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ELSEVIER
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JOURNAL
Finally, Making the Connection
Can Smart Grid Technology Fix the Disconnect Between Wholesale and Retail Pricing?
Ashley Brown and Raya Salter
Redefining Renewable Portfolio Standards: The Value of Installed Renewable Capacity
Adil Caner Sener
Residential and Regional Electricity Consumption in the U.S. and EU: How Much Will Higher Prices Reduce CO2 Emissions?
Inês M. Lima Azevedo, M. Granger Morgan and Lester Lave
For Municipality-Operated Coal-Fired Plants, What Does EPA's Kinder and Gentler Approach on New Source Review Portend?
Karl Karg
Greenhouse Gas Management: Are U.S. Public Utility Companies Ready?
Peter A. Soyka and Mark E. Bateman
Property Assessed Clean Energy Financing: The Ohio Story
Raymond C. Headen, Sally W. Bloomfield, Matt Warnock and Caleb Bell
What Does the Evidence Really Say about the Residual Supply Index?
Oscar Arnedillo
A Response
Gregory Swinand
The Boomerang Paradox, Part I: How a Nation's Wealth Is Creating Fuel Poverty
Paul Simshauser, Tim Nelson and Thao Doan
Snakes in the Grass: The Energy Security Implications of Medupi
Benjamin K. Sovacool and William Rafey

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Residential and Regional Electricity Consumption in the U.S. and EU: How Much Will Higher Prices Reduce CO_2 Emissions?

Results of our analysis suggest that, given the price-inelastic behavior in both the U.S. and EU regions, public policies aimed at fostering a transition to a more sustainable energy system in order to address the climate change challenge will require more than an increase in electricity retail price if they are to induce needed conservation efforts and the adoption of more efficient technologies by households.

Inês M. Lima Azevedo, M. Granger Morgan and Lester Lave

I. Introduction

Global climate change is becoming an increasingly important problem. Much effort has been devoted to understanding its main implications, and the mitigation and adaptation strategies that will be required if different emission levels are achieved [1]. In 1997, under the Kyoto Protocol, the European Union and United States committed to reductions from their 1990 emissions of greenhouse gas (GHG) of 8 percent and 7 percent, respectively, during the period from 2008 to 2012 [2]. Under the Copenhagen Accord, the EU and its Member States pledged a 20 percent reduction by 2020, compared with 1990 levels, with a conditional offer to increase this reduction to 30 percent, ''provided that other developed countries commit themselves to comparable emission reductions and that developing countries contribute adequately according to their responsibilities and respective capabilities'' [3]. The U.S. did not ratify the Kyoto protocol, but has now pledged to make reductions under the Copenhagen Accord ''in the range of 17 percent [based on 2005 levels], in conformity with anticipated U.S. energy and climate legislation, recognizing that the final target will be reported to the Secretariat in light of enacted legislation'' [3].

Fossil fuels burned for transportation and in the production of electricity and heat for homes, businesses, and industries are the primary contributors to U.S. and EU greenhouse gas emissions. An effective climate policy will need to attain large reductions of emissions in each of these sectors. Economists argue that energy prices should include all externalities if they are to provide the right price signal to consumers. However, at present too little is known about how changes in energy prices will affect consumption.

In this article we assess the price and income elasticity for household electricity consumption in the U.S. and in the EU. We focus on the response of consumers in the two regions taking their different mixes of electricity generation, rate and regulatory structures, and different overall wholesale markets as given.

In the U.S., the residential sector accounts for 37 percent of national electricity consumption,[1] 17 percent of greenhouse gas emissions,[2] and 22 percent of primary energy consumption.[3] The use of electrical equipment and appliances accounts for roughly 21 percent of primary energy consumption in the U.S. residential sector,[4] which is critical given that the conversion losses from primary energy to a plug in the home are roughly 66 percent, due largely to the thermodynamic efficiency of generation plants [4]. While it is widely acknowledged that the residential sector holds the potential for large energy and greenhouse gas savings, the design of effective policies to realize that potential is challenging.

Economists argue that energy prices should include all externalities if they are to provide the right price signal to consumers.

The change in electricity consumption as a function of variables such as electricity prices, personal income, or weather can be described with quantities that economists define as ''own-elasticities.'' Such elasticities are computed as the ratio of the percentage change in electricity consumption that occurs given some percentage change in electricity price, income, or weather. When that absolute value is less than one, it is termed inelastic. While a number of studies have estimated elasticities for residential electricity consumption in the past, there have been few recent studies and even fewer international comparisons in this field. Furthermore, in the case of the U.S., until recently, real spending on electricity was increasing, but beginning in 2005 real spending on electricity has declined [5].

Our analysis uses annual data. The time period of analysis is from 1990 to 2004. The impacts of weather are aggregated at country or state level. We also use average income per capita, and therefore do not consider issues of distribution of income within each state or country.

The article is organized as follows: Section II provides an overview of the residential electricity consumption and its trends in the U.S. and in the EU; Section III describes several residential electricity demand models; Section IV outlines the model specification; Section V reports the results, and in Section VI we present our conclusions and policy recommendations.

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2010.12.004

II. Residential Electricity Consumption

Figures 1 and 2 compare the trends in residential electricity consumption in the U.S. and in selected EU countries. They were constructed using data from ENERDATA, EUROSTAT, and the U.S. DOE. We have separated countries into ''low per-capita residential electricity consumption'' (Figures 1a and 2a) and ''high per-capita residential electricity consumption'' (Figures 1b and 2b), and use different scales in the *y*-axis for each group. We include the observations for the EU15 average in all the figures in order to provide a clear comparison with the U.S. data.

In Figure 1a and b, we present the trends in per capita residential electricity consumption between 1990 and 2003 for several EU countries and for the U.S. Figure 1a shows that electricity consumption in the residential sector has grown only slightly in the EU15 since 1990, with an average annual consumption of 1,800 kWh/capita in 2003. During the same period the average annual electricity consumption in the U.S. also grew only slightly, averaging 4,400 kWh/capita. Within the EU there is large regional disparity in annual per capita residential electricity consumption. Denmark, Germany, Italy, and Luxemburg experienced less than a 300 kWh/capita change over the period from 1990 to 2003, while others, like Finland, France, Greece, Ireland, Portugal, and Norway, have changes larger than 500 kWh/capita. Moreover, while the U.S., Finland, Portugal, Spain, Italy, Netherlands, Ireland, and Austria show clear upward trends during these years, others (Norway, Sweden, France) show a less clear pattern. Denmark and Luxemburg actually show a downward trend.

Figure 1b shows that the U.S. residential electricity consumption is similar to some Scandinavian countries, such as Sweden and Finland. Note, however, that the carbon intensity of electricity generation is different between the U.S. and Scandinavia.

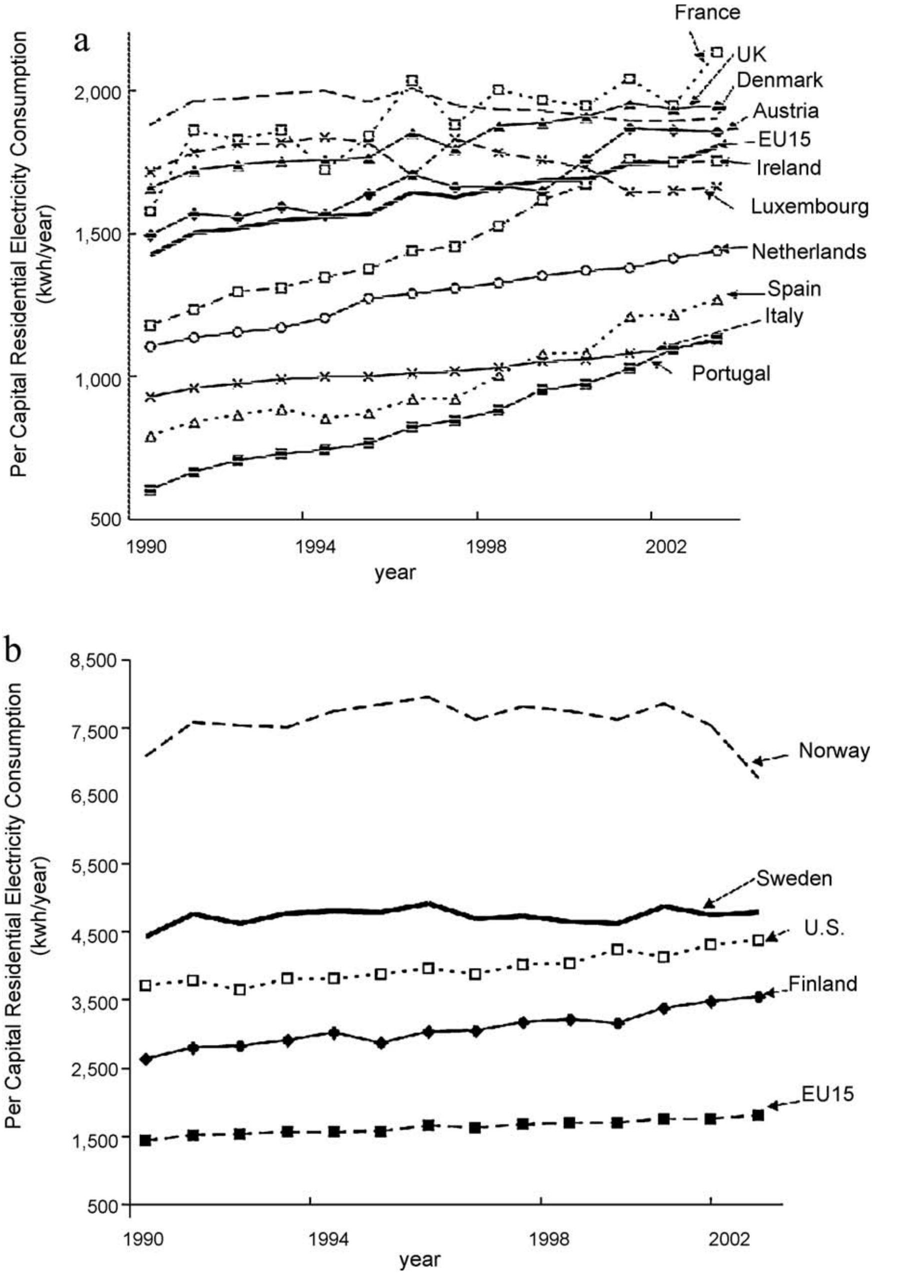

Figure 1: Per Capita Residential Electricity Consumption (in Annual kWh per Capita) from 1990 to 2003, for (a) Selected EU Countries, and (b) for the Scandinavian Countries, the EU15 Average, and U.S.

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2010.12.004

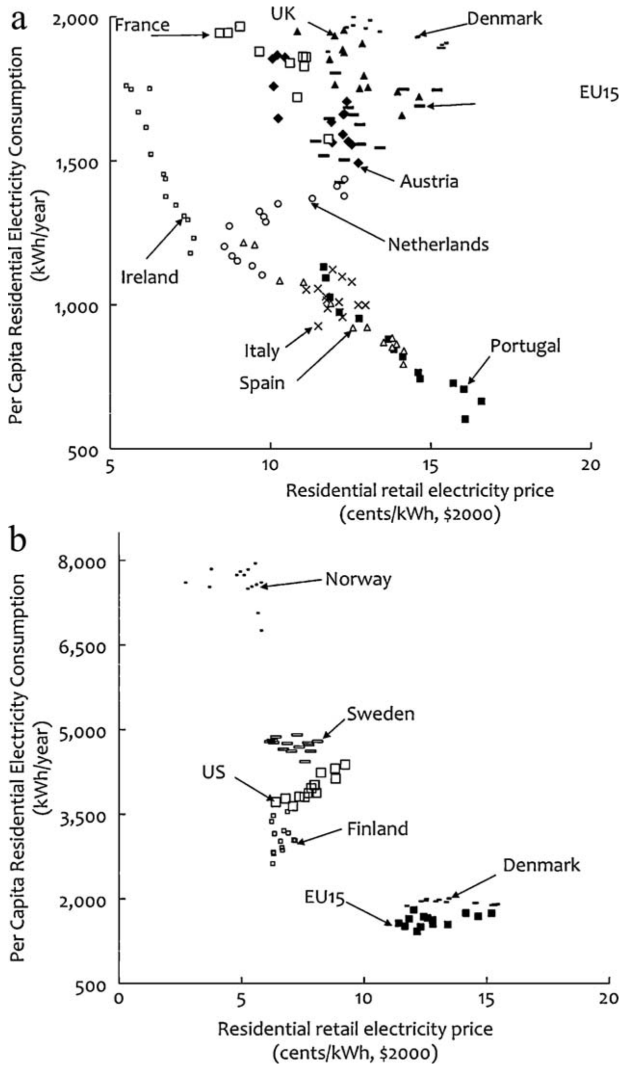

Figure 2: Per Capita Residential Electricity Consumption as a Function of Residential Retail Electricity Price, from 1990 to 2003, for (a) Selected EU Countries, and (b) for the Scandinavian Countries, the EU15 Average, and U.S.

Figure 2a and b display the trends in per capita residential electricity consumption for each year between 1990 and 2003 as a function of the average retail residential electricity price without controlling for variations in other factors. The figures suggest that in France, Ireland, Portugal, and Spain, an increase in electricity prices might have led to a decrease in consumption, whereas in the remaining countries such trends are not apparent.

III. Residential Electricity Demand Models

While several studies assess the price elasticity for total energy or total electricity demand, only a few recent studies assess the price elasticity for residential electricity demand. Studies differ in the time periods of analysis, the geographic region considered, and other independent variables. The econometric model considered also varies from study to study. That said, most studies generally found inelastic price and income elasticity for residential electricity demand, with the expected sign. **Table 1** reports the ranges of price elasticity that have been found in previous studies.

IV. Model Specifications

In order to study the influence of each of the factors discussed above on residential electricity consumption, we tested several econometric model specifications that are described below. The general model tested is of the form:

$$\ln(cons_{it}) = \alpha_i + \alpha_1 \ln(price_{it}) + \alpha_2 \ln(cons\,\exp_{it}) + \alpha_3 \ln(hdd_{it}) + \varepsilon_{it}$$

In this equation, subscript *i* denotes a region and *t* a year. The variable *price* is the retail electricity price for the residential sector (in year 2000 $ per kWh); *cons exp* is the per capita consumption expenditure (adjusted for PPP and in year 2000 $); *hdd* are the annual average heating degree day (in Celsius) and *year* is the year of analysis (*year* ranges from 1990 to 2003 for the EU observations and from 1990 to 2004 for the U.S.). We do not use cooling degree-day data because these data were not available for the EU for the time covered by this study.

The average per capita yearly residential electricity consumption, *cons* (annual kWh per capita), is the dependent

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2010.12.004

Table 1: Review of Price Elasticity Estimates for Residential Electricity Consumption

Author	Region	Time Period	Price Elasticity
Houthakker, 1951 [6]	United Kingdom	1937–1938	−0.89
Fisher and Kaysen, 1962 [7]	U.S. states	1946–1957	−0.16 to −0.24
Houthakker and Taylor, 1974 [8]	U.S. states (46 states)	1960–1971	−0.13 (SR) −1.89 (LR)
Mount, Chapman and Tyrrell, 1973 [9]	U.S. states (47 states)	1947–1970	−0.14 (SR) −120 (LR)
Taylor, 1975 [10]	Review of several studies	Review of several studies	−0.90 to −0.13 (SR) −2.00 to 0 (LR)
Bohi and Zimmerman, 1984 [11]	Review of several studies	Review of several studies	−0.2 (SR) −0.7 (LR)
Maddala et al., 1997 [12]	U.S. states (49 states)	1970–1990	−0.28 to −0.06 (SR) −0.87 to 0.24 (LR)
Garcia-Cerrutti, 2000 [13]	California	1983–1997	−0.79 to 0.01
Paul, Myers and Palmer [14]	U.S. states	1990–2004	−0.15 to −0.11 (SR)
Lee and Lee [15]	25 OECD countries	1978–2004	−0.01 (LR)

Note: SR: short-run; LR: long-run.

variable for the econometric models used to assess the overall EU and U.S. price elasticity.

Because we are specifically interested in understanding international differences, we used countries as units of observation. However, comparing countries with large differences in population and area would leave out aspects of scalability of energy resources and energy usage. Therefore, we created a second database that includes information on annual residential electricity consumption, population, heating degrees day, income, and electricity price, where the unit of observation is the country (and U.S. states for the U.S. observations).

EU data on residential electricity consumption, heating degrees day, residential retail electricity prices and population are from ENERDATA. The U.S. residential electricity consumption and retail electricity price data are from EIA.[5] Data on the average U.S. annual heating degree days are from NOAA.[6] The data on U.S. state population and state average annual disposable income are from the U.S. Census Bureau. For the EU country-level observations, instead of disposable income, consumer expenditure data from the World Development Indicators of the World Bank Group are used. We estimate the average consumer expenditures for each U.S. state using the information on average U.S. disposable income and U.S. total consumer expenditures. U.S. disposable income and consumer expenditures are highly correlated (corr = 0.99), therefore justifying this option. Table 2 provides the descriptive statistics

Table 2: Descriptive Statistics

Variable	Mean	Std. Dev.	Min.	Max.
EU countries and U.S. states (Obs = 946)				
price	8.3	2.6	3	18
hdd	2,566	924	899	4,975
cons exp	19,678	4,830	4,912	33404
cons	3,800	1,505	603	7,950
EU countries (Obs = 182)				
price	10.1	3.1	3	17
hdd	2769	934	899	4975
cons exp	11,578	3002	4912	19,156
cons	2315	1825	603	7,950
U.S. states (Obs = 765)				
price	7.9	2.27	4	18
hdd	2521	917	1002	4,063
cons exp	21605	2721	16,600	33,405
cons	4153	1169	2,096	6,648

Table 3: Models' Specifications

Model	Equation
Model 1	$\ln(cons_{it}) = \alpha_i + \alpha_1 \ln(price_{it}) + \alpha_2 \ln(\text{cons exp}_{it}) + \alpha_3 \ln(hdd_{it}) + \alpha_4 \sum_{t=1}^{n} d_t + \varepsilon_{it}$
Model 2	$\ln(cons_{it}) = \alpha_i + \alpha_1 \ln(price_{it}) + \alpha_2 \ln(\text{cons exp}_{it}) + \alpha_3 \ln(hdd_{it}) + \alpha_4 year + \varepsilon_{it}$

Note: that d_t is a year-specific dummy variable.

and correlations between the stated independent variables.

We tested two models, as summarized in Table 3. In order to account for regional differences that are assumed to be time-independent over the period of analysis (e.g., fixed infrastructure and resource availability, cultural patterns and other) Model 1 uses regional-fixed effects and time-fixed effects. Model 2 is similar to Model 1 but instead of time-fixed effect, we explicitly include a linear time effect. Energy and climate policies in the EU and in the U.S. vary substantially. In order to provide models that are regionally specific while maintaining some statistical power, regional-fixed effects models were also tested for the two regions separately.

Estimates of price elasticity for residential electricity consumption provide an indication of how consumers react to changes in price. Some of the possible responses from consumers to price changes can include buying another good as a substitute, buying less of the good or continuing to purchase the same amount of the good while reducing expenditures on other goods. Several studies use models similar to the stock adjustment model from Houthakker [6], where lag variables for residential electricity consumption are used to account for changes in the stock of appliances. However, as noted by Paul, Myers and Palmer [13], the use of OLS with a partial adjustment model may lead to bias of the coefficient estimates. In this study, we have taken a simplified approach. We use a fixed-effect OLS specification and test several models. However, in order to avoid autocorrelation, lag variables are not included. Hence, our model provides a static estimate of price elasticity in residential electricity consumption. This approach is justified by the use of annual data, since adjustments to price changes are likely to occur on a shorter time span (for reductions in consumption) or over the course of several years (for changes in the stock of appliances).

In this analysis, we treat price as an exogenous variable. This assumption seems plausible for countries and states where the retail residential electricity rates are regulated, or where residential rates don't heavily depend on fluctuations in wholesale electricity prices.

V. Key Findings from the Regressions and Implications for Future Emissions of Carbon Dioxide

The results for all the model specifications are presented in Table 4. For all models, the price elasticity has the expected sign and is significant at the 90 percent level. Price elasticity ranges from −0.2 to −0.25 depending on the model specification, and in the regions included. These estimates are in close agreement with the ranges that have been estimated previously in the literature. Income elasticity also has the expected sign in all models. Considering only EU countries, we conclude that EU price elasticity is estimated to be roughly −0.20 for all the models tested, and it is always significant at least at the 90 percent level. Considering only U.S. data, the U.S. price elasticity ranges from −0.25 to −0.21, depending on the model specification, and it is also always significant at least at the 90 percent level.

There is, of course, no way to know how electricity prices will evolve across the EU and the U.S. in the years to come. If we use our estimates of price elasticity from Table 4, a 10 percent increase today in residential electricity price in the EU could be expected to result in a 2 percent reduction in CO_2 emissions from the residential sector. Similarly, a 10 percent price increase in residential electricity price in the U.S. could be expected to result in

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2010.12.004

Table 4: Results of the Different Model Specifications

Variables	EU Country and U.S. States Observations; Fixed Regional Effects, Time Trend	EU Country and U.S. States Observations; Fixed Regional Effects, Time-Fixed Effect	EU Country Observations; Fixed Regional Effects; Time-Trend	U.S. States Observations; Fixed Regional Effects; Time-Trend	EU Country Observations; Fixed Regional Effects and Fixed Temporal Effects	U.S. States Observations; Fixed Regional Effects and Fixed Temporal Effects
	(1)	(2)	(3)	(4)	(5)	(6)
ln(*price*)	−0.202*** **(0.053)**	−0.207***(0.054)	−0.205*(0.106)	−0.253***(0.038)	−0.206*(0.113)	−0.248***(0.040)
ln(*hdd*)	0.060(0.039)	0.052(0.062)	−0.034(0.165)	0.076***(0.023)	−0.208(0.196)	0.118***(0.036)
ln(*cons exp*)	0.210(0.135)	0.192(0.159)	0.252(0.184)	−0.019(0.219)	0.381*(0.175)	−0.157(0.259)
year	0.011***(0.004)		0.007(0.005)	0.018***(0.006)		
constant	−15.02**(5.937)	−0.207***(0.054)	−8.866(8.035)	−26.970***(8.992)	6.000**(2.151)	9.305***(2.639)
Observations	946	946	181	765	181	765
Case_id	64	64	13	0.651	13	51
R-squared	0.613	0.647	0.556	51	0.605	0.710

Robust standard errors in parentheses. In (2), (5) and (6) year dummies are not reported but all were significant at 90 percent level.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 5: Results of Different NERC Regions for a 10 percent Increase in Retail Electricity Price

NERC region acronym	Price Elasticity	Reductions in Residential GHG Emissions that Would Result from a 10 percent Increase in Retail Electricity prices	Share of Residential Electricity in Total Electricity Consumption in 2009	Average Carbon Intensity of CO_2 Emissions ($kgCO_2$/kWh)	Reductions in Total GHG Emissions from Electricity that Would Result from a 10 percent Increase in Retail Electricity Prices
Midwest Reliability Organization (MRO)	−0.203*(0.086)	2.0%	34%	1.032	0.8%
Northeast Power Coordinating Council (NPCC)	−0.269**(0.091)	2.6%	37%	0.651	1.5%
Reliability First Corporation (RFC)	−0.282*(0.136)	2.8%	36%	0.885	1.3%
SERC Reliability Corporation	−0.171***(0.0276)	1.7%	41%	0.856	0.9%
Western Electricity Coordination Council (WECC)	−0.320***(0.0532)	3.2%	37%	0.756	1.7%
U.S.	−0.248***(0.0403)	2.5%	38%	0.603	0.86%

Robust standard errors in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

a 2.5 percent reduction in CO_2 emissions from the residential sector.

There is a lot of regional variation in carbon intensities across U.S. states. Using a model with fixed regional and temporal effects, we have estimated price elasticity for each North American Electric Reliability Corporation (NERC) region (running the regressions at the states level does not provide statistically significant estimates for most states). The results are reported in **Table 5** for the cases where price elasticity is statistically significant at least at the 10 percent level. For example, increasing household retail electricity prices by 10 percent in the Reliability First Corporation (RFC) NERC region will reduce carbon dioxide emissions from the residential sector by 2.8 percent. In the SERC Reliability Corporation, an increase in household retail electricity prices by 10 percent would only lead to a reduction of carbon dioxide emissions from the residential sector by 1.7 percent.

Using eGRID carbon intensity electricity generation (for year 2005) at the NERC regional level (which uses data from 2005), our estimates of price elasticity, and data from Energy Information Administration (EIA) on the share of residential electricity sales on total electricity sales, we have estimated the total electricity-related carbon reductions from a 10 percent price increase in each of these regions. The last column in Table 5 reports the impact of a 10 percent increase in residential electricity prices as a percent reduction on total carbon dioxide emissions from electricity in that region. Even the highest reduction provides only a very modest impact on carbon dioxide emissions: a 10 percent increase in residential electricity prices in the Western Electricity

Coordination Council would lead to less than 2 percent reduction in total carbon dioxide emissions in that region. Overall, increasing residential electricity prices by 10 percent in the U.S. would lead to less than a 1 percent reduction on total carbon dioxide emissions.

VI. Conclusions and Policy Recommendations

We have made estimates of price and income elasticity under different model specifications in the U.S. and the EU. While the study provides an update from earlier literature, we find similar results: that residential electricity demand is price-inelastic. The model specifications considered differ from earlier work both in the region covered and in the consideration of regional-fixed effects, time-fixed effects, and time trends. Using these different models with panel data for the U.S. states and EU countries jointly, price elasticity estimates range from −0.18 to −0.21. Similarly, using EU country observations only, price elasticity estimates range from −0.20 to −0.21. Using only the U.S. states observations, price elasticity estimates range from −0.21 to −0.25. All of these results confirm most previous studies that have found inelastic values for both price and income elasticity. However, past studies didn't incorporate international comparisons, and generally didn't test multiple model specifications. Determining price elasticity for the residential sector is a fundamental task that needs further attention, given that (among other things) such estimates are then incorporated in large energy and economy-wide models to estimate future residential electricity consumption.

Our results suggest that given the price-inelastic behavior in both the U.S. and EU regions, public policies aimed at fostering a transition to a more sustainable energy system in order to address the climate change challenge will require more than an increase in electricity retail price if they are to induce needed conservation

 1040-6190/$–see front matter doi:/10.1016/j.tej.2010.12.004

efforts and the adoption of more efficient technologies by households. For example, a 10 percent increase today in residential electricity price in the EU could be expected to result in a 2 percent reduction in CO_2 emissions from residential electricity consumption. Similarly, a 10 percent price increase in residential electricity price in the U.S. could be expected to result in a 2.5 percent reduction in CO_2 emissions from residential electricity consumption.

Further work on residential electricity demand could include better estimates of price and income elasticity, taking into account such structural factors as housing size and demographics. There is no substantial prior literature on international comparison on residential electricity consumption and the importance of the underlying factors of electricity consumption. Thus, future studies should be developed in this area in order to gain insight from experience around the world and help guide effective policies on the demand side.■

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Endnotes:

1. Using 2008 AEO detailed tables, Table 10: Energy Consumption by Sector and Source.

2. Using EIA GHG flow from 2006. EIA reports that the residential sector is responsible for 1,234 million metric tons of carbon dioxide equivalent, and that total greenhouse gas emissions in the U.S. are 7,076 million metric ton of carbon dioxide equivalent.

3. Using AEO 2008 detailed tables, Table 10: Energy Consumption by Sector and Source. In 2008, the residential sector accounted for 22 quads of primary energy consumption. The national primary energy consumption was 102 quads.

4. Using AEO 2008 detailed tables. Assumes all electricity in the residential sector is used in end-use equipments and appliances. The figures account for electricity related losses in electricity generation.

5. The data used in this work can be found at http://www.eia.doe.gov/cneaf/electricity/page/at_a_glance/sales_tabs.html.

6. This information can be found at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/.