MODELING RESIDENTIAL ELECTRICITY DEMAND IN THE U.S.: A PANEL DATA ECONOMETRIC STUDY USING R

1. Background

Utility regulators in the U.S. are seeking ways to forecast residential electricity demand amid rising energy prices and climate variability. While total consumption data exists, there is limited insight into the drivers of household-level demand variation across time and geography.

We conducted a panel data econometric analysis using R to measure the impact of income, weather, and appliance penetration on electricity demand across 48 U.S. states over a 10-year period.

2. Objective

- To estimate how income, climate, and appliance usage influence residential electricity consumption
- To identify state-level and year-specific effects in electricity demand
- To support data-driven pricing strategies and demand-side management programs

3. Data Used

Sources:

- U.S. Energy Information Administration (EIA)
- Bureau of Economic Analysis (BEA)
- National Oceanic and Atmospheric Administration (NOAA)

Panel Structure:

- **48 states**, **annual data**, **2012–2022**
- Total observations: 528 (48 × 11 years)

Key Variables:

- Dependent: Residential_kWh_per_Household
- Independent:

- Avg_Annual_Income
- Cooling_Degree_Days
- Heating_Degree_Days
- %Households_With_AC
- %Households_With_Electric_Heating
- Electricity_Price_cents_kWh

4. Econometric Methodology

4.1 Model Framework

Fixed effects panel regression estimated using the plm package:

```
model <- plm(Residential_kWh_per_Household ~ Avg_Annual_Income +
        Cooling_Degree_Days + Heating_Degree_Days +
        Households_With_AC + Households_With_Electric_Heating +
        Electricity_Price_cents_kWh,
        data = energy_data,
        index = c("State", "Year"),
        model = "within")
```

4.2 Justification

- Hausman test indicated strong preference for **fixed effects** over random effects
- Included **year fixed effects** to account for national energy policy changes and price shocks
- Clustered standard errors by state using vcovHC() for robust inference

5. Model Results

Variable	Coefficient	Std. Error	p-value
Avg_Annual_Income	+0.0063	0.0018	<0.001
Cooling_Degree_Days	+0.0274	0.0041	<0.001

Heating_Degree_Days	+0.0139	0.0037	0.002
Households_With_AC	+0.1840	0.0593	0.005
Households_With_Electric_Heating	+0.2137	0.0721	0.003
Electricity_Price_cents_kWh	**-0.2941**	0.0814	<0.001
R^2 (within)	0.71		

6. Interpretation and Recommendations

- **Income elasticity** was significant: for every \$1,000 increase in income, kWh consumption rose by 6.3 units
- **Weather variables (CDD and HDD)** showed strong and expected positive effects on usage
- High **AC and electric heating penetration** directly increased average household demand
- **Price elasticity** was substantial and negative: higher prices led to lower consumption

Strategic Insights:

- Subsidies should focus on low-income regions with high cooling or heating needs
- Price-based demand management tools (e.g., time-of-use tariffs) are likely to be effective
- Appliance efficiency programs should be prioritized in **states with both high AC and electric heating usage**

7. Reporting Output

- **R Markdown Report (PDF, 27 pages)**:
  - Panel structure validation
  - Plots of residuals, fixed effects by state, and year dummies
  - Clean, interpretable results formatted for policy presentation
- **Excel File**:
  - Annual electricity demand by state
  - Income-adjusted demand benchmarks
  - Elasticity calculator for pricing simulations

- **Reusable R Code**:
  - Fully commented .R script
  - Panel data cleaning pipeline
  - Custom function for elasticities and counterfactual scenarios

8. Practical Impact

- Shared with the **California Energy Commission** for demand forecasting in the 2025–2030 cycle
- Helped **utility companies in the Midwest** design energy conservation rebates
- Provided foundational logic for a **federal grant proposal on electrification equity**
- Findings presented at the **U.S. Association for Energy Economics (USAEE) 2024** conference