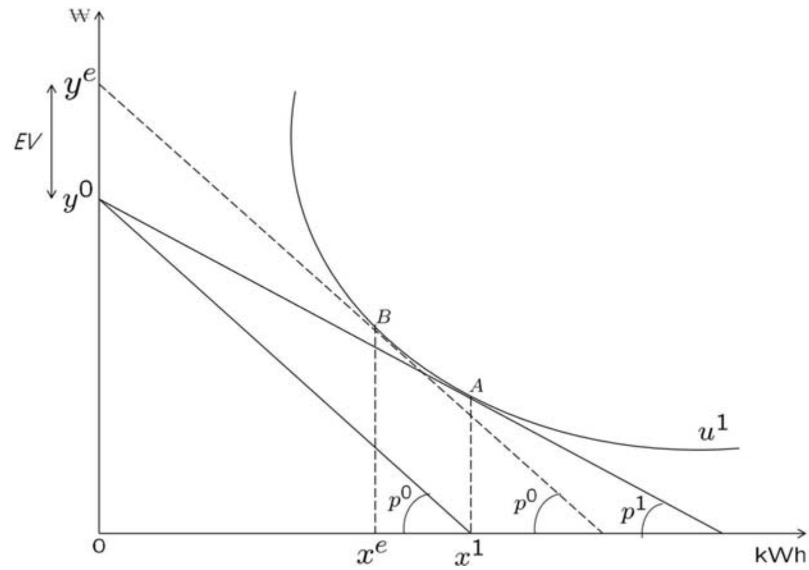
This section explains how to compute equivalent variation as a measure of individual welfare under a non-convex block pricing system. The resulting formula is directly applicable to the general convex budget set if the fixed fees are set to zero. For the general non-convex pricing, the non-convex budget set can be divided into convex subsets. Then, we can apply the method and formula explained here to those subsets and choose the price and demand corresponding to the block yielding the highest indirect utility. Finally, we introduce our measure of social welfare.

Consider a two-good economy that only produces electricity and an aggregate commodity as a numeraire. In this section, we indicate the initial pricing system and new pricing system with superscripts 0 and 1, respectively. A subscript indicates the block number. Bold face type indicates a vector. The price vector is $\mathbf{p} = (p,1)$ where the economy adopts only a flat rate, p, for electricity. A consumer faces the initial price of $\mathbf{p}^0 = (p^0,1)$ and his income is y^0. If the price of electricity decreases to p^1, his budget line will become flatter as Figure 1 shows. Facing new price p^1, the consumer will achieve utility level u^1 at point A from consuming x^1 units of electricity. Now suppose that the price of electricity stays the same at p^0, but the consumer still achieves the utility level

4. Residential electricity demand and bill changes when switching from a block pricing to the flat rate are also studied in the following works: Borenstein (2009), Borenstein (2011), Maddock and Castano (1991), Olmstead et al. (2007), Pashardes and Hajispyrou (2002), Rietveld et al. (2000), Whittington (1992), Ziv et al. (2006).

5. Compensating variation (CV) does not necessarily ranks prices correctly (Mas-Colell et al., 1995). For example, consider L-shaped indifference curves whose kinks occur at vectors (1,1), (4,2) and (5,3). Let the level of utility from consuming (1,1) be $u(1,1) = 1$ and let a demand correspondance $x(p,w)$ where p is a price vector and w is income. We denote an indirect utility function by $V(p,w)$ and expenditure function by $e(p,u)$. Let $p^0 = (1,1), p^1 = (1/2,0), p^2 = (0,2/3)$ and $w = 2$. Then $x(p^0,w) \ni (1,1)$, $x(p^1,w) \ni (4,2)$, $x(p^2,w) \ni (5,3)$, implying $V(p^2,w) > V(p^1,w)$. However, $\mathrm{CV}(p^0,p^1,w) = w - e(p^1,1) = 2 - 1/2 = 3/2$ and $\mathrm{CV}(p^0,p^2,w) = 2 - e(p^2,1) = 2 - 2/3 = 4/3$ concluding that $\mathrm{CV}(p^0,p^1,w) > \mathrm{CV}(p^0,p^2,w)$.

Figure 1: Equivalent Variation



u^1 with his income increased. Choosing consumption point B where he consumes x^e units of electricity, the consumer achieves utility u^1. The hypothetical consumption x^e is called *virtual consumption*. Achieving utility u^1 under the initial price will require income increase to support the consumption point B. *Virtual income* y^e is the income the consumer would need, in order to be as well-off as he would be after the price change. Equivalent variation (EV) is defined as the difference between the virtual income and the initial income, that is, $\text{EV}(p^0,p^1,y^0) = y^e - y^0$. The problem is that we do not observe indifference curves or virtual income. However, once we know the Marshallian demand function, we are able to compute the EV.

Suppose Marshallian market demand function is linear as

$$x(p,y) = \alpha p + \beta y + \gamma z \tag{1}$$

with coefficients α, β, γ and price p, income y and a vector of covariates z. For the demand function (1), the indirect utility function has the following form

$$V(p,y) = \exp(-\beta p)\left[y + \frac{1}{\beta}\left(\alpha p + \frac{\alpha}{\beta} + \gamma z\right)\right] \tag{2}$$

and the expenditure function is derived as

$$e(p,u) = u\exp(\beta p) - \frac{1}{\beta}\left(\alpha p + \frac{\alpha}{\beta} + \gamma z\right). \tag{3}$$

We compute EV for the case of nonlinear pricing system which generates a non-convex budget curve. Our argument is also applicable to the case of a convex budget curve. Our example, the electricity pricing system in Korea, is shown in Figure 2. Its fixed fee is increasing at each threshold and the usage fee is increasing in block. To derive the equation of EV, we introduce the following notations. Let the current (initial) n-tier block pricing system consist of a vector of thresholds $\bar{\mathbf{x}}^0 = (\bar{x}_0^0, \ldots, \bar{x}_n^0)$ where $\bar{x}_0^0 = 0$ and $\bar{x}_n^0 = \infty$, a vector of usage fees $\mathbf{p}^0 = (p_1^0, \ldots, p_n^0)$, and a vector of fixed fees $\mathbf{f}^0 = (f_1^0, \ldots, f_n^0)$. Let an alternative m-tier block pricing system consist of a vector of thresholds $\bar{\mathbf{x}}^1 = (\bar{x}_0^1, \ldots, \bar{x}_m^1)$ where $\bar{x}_0^1 = 0, \bar{x}_m^1 = \infty$, a vector of usage fees $\mathbf{p}^1 = (p_1^1, \ldots, p_m^1)$, a vector of fixed fees $\mathbf{f}^1 = (f_1^1, \ldots, f_m^1)$.

The calculation of EV depends on whether virtual consumption x^e belongs to the interior of any i-th block or coincides with any threshold $\bar{x}_i^0$ of the initial n-tier block pricing system. Let optimal consumption x^1 after price change belong to the l-th block of the new pricing system, that is, $\bar{x}_{l-1}^1 < x^1 \leq \bar{x}_l^1$. Let virtual consumption x^e occur in the interior of the i-th block of the initial pricing system. For convenience, we define $\sum_{j=a}^{b} = 0$ for $a > b$. The utility level after price change is

$$u^1 = V\left(p_l^1, y^0 - f_l^1 + \sum_{j=1}^{l-1} (p_{j+1}^1 - p_j^1)\bar{x}_j^1\right), \tag{4}$$

and the equivalent variation is written as

$$\mathrm{EV}(\mathbf{p}^0, \mathbf{p}^1, y^0) = y^e - y^0 = e(p_i^0, u^1) + f_i^0 - \sum_{j=1}^{i-1} (p_{j+1}^0 - p_j^0)\bar{x}_j^0 - y^0. \tag{5}$$

If virtual consumption x^e occurs at an initial threshold $\bar{x}_i^0$, equivalent variation is found as

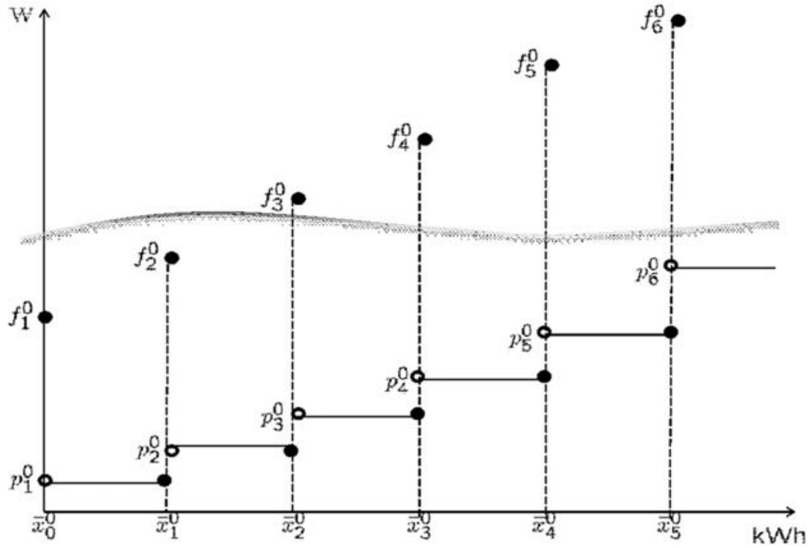
$$\begin{aligned} \mathrm{EV}(\mathbf{p}^0, \mathbf{p}^1, y^0) &= -\frac{1}{\beta}\left(\bar{x}_i^0 + \frac{\alpha}{\beta}\right)\ln\left(\frac{\bar{x}_i^0 + \frac{\alpha}{\beta}}{x^1 + \frac{\alpha}{\beta}}\right) + f_i^0 + \sum_{j=1}^{l-1} (p_{j+1}^1 - p_j^1)\bar{x}_j^1 \\ &\quad - \sum_{j=1}^{i-1} (p_{j+1}^0 - p_j^0)\bar{x}_j^0 + (p_i^0 - p_l^1)\bar{x}_i^0 + \frac{1}{\beta}(\bar{x}_i^0 - x^1) \quad \text{for } i \geq 1, \\ &= -\frac{\alpha}{\beta^2}\ln\left(\frac{\frac{\alpha}{\beta}}{x^1 + \frac{\alpha}{\beta}}\right) + \sum_{j=1}^{l-1} (p_{j+1}^1 - p_j^1)\bar{x}_j^1 - \frac{1}{\beta}x^1 \quad \text{for } i = 0. \end{aligned} \tag{6}$$

So far we have assumed that the location of virtual consumption x^e is known. However, a tricky part of computing EV is to locate the virtual consumption x^e. Our online appendix explains how to find the virtual consumption and the procedure to derive equation (6). It also contains the extended version of this section.[6]

Once we measure the welfare change of an individual household, we are able to measure an aggregate welfare change of consumers from the change in pricing system. The aggregate welfare

6. https://sites.google.com/site/jungyouhomepage/

Figure 2: Baseline Pricing System



of all households is called the social welfare. The most popular measure of social welfare is the Atkinson measure. The Atkinson measure allows us to adjust the degree of inequality aversion. Given income level y_i of household i, $i = 1, \ldots, N$, social welfare is defined as $W = \frac{1}{N}\sum_{i=1}^{N} u(y_i)$ where $u(y_i)$ is household i's utility with income y_i. We denote by ρ the degree of inequality aversion. The individual utility function u is $u(y_i) = \frac{y_i^{1-\rho}}{1-\rho}$ for $\rho \neq 1$ and otherwise, $u(y_i) = \ln y_i$. Without loss of generality, for $\rho \neq 1$, it is assumed that $\frac{\partial W}{\partial y_i} = \frac{y_i^{-\rho}}{N} > 0$ and $\frac{\partial^2 W}{\partial y_i^2} = -\rho \frac{y_i^{-\rho-1}}{N} < 0$. This implies that the more a society averts inequality, the more it cares about the poor. For example, utilitarian social welfare function is associated with the degree of inequality aversion $\rho = 0$, which is the average of all individual utilities. Rawlsian maximin social welfare function follows from the infinite inequality aversion with $\rho = \infty$. Usually the degree of inequality aversion ρ is chosen between 0 and 2.

3. ELECTRICITY DEMAND AND INDIVIDUAL PRICE ELASTICITY

In this section, we estimate the Marshallian demand function of residential electricity and compute price elasticity. This will allow us to compute a change of each household's electricity consumption under an alternative pricing system. Our household data is not panel data but yearly survey data for the year 2011 from Statistics Korea (KOSTAT). The household data has very limited price variation. There is no regional variation in the pricing system because electricity in Korea is supplied by the monopolistic state-owned entity, Korea Electric Power Corporation (KEPCO). Any price change occurs only once a year. Due to the limitation of the household data, we use aggregate data to estimate the demand function. When we compute each household's price elasticity and consumption levels under alternative scenarios, however, we use its consumption, income and marginal price from household data.[7]

7. Ruijs (2009) applies the estimates in Ruijs et al. (2008) to welfare analysis for income quantiles. Ruijs et al. (2008) estimate water demand function using aggregate data for the Brazilian Metropolitan Region of São Paulo. The micro-level

Table 1: Descriptive Statistics: Aggregate Data

Variable	Average	Standard deviation	Minimum	Maximum
Usage(kWh)	269	145	80	499
Price(Won/kWh)	153	48	101	253
GDP per capita (Real,10,000 won)	1,024	755	101	2,492
Heating degree days (HDD)	722	102	451	946
Cooling degree days (CDD)	2,723	210	2,323	3,103

Our aggregate data is annually reported by KEPCO. KEPCO announces its total sales value, the number of households as its customers, and the total usage for each year. Adjusting for inflation, we calculate average price as the total sales value divided by total usage.[8] The annual data covers the period 1980 through 2011. To estimate the demand function, we use real GDP per capita as a proxy to average income. Table 1 shows descriptive statistics of the aggregate data from 1980 through 2011. On average, a household consumes 269 kWh per month for average price of 153 won per kWh. During the sample period, the average real GDP per capita is approximately 10 million won and reaches 25 million won at the end of sample period. As weather is a significant factor for the consumption of electricity, we use heating degree days (HDD) and cooling degree days (CDD) as explanatory variables as well.

We will estimate a linear demand equation as follows

$$x_t = \alpha p_t + \beta y_t + \gamma z_t + e_t \tag{7}$$

where $E[e_t | \Xi_t] = 0$ and Ξ_t represents the explanatory variables in (7). We denote household usage by x_t, price by p_t, household income by y_t at time t.[9] Additional covariates are denoted by a vector z_t. Since we find that x_t, p_t, y_t are unit root time series and they are not cointegrated, we estimate with differenced series as follows

$$\Delta x_t = \alpha \Delta p_t + \beta \Delta y_t + \gamma \Delta z_t + \epsilon_t. \tag{8}$$

Choi et al. (2008) use the same procedure as this article and call it GLS corrected estimation.[10] They prove that coefficients in a spurious regression can be consistently estimated by taking the

data was not available for their analysis. They assume that price elasticity of demand is the same for every household. They compute consumption change plugging household income to demand function.

8. Using residential bill data from Southern California Edison, Borenstein (2009) examines the change in consumption in response to change in actual price schedule. He tests what concept of price consumers respond to. He finds both average price and marginal price are highly significant in the regressions of the elasticity of demand.

9. When estimating aggregate demand (7) with average price, however, we do not include virtual compensation (Ruijs et al., 2008).

10. Choi et al. (2008) assume serial uncorrelatedness between the innovations of Ξ_t and e_t. However, even with a weaker condition such that $E[\Delta\Xi_t \Delta e_t] = 0$, coefficients in (8) can be consistently estimated. For example, the following model satisfies the condition $E[\Delta\Xi_t \Delta e_t] = 0$: we can write $p_t = p_{t-1} + u_{1,t}$, $y_t = y_{t-1} + u_{2,t}$ and $e_t = \psi e_{t-1} + \eta_t$ where $u_{1,t}$,$u_{2,t}$ and η_t are mean-zero stationary processes with $E[u_{1,t}\eta_t] = 0$ and $E[u_{2,t}\eta_t] = 0$. The explained and explanatory variables are cointegrated only if $|\psi| < 1$. We would like to check the validity of regressing equation (8). Differencing equation (7) and repeating equation (8) let us write the following two equalities and the last equality, respectively.

$$\Delta x_t = \alpha \Delta p_t + \beta \Delta y_t + \gamma \Delta z_t + (e_t - e_{t-1}) = \alpha \Delta p_t + \beta \Delta y_t + \gamma \Delta z_t + (\psi - 1)e_{t-1} + \eta_t = \alpha \Delta p_t + \beta \Delta y_t + \gamma \Delta z_t + \epsilon_t.$$

If $\psi = 1$ holds, then $E[\Delta p_t \epsilon_t] = E[u_{1,t}\eta_t] = 0$ and $E[\Delta y_t \epsilon_t] = E[u_{2,t}\eta_t] = 0$. As $e_t = e_0 + \sum_{i=0}^{t} \eta_i$ with $E[\eta_t] = 0$, we can rather assume $E[e_0] = 0$ instead of $E[e_t] = 0$. It's hard to tell what is the mean of nonstationary process.

Table 2: Regression Results

Variables	Model 1	Model 2
Price	-0.494**	-0.582**
	(0.204)	(0.246)
Real GDP per capita	0.134***	0.125***
	(0.035)	(0.037)
CDD		0.032
		(0.024)
HDD		0.001
		(0.008)

Note : 1) *, **, *** represent significance at the 10%, 5% and 1% level, respectively.
2) Standard errors are in parentheses.

full first difference and the estimators are asymptotically normal. Regressing Δx_t on differenced explanatory variables generates consistent estimators for α and β.

We expect that the endogeneity between differenced price, Δp_t, and differenced consumption, Δx_t, is not significant in our model. The endogeneity tests on price Δp_t support this conjecture, so that we can run OLS to estimate (8). We use one-period and two-period lagged prices Δp_{t-1} and Δp_{t-2} as instruments. The Sargan test statistic of overidentifying restrictions is 1.834 with a p-value of 0.1757, so we cannot reject the null hypothesis such that all instruments are uncorrelated with error. The Hausman test statistic is 1.05 and the p-value is 0.5906, supporting the null hypothesis of no endogeneity between Δp_t and Δx_t. Finally, the Cragg-Donald Wald F statistic is 10.278, thus there is little concern about weak instruments.

We conduct two OLS regressions of models with different specifications, one with only price and income variables and the other also including weather variables. The results of the regressions are described in Table 2. In Model 1, the price coefficient is -0.494 and the income coefficient is 0.134. Model 2 shows that the estimated price coefficient is -0.582 and the estimated income coefficient is 0.125. While both models show statistically-significant estimates of price and income coefficients, the coefficient estimates of CDD and HDD in Model 2 are not significant. EV computation requires the coefficient estimates to be as precise as possible. Therefore, we will use the estimates from Model 1.

Our micro-level data from Family Budget Survey (FBS) shows household's income and expenses during a representative month of the year 2011. FBS is conducted by KOSTAT and it is nationally representative.[11] The data includes 10,543 households surveyed, but the sample we use in our scenario analysis includes 10,504 households. Since KEPCO charges every household a minimum fee of 1,000 won and taxes of 130 won per month, we omit households whose incomes are lower than 1,130 won. Factors that affect electricity consumption, such as the size and composition of a household, its residence type, and the ownership of electrical appliances are not considered in our analysis. Table 3 shows household electricity consumption and expense averaged for each income group under the current pricing system as of July 2011. Not surprisingly, higher income households have higher usage of electricity and pay more than lower income households. However, electricity expense as percentage of income decreases with the level of household income.

11. KOSTAT surveys households on monthly basis and it announces monthly data, quarterly data and yearly data. We recover each household's electricity usage from its electricity bill at prices as of July 2011.

Table 3: Descriptive Statistics: Monthly Household Data

Income deciles	Income (won)	Electricity demand (kWh per month)	Electricity bill (won per month)	Electricity bill as % of income
1st	468,813	231	29,730	6.3
2nd	1,086,116	264	36,159	3.3
3rd	1,670,077	281	39,438	2.4
4th	2,207,402	292	41,478	1.9
5th	2,732,661	308	45,079	1.6
6th	3,245,252	322	48,012	1.5
7th	3,803,614	329	49,789	1.3
8th	4,479,096	337	51,556	1.2
9th	5,468,613	348	55,131	1.0
10th	8,304,555	372	60,694	0.7
Average	3,346,285	308	45,705	1.4

Note: The price schedule applied is as of July 2011.

This suggests that economic burden from paying for electricity consumption is greater among low-income households.

The computation of price elasticity is more involved for the case of nonlinear pricing systems (Reiss and White, 2005). Let an electricity pricing system consist of block usage fees $\mathbf{p} = (p_1, \ldots, p_n)$ and fixed fees $\mathbf{f} = (f_1, \ldots, f_n)$. Thresholds for blocks are denoted by $\bar{\mathbf{x}} = (\bar{x}_0, \bar{x}_1, \ldots, \bar{x}_n)$ where $\bar{x}_0 = 0$ and $\bar{x}_n = \infty$. A household's income is denoted by y^0. Let x^* be the household's optimal consumption level under the pricing system. We denote by p^* the household's equilibrium marginal willingness-to-pay (*mwtp*, which may differ from the marginal price if x^* occurs at a threshold). Let y^* be the household's income level that would induce x^* at price p^*. Let the household consume x^* units of electricity in the l-th block, i.e., $\bar{x}_{l-1} < x^* \le \bar{x}_l$ for $1 \le l \le n$. The consumption x^* can be written from equation (7) as follows

$$x^* = \alpha p^* + \beta y^* + \gamma z \tag{9}$$

where $y^* = y^0 - f_l + \sum_{j=1}^{l-1}(p^* - p_j)(\bar{x}_j - \bar{x}_{j-1})$. When the household's consumption x^* does not occur at threshold $\bar{x}_l$, marginal price p_l is the same as the household's *mwtp* for the last unit consumed. If x^* occurs at $\bar{x}_l$ where the price rises from p_l to p_{l+1}, the marginal price (*mp*) may differ from *mwtp*.

Denoting the price elasticity as $\xi = \frac{(mp)}{x^*}\frac{dx^*}{d(mp)}$, the total change in consumption can be written as

$$\frac{dx^*}{d(mp)} = \left[\frac{\partial x^*}{\partial(mwtp)} + \frac{\partial x^*}{\partial y} \cdot \frac{d\Delta y}{d(mwtp)}\right]\frac{d(mwtp)}{d(mp)} \tag{10}$$

where $\Delta y = -f_l + \sum_{j=1}^{l-1}(p^* - p_j)(\bar{x}_j - \bar{x}_{j-1})$. Note that the first term in the brackets, $\frac{\partial x^*}{\partial(mwtp)}$, is the slope of demand. The ratio $\frac{\partial x^*}{\partial y}$ is marginal income effect and $\frac{d\Delta y}{d(mwtp)}$ is the change in intra-marginal expenditure. The term outside the brackets satisfies $\frac{d(mwtp)}{d(mp)} = 0$ if $x^* = \bar{x}_l$ and $\frac{d(mwtp)}{d(mp)} = 1$ otherwise. We can arrange (10) to the following equation

Table 4: Price Elasticities (Average: −0.297)

Income deciles	1	2	3	4	5	6	7	8	9	10
Price elasticity	-0.337	-0.315	-0.303	-0.301	-0.287	-0.289	-0.283	-0.287	-0.286	-0.283

$$\frac{dx^*}{d(mp)} = (\alpha + \beta \bar{x}_{l-1}) \cdot 1\{\bar{x}_{l-1} < x^* < \bar{x}_l\}$$

where $1\{\cdot\}$ is the indicator function. Finally, we write price elasticity at consumption level x^* with marginal price p_l as follows

$$\xi = \frac{p_l}{x^*} \cdot (\alpha + \beta \bar{x}_{l-1}) \cdot 1\{\bar{x}_{l-1} < x^* < \bar{x}_l\}. \tag{11}$$

Using marginal price and current consumption levels from the cross-sectional micro data, we compute elasticity in (11) for each household.

Table 4 presents average price elasticities for each income decile. The price elasticity averaged for all households is −0.297, which implies inelastic demand. The absolute value of price elasticity decreases as a household income increases. The average price elasticity estimated in Yoo et al.(2007) is −0.2463, which is consistent with our price elasticity estimate.

4. SCENARIO ANALYSIS

Our scenario analysis will address the impact of alternative pricing systems on consumers. We compute consumption changes, bill changes, and welfare changes of individual households. In addition, we measure the change in social welfare to evaluate the alternative pricing systems. Six scenarios are set up as alternative pricing systems. Three scenarios will be presented in this section and the rest will be shown as a robust check in the Appendix. Our scenarios are designed to maintain revenue neutrality under the assumption of perfectly inelastic demand as does Borenstein (2012).[12] The summary of our scenarios is shown in Table 5.

The baseline scenario is the pricing system in Korea as of July 2011. It is a six-tier pricing system shown in Table 5. The residential electricity is differently priced by voltage, low and high, that depends on the housing type.[13] Moreover, fees are composed of two parts, fixed fee and usage fee for each usage block. The Korean electricity pricing system is more complicated than any in other countries, since not only usage fees but also fixed fees increase by usage block. Moreover, the baseline has very large progressivity: the usage fee of the sixth block is eleven times that of the first block.[14]

Scenario S1 maintains six-tiers with the same thresholds as the baseline system, but it adopts the progressivity of three. Scenarios S2 examines the effect of removing tiers by using flat

12. Note that it is impossible to design scenarios that maintain revenue neutrality when we do not have perfectly inelastic demand. Thus, revenue neutrality will not be necessarily maintained under our scenarios.

13. For example, a large apartment complex has elevators and heating systems that require high voltage electricity. Low voltage electricity is supplied to single family homes.

14. Baseline in Table 5 describes the current pricing system in Korea. For example, if a household using low voltage consumes 180 kWh in a month, it is in the 2nd block. The household pays a fixed fee of 840 won, a usage fee of 14,908 won (56.2 won/kWh for its first 100 kWh consumption and 116.1 won/kWh for the next 80 kWh) and additional taxes.

Table 5: Current Pricing System and Scenarios

<table>
<tr><th colspan="3">Usage block(kWh)</th><th>1 ~ 100</th><th>101 ~ 200</th><th>201 ~ 300</th><th>301 ~ 400</th><th>401 ~ 500</th><th>501 ~</th></tr>
<tr><td rowspan="4">Baseline</td><td rowspan="2">Low voltage</td><td>Fixed</td><td>380</td><td>840</td><td>1,460</td><td>3,490</td><td>6,540</td><td>11,990</td></tr>
<tr><td>Usage</td><td>56.2</td><td>116.1</td><td>171.6</td><td>253.6</td><td>373.7</td><td>656.2</td></tr>
<tr><td rowspan="2">High voltage</td><td>Fixed</td><td>380</td><td>680</td><td>1,170</td><td>2,890</td><td>5,470</td><td>9,970</td></tr>
<tr><td>Usage</td><td>53.4</td><td>91.2</td><td>135.1</td><td>196.3</td><td>294.5</td><td>531.9</td></tr>
<tr><td rowspan="4">S1</td><td rowspan="2">Low voltage</td><td>Fixed</td><td>1,493</td><td>2,091</td><td>2,688</td><td>3,285</td><td>3,883</td><td>4,480</td></tr>
<tr><td>Usage</td><td>89.9</td><td>125.8</td><td>161.8</td><td>197.7</td><td>233.7</td><td>269.6</td></tr>
<tr><td rowspan="2">High voltage</td><td>Fixed</td><td>1,362</td><td>1,907</td><td>2,452</td><td>2,997</td><td>3,541</td><td>4,086</td></tr>
<tr><td>Usage</td><td>73.3</td><td>102.6</td><td>131.9</td><td>161.2</td><td>190.5</td><td>219.8</td></tr>
<tr><th colspan="3">Usage block(kWh)</th><th colspan="6">No blocks</th></tr>
<tr><td rowspan="4">S2</td><td rowspan="2">Low voltage</td><td>Fixed</td><td colspan="6">2,933</td></tr>
<tr><td>Usage</td><td colspan="6">131.9</td></tr>
<tr><td rowspan="2">High voltage</td><td>Fixed</td><td colspan="6">2,888</td></tr>
<tr><td>Usage</td><td colspan="6">110.9</td></tr>
<tr><th colspan="3">Usage block(kWh)</th><th colspan="2">1~ 260</th><th colspan="2">261~ 340</th><th colspan="2">341~</th></tr>
<tr><td rowspan="4">S3</td><td rowspan="2">Low voltage</td><td>Fixed</td><td colspan="2">1,582</td><td colspan="2">3,163</td><td colspan="2">4,745</td></tr>
<tr><td>Usage</td><td colspan="2">103.7</td><td colspan="2">207.4</td><td colspan="2">311.1</td></tr>
<tr><td rowspan="2">High voltage</td><td>Fixed</td><td colspan="2">1,318</td><td colspan="2">2,636</td><td colspan="2">3,954</td></tr>
<tr><td>Usage</td><td colspan="2">83.3</td><td colspan="2">166.6</td><td colspan="2">249.9</td></tr>
</table>

Note: Fixed (won) and Usage (won/kWh)

charges. Scenario S3 adopts three-tiers with progressivity of three, which is proposed by multiple parties: The major party and Ministry of Trade, Industry and Energy claim the progressivity should be three. Some of them request an alternative pricing system that has three usage blocks, separated by thresholds at 260kWh and 340kWh. In the Appendix, we perform a robust check using scenarios S2b, S3b and S3c. Scenario S2b is a flat charge without the fixed fee as a variation of S2. As variations of S3, scenarios S3b and S3c still have three blocks with progressivity of three. However, S3b has thresholds at 150kWh and 300kWh, and S3c has thresholds at 100kWh and 200kWh.

Table 6 shows electricity demand, electricity bill, marginal price and equivalent variation for each income decile under S1, S2 and S3. The marginal price each income decile faces under any alternative pricing system decreases from the one under the baseline. This explains why all income groups increase their electricity demand in every scenario. The flat charge scenario S2 brings out the most drastic change in consumption and bills. Under scenario S2, the consumption among the lowest income group increases by 6.3 percent but the bill jumps up by 30.1 percent from the baseline. On the other hand, the consumption of the highest income group rises by 15.4 percent from the baseline while its expense decreases by 1.2 percent. Low-income households will be worse off and high-income households will be better off under flat charge system in terms of monthly bill. Also, the lowest income households experience the smallest increase in EV under flat charges while highest income households experience the largest increase in EV. This demonstrates that a tier system serves one of its original purposes, which is to protect low-income households.

The values of EV are positive for all income groups under every scenario. This implies that changing the electricity pricing system from the baseline is considered desirable. Low-income households prefer a three-tier system with progressivity three to a six-tier system or a flat charge system. The first to fifth income deciles have the largest EV under scenario S3, the second under S1, the smallest under S2. Overall, low-income households improve their welfare under S3 as the most and under S2 as the least. Households from the sixth to tenth income deciles improve their welfare under S2 as the most. Their EV increases the least under S3. The richest households from

Table 6: Change in Demand, Bill, Marginal Price and Equivalent Variation

Income deciles	Electricity demand (kWh)	Electricity bill (Won)	Marginal price (Won/kWh)	Equivalent variation (Won)
Scenario S1: a six-tier with progressivity of three, 38.5% revenue increase				
1st	238 (3.0)	34,949 (17.6)	148.25 (-9.8)	12,985
2nd	275 (4.3)	41,450 (14.6)	157.39 (-14.7)	20,821
3rd	296 (5.1)	44,913 (13.9)	161.35 (-17.2)	25,601
4th	307 (5.3)	46,786 (12.8)	164.08 (-18.3)	25,063
5th	326 (5.6)	49,973 (10.9)	167.56 (-19.9)	18,019
6th	343 (6.5)	52,734 (9.8)	169.02 (-22.5)	78,255
7th	351 (6.7)	54,440 (9.3)	170.64 (-23.6)	43,064
8th	361 (7.1)	55,942 (8.5)	172.16 (-24.8)	133,448
9th	375 (7.7)	58,684 (6.4)	173.16 (-26.8)	111,564
10th	404 (8.7)	63,649 (4.9)	176.71 (-30.7)	280,988
Average	328 (6.5)	50,352 (10.2)	166.03 (-21.5)	74,981
Scenario S2: a flat charge with a fixed fee, 41.7% revenue increase				
1st	247 (6.3)	38,683 (30.1)	126.46 (-23.1)	3,019
2nd	289 (9.7)	44,272 (22.4)	125.19 (-32.2)	14,776
3rd	312 (11.0)	47,182 (19.6)	123.86 (-36.5)	19,454
4th	325 (11.0)	48,753 (17.5)	123.16 (-38.7)	20,072
5th	345 (12.4)	51,270 (13.7)	122.30 (-41.5)	18,485
6th	364 (13.2)	53,143 (10.7)	120.29 (-44.8)	80,250
7th	373 (13.0)	54,297 (9.1)	120.36 (-46.1)	52,114
8th	384 (14.0)	55,347 (7.4)	119.17 (-48.0)	138,372
9th	398 (14.5)	56,877 (3.2)	118.20 (-50.0)	139,575
10th	429 (15.4)	59,939 (-1.2)	116.05 (-54.5)	345,630
Average	347 (12.7)	50,976 (11.5)	121.50 (-42.6)	83,175
Scenario S3: a three-tier with progressivity of three, 22.4% revenue increase				
1st	242 (4.0)	33,875 (13.9)	140.15 (-14.8)	17,069
2nd	275 (4.5)	39,663 (9.7)	160.36 (-13.1)	25,878
3rd	292 (4.0)	42,716 (8.3)	171.01 (-12.3)	31,607
4th	302 (3.2)	44,224 (6.6)	178.65 (-11.0)	29,920
5th	317 (3.4)	47,244 (4.8)	190.15 (-9.1)	20,876
6th	333 (3.3)	50,109 (4.4)	195.86 (-10.2)	78,373
7th	339 (2.8)	51,889 (4.2)	202.24 (-9.4)	40,951
8th	348 (3.3)	53,482 (3.7)	205.38 (-10.3)	130,194
9th	360 (3.5)	56,837 (3.1)	209.65 (-11.4)	98,109
10th	387 (3.8)	62,746 (3.4)	221.33 (-13.2)	246,704
Average	320 (3.9)	48,279 (5.6)	187.47 (-11.4)	71,968

Note: The percentage changes from the baseline in demand, bill and marginal price are in parentheses. Baseline revenue for KEPCO is 480,088,296 won.

the ninth and tenth income deciles have significant EV increases in every scenario. Thus, the average household for all income deciles ranks scenarios in the same way as a household from the ninth and tenth income deciles ranks them.

Now we evaluate scenarios from the perspective of social welfare. Having each household's EV, we compute social welfare according to the Atkinson measure of social welfare. We set the degree of inequality aversion, ρ, to vary from 0 to 1.5. The results in Table 7 show the percentage

Table 7: Percentage Changes in Social Welfare

Inequality Aversion	Scenario S1	Scenario S2	Scenario S3
ρ=0	2.24333	**2.48852**	2.15318
ρ=0.5	1.05569	**1.09455**	1.05739
ρ=1	0.16730	0.15669	**0.17599**
ρ=1.5	3.07576	2.83240	**3.24837**

Note: Percentage changes are compared to the social welfare of the baseline pricing system. Numbers in bold indicate the largest values of social welfare.

changes compared to the social welfare of the baseline pricing system. When a society is concerned less about inequality, that is, ρ is less than 1, a flat charge with a fixed fee S2 is the best pricing system. This result is predictable from the previous analysis showing that the average household for all income deciles have the largest EV under S2, the second largest under S1, and the smallest under S3.

However, when a society likes to avoid inequality, with ρ greater than or equal to 1, the three-tier systems S3 achieve greater social welfare than the six-tier pricing system S1 or flat charges S2. This implies that if a society is highly concerned with inequality, it should change its pricing system to a three-tier system with progressitivity three whose first two blocks are wider than the baseline's. Thus, decreasing progressivity and the number of blocks to three from the current pricing system is desirable if society abhors inequality. In addition, the flat charge system S2 generates the smallest social welfare under ρ greater than or equal to 1. This implies that keeping multiple blocks serves to protect low-income households.

5. CONCLUSIONS

Our work draws practical implications of residential electricity block pricing for policy makers. It also demonstrates a concrete welfare analysis of a block pricing. Our results indicate that the complex block pricing system reduces consumer welfare for every income group by sup-

Table 8: Additional Scenarios

Usage block(kWh)			No blocks		
S2b	Low voltage	Fixed	0		
		Usage	142		
	High voltage	Fixed	0		
		Usage	119.7		
Usage block(kWh)			1~ 150	151~ 300	301~
S3b	Low voltage	Fixed	1,249	2,499	3,748
		Usage	81.7	163.3	245
	High voltage	Fixed	1,110	2,220	3,330
		Usage	65.3	130.6	195.9
Usage block(kWh)			1 ~100	101~200	201~
S3c	Low voltage	Fixed	1,047	2,094	3,142
		Usage	66	132.1	198.1
	High voltage	Fixed	985	1,970	2,954
		Usage	53	105.9	158.9

Note: Fixed (won) and Usage (won/kWh)

pressing demand increases. Thus, such a pricing system may function as a passive energy conservation method, but it does not function well as a redistribution method. In conclusion, our result suggests that a tier system should be maintained to protect low-income households, but that a simpler tier system will benefit all income groups. When we attain access to the production cost data, we plan to examine whether the existing electric power market is able to serve higher electricity demands, such as those in our scenarios.

Table 9: Change in Demand, Bill, Marginal Price and Equivalent Variation

Income deciles	Electricity demand (kWh)	Electricity bill (Won)	Marginal price (Won/kWh)	Equivalent variation (Won)
Scenario S2b: a flat charge without a fixed fee, 40.4% revenue increase				
1st	243 (4.4)	37,439 (25.9)	136.25 (-17.1)	5,359
2nd	284 (8.1)	43,485 (20.3)	134.90 (-26.9)	15,851
3rd	308 (9.5)	46,634 (18.2)	133.49 (-31.5)	19,767
4th	321 (9.6)	48,353 (16.6)	132.74 (-33.9)	19,411
5th	341 (11.1)	51,085 (13.3)	131.82 (-37.0)	17,447
6th	360 (11.9)	53,135 (10.7)	129.69 (-40.5)	79,826
7th	369 (11.8)	54,383 (9.2)	129.76 (-41.9)	49,519
8th	380 (12.8)	55,526 (7.7)	128.50 (-43.9)	133,023
9th	394 (13.4)	57,196 (3.7)	127.47 (-46.1)	134,558
10th	426 (14.4)	60,560 (-0.2)	125.18 (-50.9)	336,303
Average	343 (11.4)	50,780 (11.1)	130.98 (-38.1)	81,106
Scenario S3b: a three-tier with progressivity of three, 20.2% revenue increase				
1st	236 (1.2)	33,036 (11.1)	153.77 (-6.5)	17,264
2nd	270 (2.7)	39,611 (9.5)	168.73 (-8.6)	24,881
3rd	290 (3.2)	43,205 (9.6)	174.89 (-10.3)	28,336
4th	301 (2.7)	44,984 (8.5)	180.11 (-10.3)	25,774
5th	318 (3.9)	48,398 (7.4)	184.07 (-12.0)	18,373
6th	336 (4.3)	51,262 (6.8)	186.76 (-14.4)	75,454
7th	344 (4.3)	53,175 (6.8)	188.01 (-15.8)	39,308
8th	353 (4.9)	54,609 (5.9)	191.01 (-16.6)	129,603
9th	368 (5.7)	57,656 (4.6)	190.18 (-19.6)	104,123
10th	398 (6.9)	63,168 (4.1)	191.88 (-24.8)	269,827
Average	321 (4.2)	48,910 (7.0)	180.94 (-14.5)	73,294
Scenario S3c: a three-tier with progressivity of three, 20.4% revenue increase				
1st	232 (-0.2)	32,878 (10.6)	160.25 (-2.5)	15,062
2nd	269 (2.5)	39,799 (10.1)	169.20 (-8.3)	22,148
3rd	291 (3.6)	43,612 (10.6)	171.14 (-12.2)	26,927
4th	303 (3.6)	45,749 (10.3)	173.24 (-13.7)	23,166
5th	322 (5.1)	49,227 (9.2)	175.18 (-16.2)	17,517
6th	342 (6.1)	52,016 (8.3)	172.85 (-20.7)	77,060
7th	350 (6.2)	53,711 (7.9)	173.51 (-22.3)	42,424
8th	361 (7.3)	55,289 (7.2)	171.88 (-25.0)	134,271
9th	376 (8.2)	57,774 (4.8)	169.59 (-28.3)	113,319
10th	409 (9.8)	62,560 (3.1)	166.27 (-34.8)	296,703
Average	326 (5.8)	49,262 (7.8)	170.31 (-19.5)	76,860

Note: The percentage changes from the baseline in demand, bill and marginal price are in parentheses. Baseline revenue for KEPCO is 480,088,296 won.

6. APPENDIX

We perform robustness checks of our analysis in two ways. First, we analyze variations of the scenarios that were discussed in the main text. As Table 8 shows, scenario S2b is a variation of the flat charge system S2 except that it removes the fixed fee. Scenarios S3b and S3c are variations of S4 that adopt a three-tier system with progressivity of three, but they use different block thresholds.

Table 9 shows electricity demand, electricity bill, marginal price and equivalent variation for each income decile under S2b, S3b and S3c. The marginal price each income decile faces under any alternative pricing system decreases from the one under the baseline. The flat charge scenario S2b brings out the most drastic change in consumption and bills. Under scenario S2b among the three scenarios, the consumption among the lowest income group increases by 4.4 percent but the bill jumps up by 25.9 percent from the baseline. On the other hand, the average consumption of the highest income group rises by 14.4 percent from the baseline while its expense decreases by 0.2 percent.

The values of EV are positive for all income groups under every scenario, confirming that a price reform is desirable. The first to fifth income deciles will be better off under S3b and S3c, three-tier systems with progressivity three, than under S2b, a flat charge system. Households from the sixth to tenth income deciles increase their EV under S2b as the most. The conclusion is the same as the implication of welfare analysis for each income group in Section 4.

The social welfare analysis in Table 10 confirms that at the lowest degree of inequality aversion $\rho = 0$, the flat charge system S2b benefits the society the most compared to three-tier systems S3b and S3c. However, with positive inequality aversion, three-tier systems with progressivity of three increase the social welfare more than a flat charge. The conclusion is the same as the implication of the social welfare analysis in Section 4.

Secondly, we provide scenario analysis under different assumptions of price elasticity. The price elasticity of each household depends on α and β in (8) that we estimate with aggregate data. The elasticity estimates may not describe recent behavior of households well since the aggregate data covers a long period and the estimates are not time-varying. Thus, we use the lower and the upper bounds of 95 percent confidence interval of coefficients α and β to generate different price elasticities for each household. Table 11 shows price elasticities for each income group with different

Table 10: Percentage Changes in Social Welfare

Inequality Aversion	Scenario S2b	Scenario S3b	Scenario S3c
ρ=0	**2.42664**	2.19287	2.29956
ρ=0.5	1.07644	1.05759	**1.08112**
ρ=1	0.15606	**0.17482**	0.17215
ρ=1.5	2.79559	**3.25390**	3.13496

Note: Percentage changes are compared to the social welfare of the baseline pricing system. Numbers in bold indicate the largest values of social welfare.

Table 11: Alternative Price Elasticities

Income deciles	1	2	3	4	5	6	7	8	9	10	Avg.
Lower bound	-0.6492	-0.6139	-0.5947	-0.5918	-0.5669	-0.5731	-0.5620	-0.5736	-0.5716	-0.5691	-0.5866
Upper bound	-0.0232	-0.0160	-0.0114	-0.0100	-0.0068	-0.0043	-0.0030	-0.0016	-0.0001	0.0037	-0.0073

Table 12: Robust Check: Bounds of Social Welfare Change

	S1	S2b	S2	S3	S3b	S3c
ρ=0	2.09528	2.17791	**2.22977**	2.05240	2.08032	2.11304
	2.40861	2.76617	**2.84626**	2.30458	2.34058	2.49682
ρ=0.5	0.96994	0.93887	0.95123	0.99420	**0.99441**	0.98792
	1.14959	1.25692	**1.28555**	1.14632	1.13078	1.17624
ρ=1	0.15480	0.12924	0.12790	0.16389	**0.16452**	0.16216
	0.17964	0.18158	0.17713	**0.18862**	0.18389	0.18338

Note: Percentage changes (upper and lower bounds in a vertical order) are compared to the social welfare of the baseline pricing system. Numbers in bold indicate the largest values of social welfare.

bounds of α and β. The price elasticity varies widely between -0.6492 and -0.0232 for the lowest income group and price elasticity for all households lies between -0.5866 and -0.0073.

Using the upper bound of price elasticities, we compute electricity demand, bill, and equivalent variations under all six scenarios and measure the corresponding social welfare. We also do the same using the lower bound of price elasticities.

Table 12 shows that if the society cares less about the inequality, the social welfare improves the most under a flat charge like S2 however widely the price elasticities vary. If the inequality aversion increases, the social welfare improves the most under S3 or S3b, the three-tier systems with progressivity of three. The results confirm that the main messages in Section 4 do not change for a reasonable range of price elasticity assumptions.

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