Determinants of Electricity Demand in the Chinese Residential Sector

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Outline

1 Background and Objectives

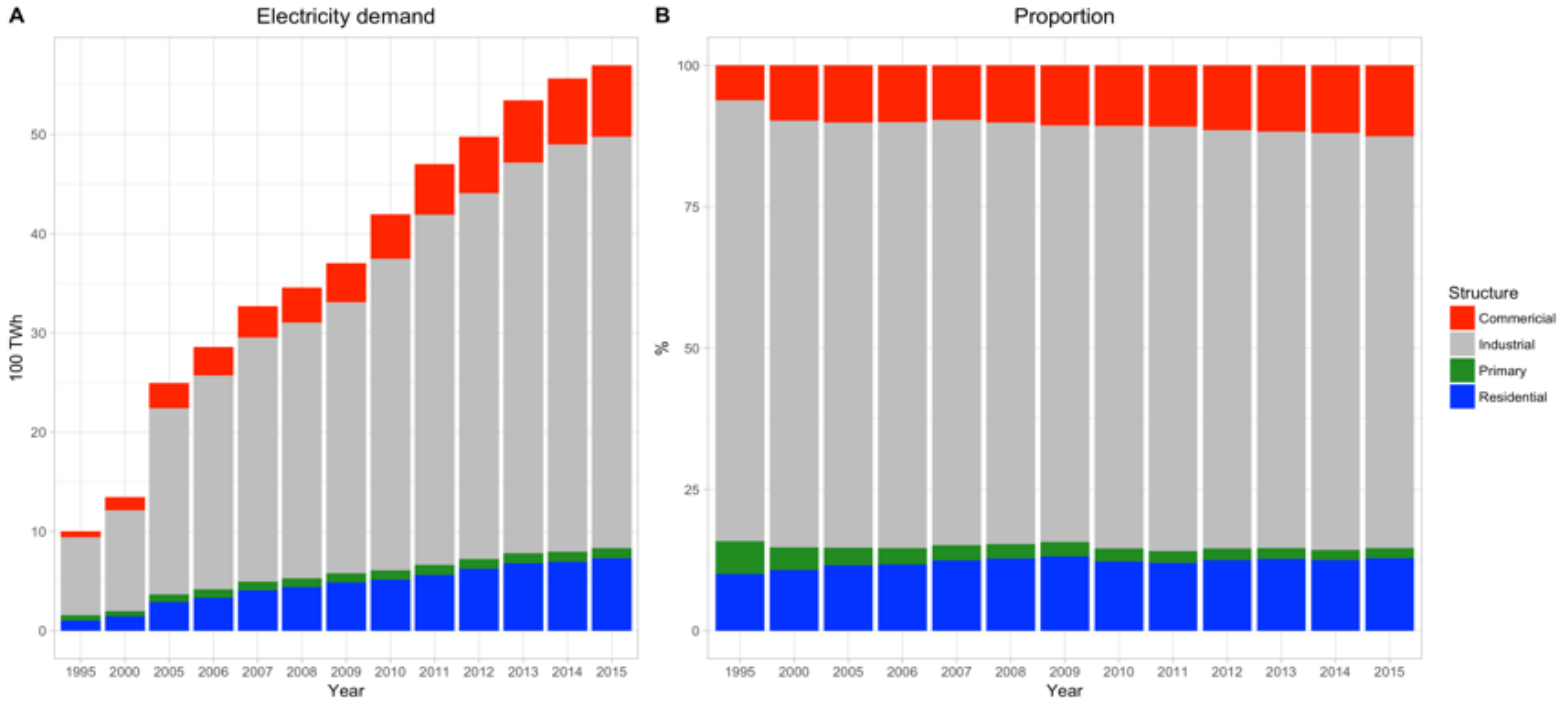
2 Modeling Framework

3 Methods, Data and Results

4 Future Work

China's Electricity Demand: Far From Saturated

- China is the top producer and consumer of electricity in the world
- However, frugality of residential and commercial sectors becomes evident
  - Per capita: China is far below developed countries
  - Structure: China's demand is mainly from the industrial sector



Existing Research in Energy Demand

Bottom-up

Long-range Energy Alternatives Planning System (LEAP) & National Energy Modelling System (NEMS)

Top-down

Associate electricity consumption with indicators such as economic, demographic and weather variables

Other research

High-resolution demand projections, but only as applied to short time scales, such as day-ahead

Methodology/model	Author(s)	Forecast object	Selected variables
MPSO-RBF	SW Yu et al. [31]	Annual electricity consumption	GDP, population, proportion of industry in GDP, urbanization rate, share of coal energy and CPI
TIMES G5 model.	UK Rout et al. [32]	Annual energy demands and emissions	Population, GDP, person-kilometers, transport of goods, heat demand per unit GDP, other electric demand per unit GDP
Partial least squares	Meng and Niu [33]	Annual electricity consumption	GDP of three terms (primary, secondary, tertiary industry), consumption of rural household, consumption of urban household and consumption of government
Energy balance model	Adams et al. [34]	Annual electricity consumption	GDP, industrial output, rate of motorization
Input output model RAS method	He et al. [35]	Annual electricity consumption in liaoning province of China	GDP, the primary industry, the secondary industry, the tertiary industry
PLSR method	Zhang et al. [36]	Annual transport energy demand	GDP, urbanization rate, passenger-turnover and freight-turnover
Cobb-Douglas function	Von Hirschhausen and Andres [37]	Annual electricity consumption	GDP, energy prices
System dynamics model	Wei et al. [38]	Annual second industrial electricity consumption in Chinese province	Electricity prices, Market factors, Second industry output
Bayesian vector autoregressive	Crompton and Wu [39]	Annual electricity consumption	Real fuel price, GDP, population
Co-integration model	Lin et al. [40]	Annual production peak of natural gas	GDP, heavy industrial added value in GDP, the proportion of urban population, coal price index
Radial basis function neural networks	Xia et al. [41]	Annual electricity consumption	GDP, total population, output value of 1st, 2nd & 3rd industry, electricity price, weather and climate data
PSO-GA	Yu et al. [42]	Annual electricity consumption	GDP, population, economic structure, urbanization rate, and energy consumption structure
SEDA™ V2 model	Yang and Yu [43]	Annual electricity consumption in rural areas in six Chinese provinces	Rural economic output, number of households, electricity intensity in rural household, rural population, township and village enterprises, etc
Semi-parametric additive model	Shao et al. [9]	Monthly electricity consumption in two cities	Temperature, relative humidity, precipitation, CPI, PPI, exports and imports, total retail sales of consumer goods, gross industrial output value, etc
Wavelet ANN	Lai et al. [44]	Monthly electricity consumption	Temperature, population, the number of tourists, hotel room occupancy and days per month
LEAP Model	Yan and Crookes [45]	Annual Transport energy	Vehicle population, annual average vehicle travel, fuel economy

Energy demand projection enjoys popularity; long-term high-temporal resolution electricity demand projection is barely discussed

Source: Shao, Z., Gao, F., Zhang, Q. and Yang, S.L., 2015. Multivariate statistical and similarity measure based semiparametric modeling of the probability distribution: A novel approach to the case study of mid-long term electricity consumption forecasting in China. *Applied Energy*, *156*, pp.502-518.

High-resolution Demand Projection Is a Necessity

- Reliability of the electric power sector depends on a perfect balance of demand and supply
- Projections of the high-resolution electricity demand are necessary for identifying:
  - The mix of supply resources needed (to have adequate capacity, reserves, flexibility)
- Electrification will drive up fluctuation of demand
  - Residential and commercial sectors cause most of the temporal fluctuations
- New trends will add to the variation of electricity consumption
  - Global warming + Penetration of electric appliances (e.g. Space heating and cooling) + New end-uses (e.g. electric vehicle)

With the increasing fluctuation of electricity demand, estimates of future electricity demand that are useful must provide information at an hourly or even intra-hourly resolution

Objective

To develop a bottom-up framework for characterizing possible futures for China's residential electricity demand at a high temporal (hourly) and spatial (provincial) resolution that considers the uncertainties about demand side technologies and policies

- To identify the determinants of electricity demand in the residential sector, and understand the mechanism by which these affect electricity consumption
- To develop scenarios of electricity demand drivers that will be used as key inputs to a modeling structure that generates a synthetic time series of hourly electricity demand

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Residential Electricity Demand Projection: Framework

Drivers

Socioeconomic Drivers
- Population
- Household structure
- GDP per capita
- Birth rate
- Education
- GNI per capita
- Death rate
- Employment
- Daily schedule

Technological Drivers
- Appliance lifetime
- Building lifetime
- Technological progress
- Insulation of building
- Appliance age status
- Building age status

Geographical and Climatic Drivers
- Longitude
- Global warming
- Latitude
- Sunny/Cloudy/...
- Climatic zone
- Wind speed

Policy Drivers

Modules

Demographic Module
- Population projection
- Urbanization
- Household size

Appliance Module
- Appliance penetration
- Technology advancement

Building Module
- Building type
  - House
  - Apartment
- Categorize
- Building stock
- Occupancy rate
- Building code
  - Length
  - Width
  - Area
  - Height
  - Orientation
  - Windows/door
  - Shade

Usage Behavior Module
- ON/OFF pattern
- Appliance settings

Climate Module
- Hourly temperature
- Solar radiation

Outputs
- Long-term: 2050 or longer
- High-resolution: hourly or sub-hourly
- By end-use

Space heating	Clothes washing
Space cooling	Entertainment (TV, PC, etc.)
Lighting	Communications (Cellphone, etc.)
Water heating	Personal care
Cooking	Working related
Food freezing	Others

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Population Projection: based on System Dynamics

Output

- Population of Chinese provinces

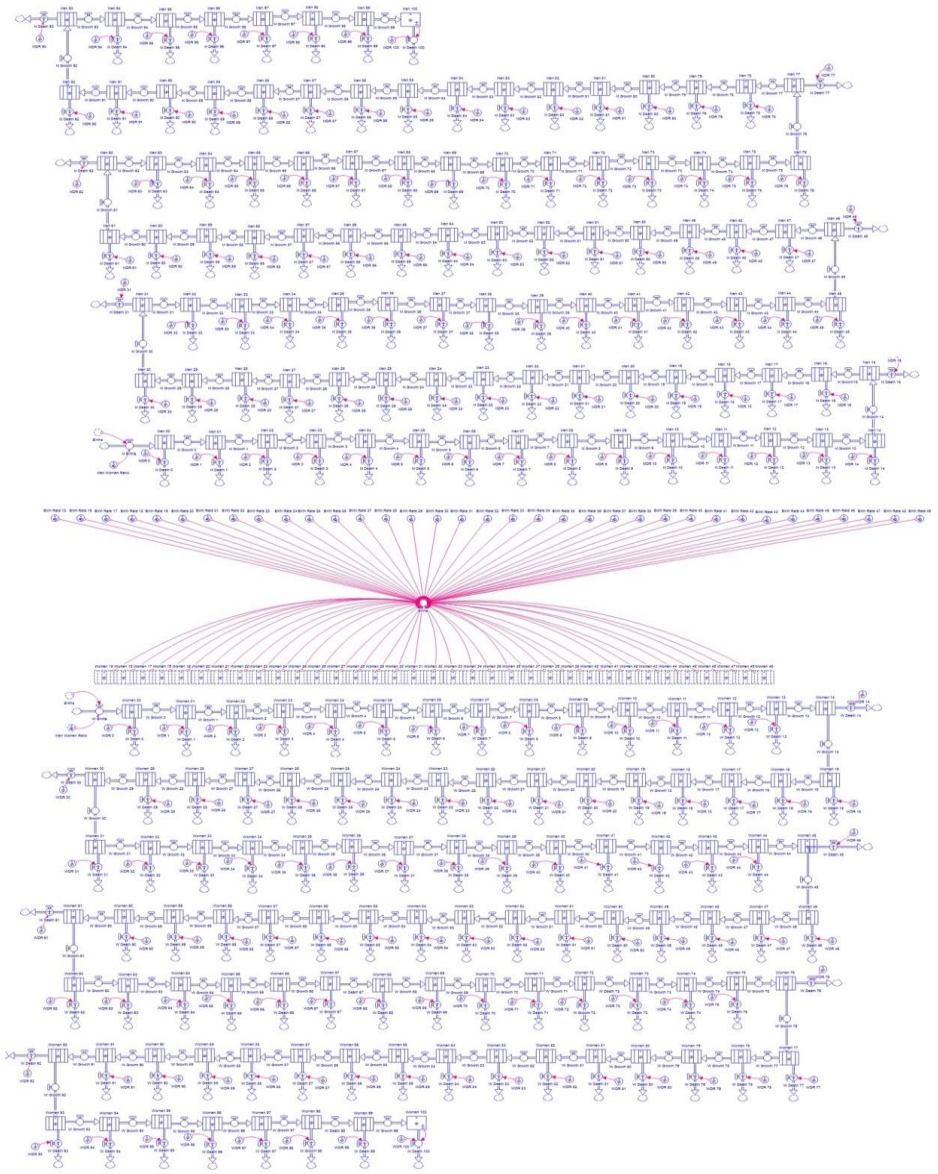
Influencing Factors

- Uncertainties in fertility rate
- Postponement of parenthood
- Increase of life expectancy
- Gradual balancing of the sex ratio at birth
- Interprovincial or international population migration

Input

- Provincial age and sex of population in the base year 2010
- Matrix of Interprovincial or international population migration in the base year 2010
- Provincial age and sex specific mortality rate for each year in the period 2011 to 2100
- Provincial age-specific birth-rate for women between 15 and 49 years for the period 2011 to 2100
- Provincial annual ratio of boys/girls among all births for the period 2011 to 2100

Population Projection: System Dynamics Model



Input

Pre-processing
Data Importing

System Dynamics

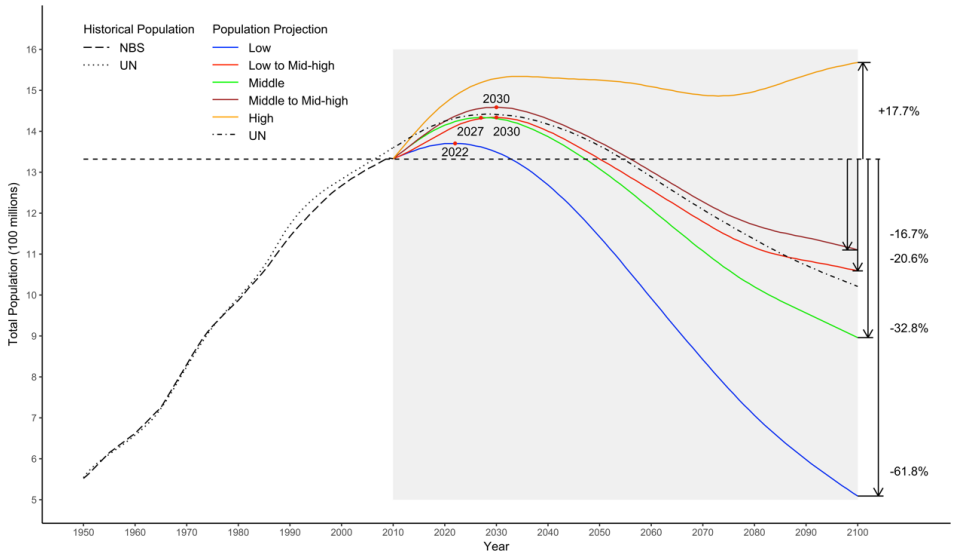
Post-processing
Data Visualization

Output

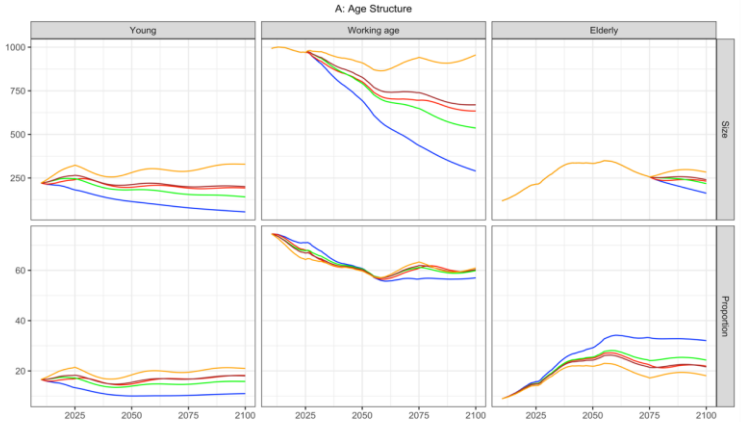
Output

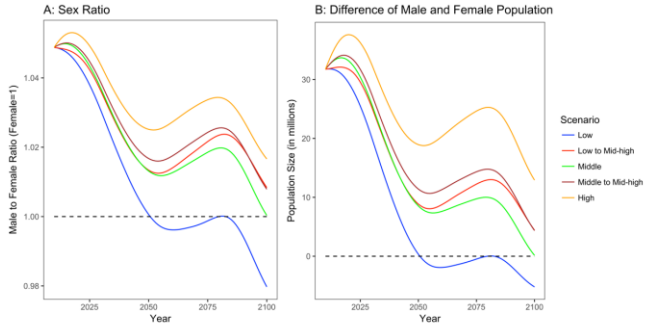
Population for each age and sex for each province in each year of the period 2011 to 2100

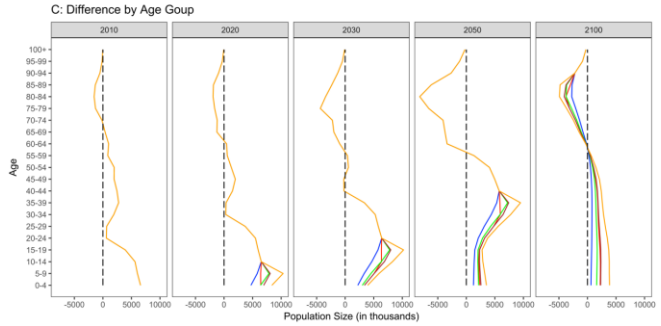
Population Projection: Major Findings

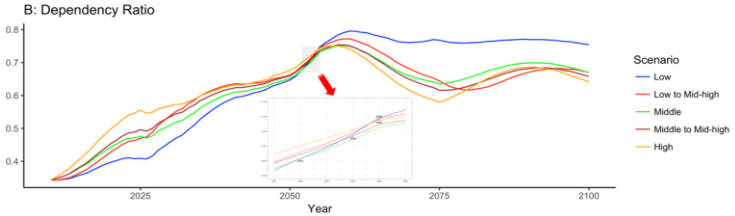


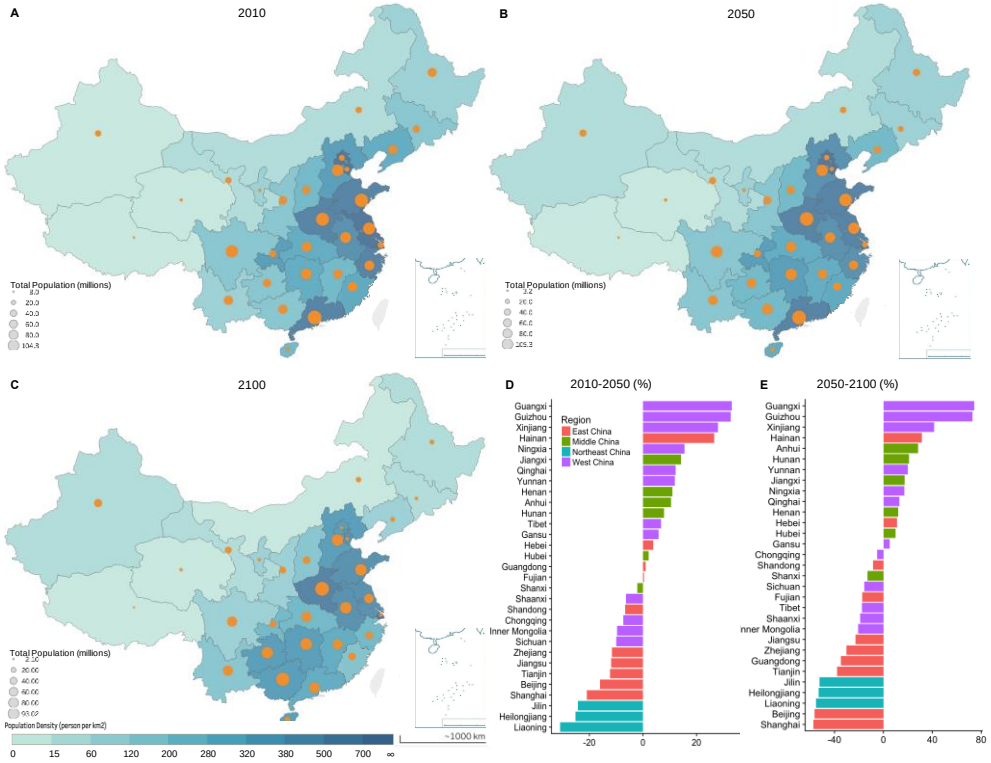
- ❖ Population will peak before 2030 in four scenarios
- ❖ Even a replacement fertility rate cannot stop societal ageing
- ❖ Current sex-ratio distortion will gradually be eliminated
- ❖ Proportion of population in the Middle and West China will rise







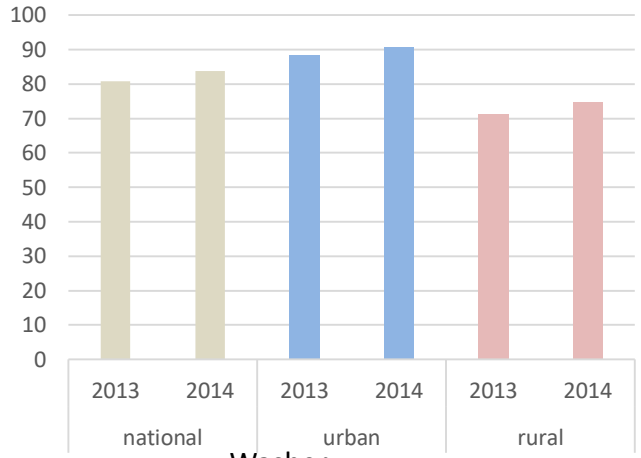




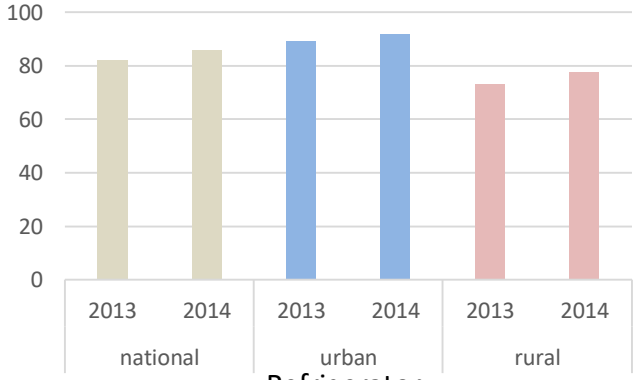
Urbanization Projection

Difference in appliance saturation between urban and rural

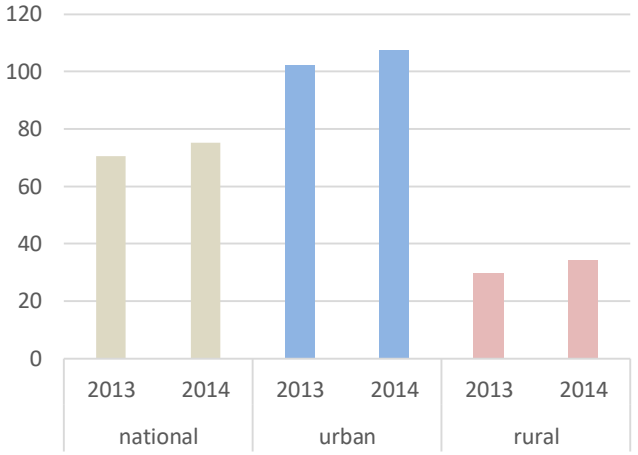
Units per 100 households



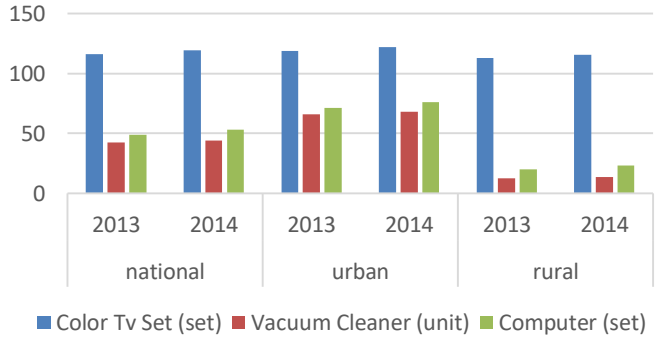
Washer

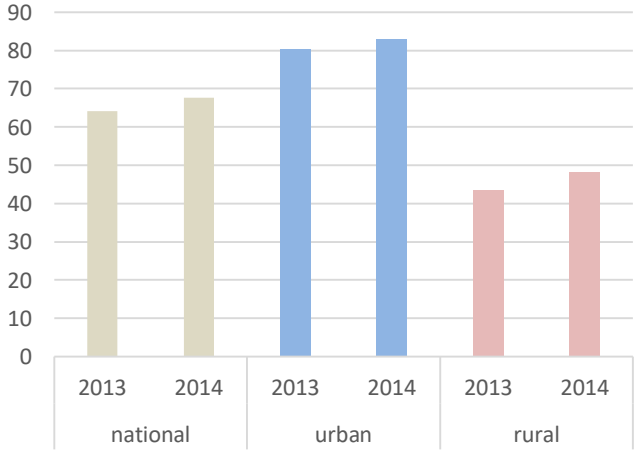


Refrigerator

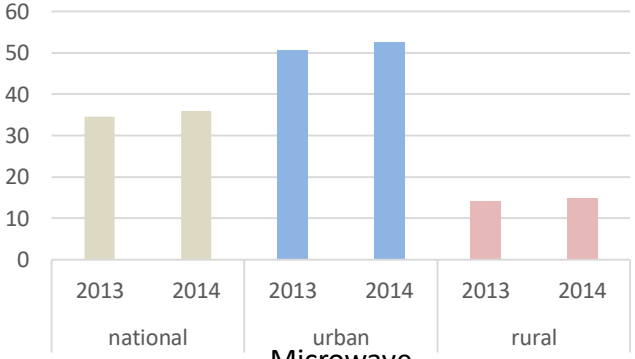


AC

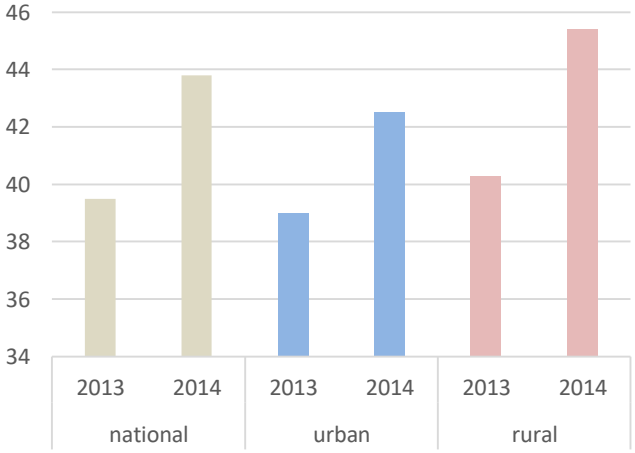




Shower Heater

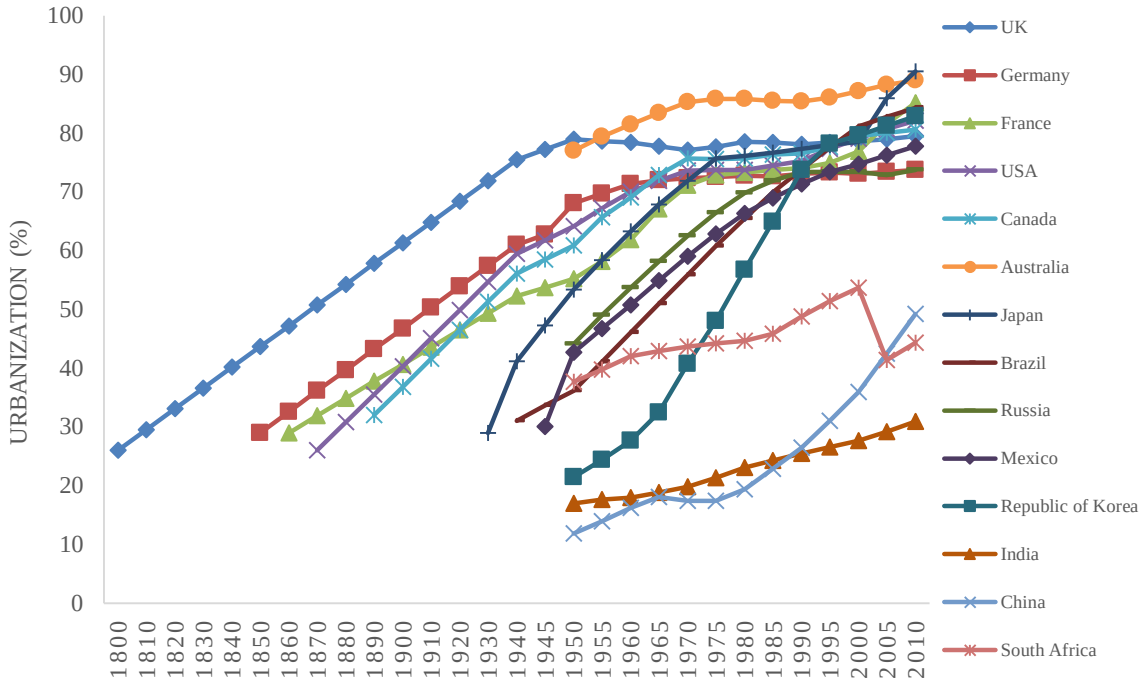


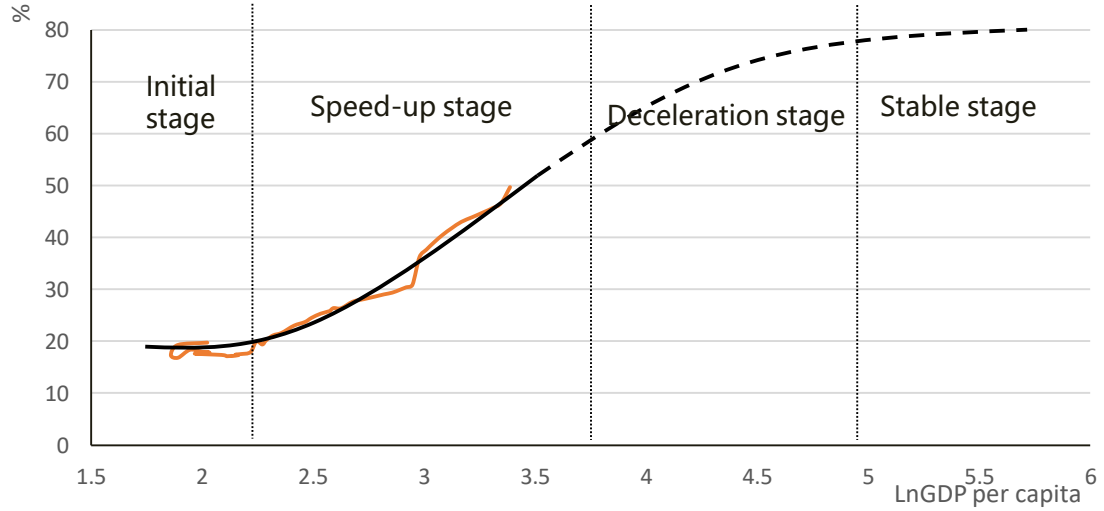
Microwave



Electric bicycle

Urbanization Projection: Regression Model





Regression model

$$ln(M - y_{i,t}) - lny_{i,t} = \alpha x_{i,t} + \beta + \varepsilon_{i,t}$$

M=80%

Beijing, Tianjin, Shanghai are excluded from the regression analysis

Panel data

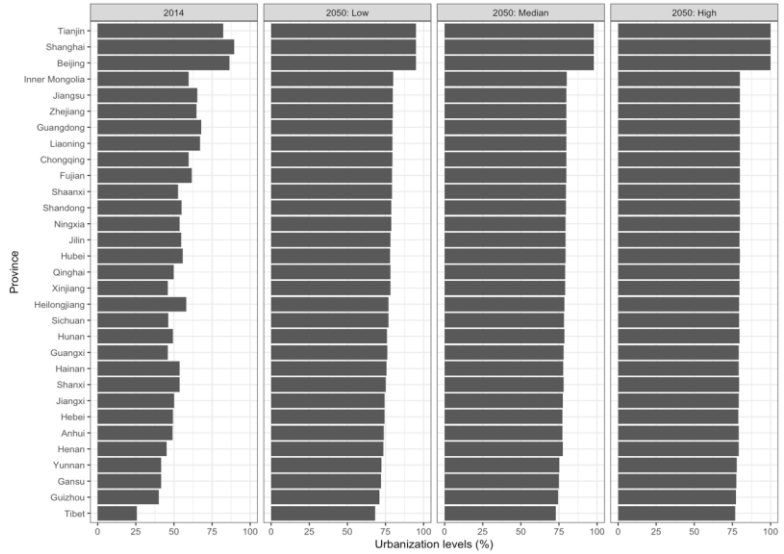
Time series: year 2005-2014; Sample: 31 provinces;
Independent variable: per capita GDP;
Dependent variable: Urbanization;

Data processing

GDP: real GDP at 2014 price obtained from nominal GDP and GDP deflator

Source: http://www.nea.gov.cn/2013-02/20/c_132180424_3.htm

Number of Households



45 scenarios of household numbers for each province in urban and rural areas up to 2050

Population projection module

Urbanization projection module

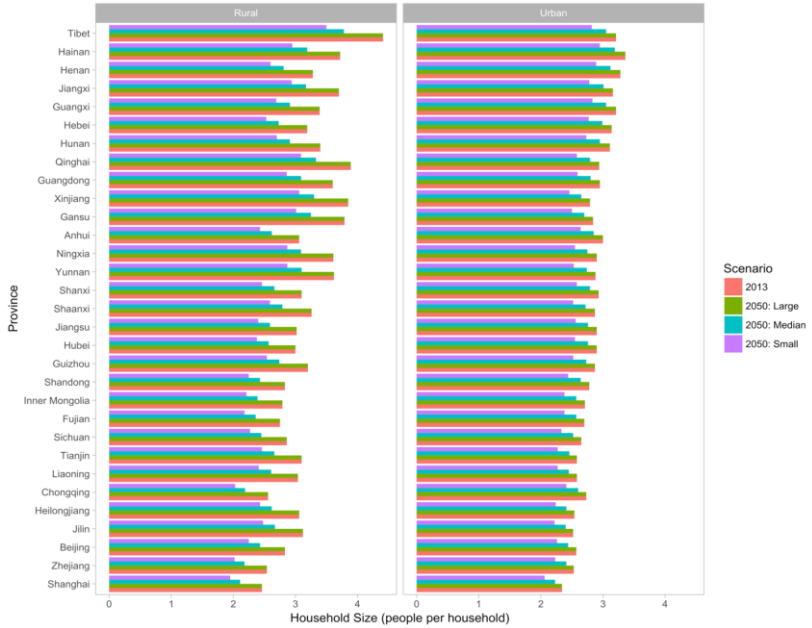
Household size module

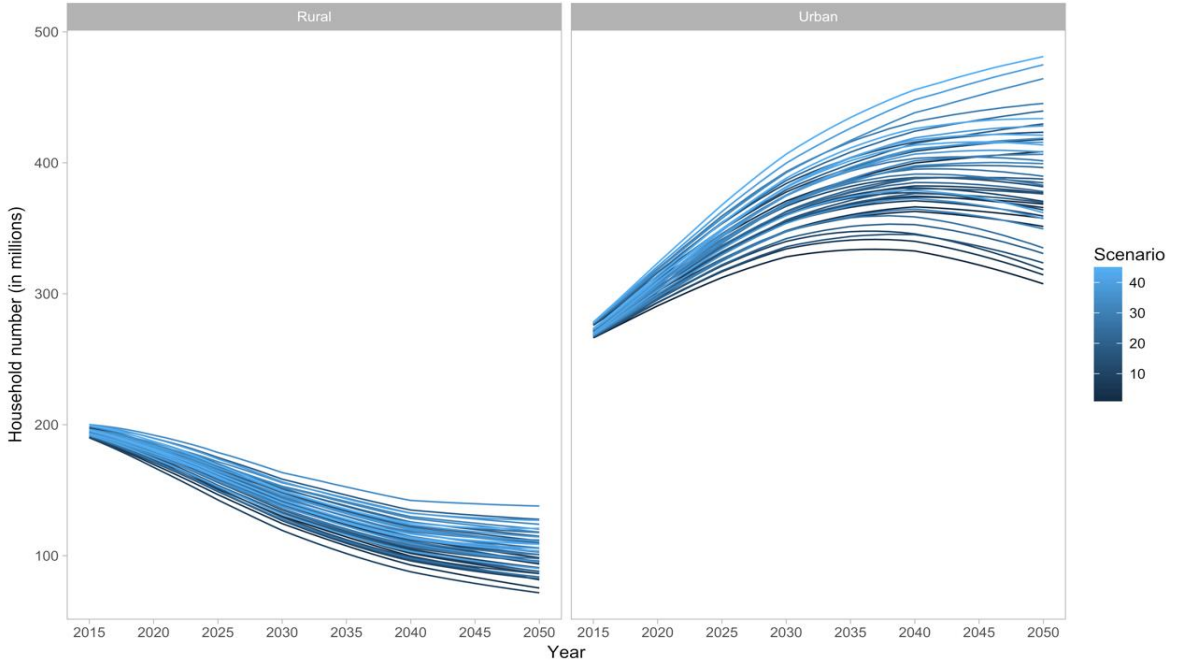
Output: Household number

	Scenario 1			
	T1	T2	…	Tn
Province 1				
Province 2				
…				
Province m				

	Scenario 2			
	T1	T2	…	Tn
Province 1				
Province 2				
…				
Province m				

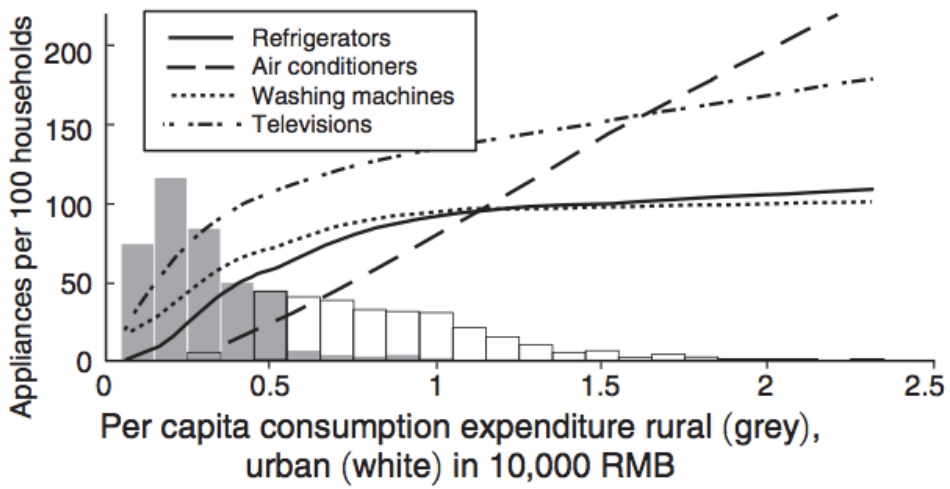
		Scenario S3			
		T1	T2	…	Tn
Province 1	Urban				
	Rural				
Province 2	Urban				
	Rural				
…	…				
Province m	Urban				
	Rural				





Saturation of Electric Appliances: Regression Model

Diffusion curve for new technology adoption



$$ln(M - y_{i,t}) - lny_{i,t} = \alpha x_{i,t} + \beta + \varepsilon_{i,t}$$

$$ln(M - y_{i,t}) - lny_{i,t} = \alpha lnx_{i,t} + \beta + \varepsilon_{i,t}$$

Appliances

Different appliances have different characters (i.e., different sensitivities with income)

Washing machine (M=1.1)	Refrigerator (M=1.1)	Air conditioner (M=1.9 (N); 2.5 (S))
Personal computer (M=2.0)	Microwave oven (M=1.0)	Television (M=2.0)

Rural vs. Urban

Because of lifestyle difference, rural and urban households present different saturation curves

Panel data analysis

Time series: 2000-2012; Sample: rural and urban households in 31 provinces

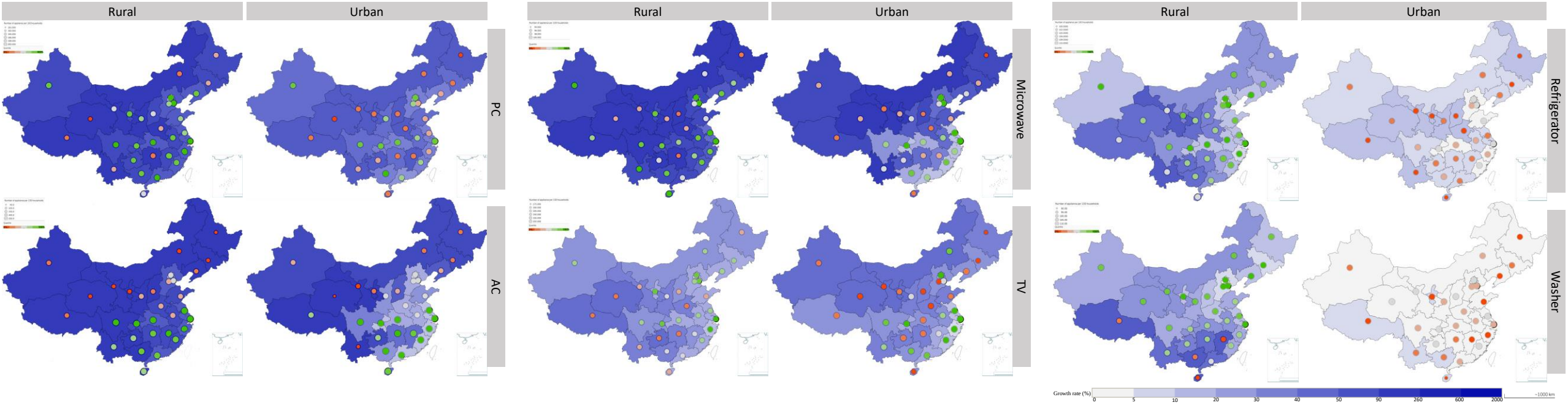
Regression model: Random or Fixed effect; Individual effect

Appliance	Urban				Rural			
	Model 1		Model 2		Model 1		Model 2	
	Household	Per-capita	Household	Per-capita	Household	Per-capita	Household	Per-capita
AC (North)	0.67	0.67	0.72	0.74 [a]	0.57	0.53	0.63	0.67 [a]
AC (South)	0.75	0.74	0.78	0.79 [a]	0.70	0.66	0.83 [a]	0.83
Microwave	0.66	0.67	0.78	0.80 [a]	0.69	0.65	0.78 [a]	0.78
PC	0.75	0.76	0.87	0.89 [a]	0.61	0.58	0.74	0.78 [a]
Refrigerator	0.44	0.43	0.50	0.51 [a]	0.78	0.74	0.86	0.89 [a]
TV	0.09	0.10 [a]	0.05	0.06	0.65	0.62	0.71	0.72 [a]
Washer	0.19	0.13	0.19	0.20 [a]	0.75	0.76	0.79	0.81 [a]

Saturation of Electric Appliances: Major Findings

We project scenarios of provincial penetrations for various appliances in urban and rural areas

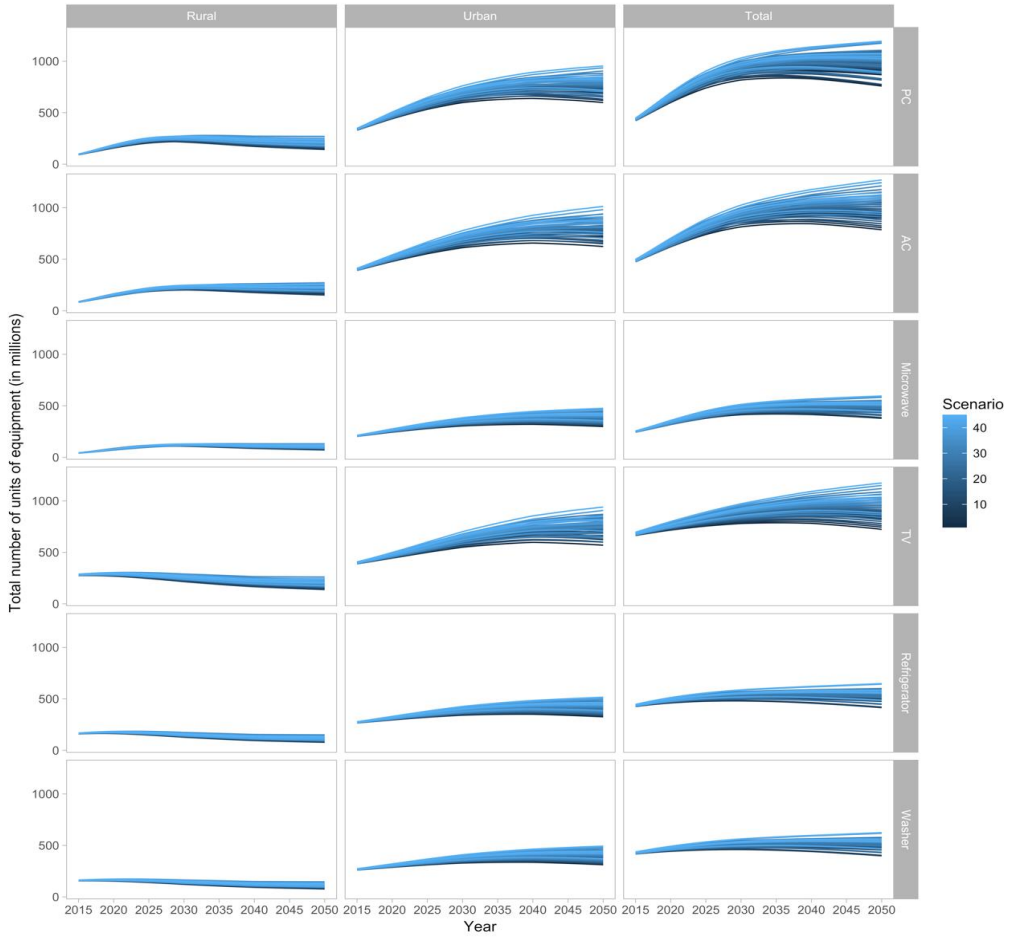
- Growth in saturation of personal computers and air conditioning equipment will be higher
- Current differences in appliances' penetration between urban and rural households narrow
- Current disparities in appliance penetration observed among geographic regions tend to disappear

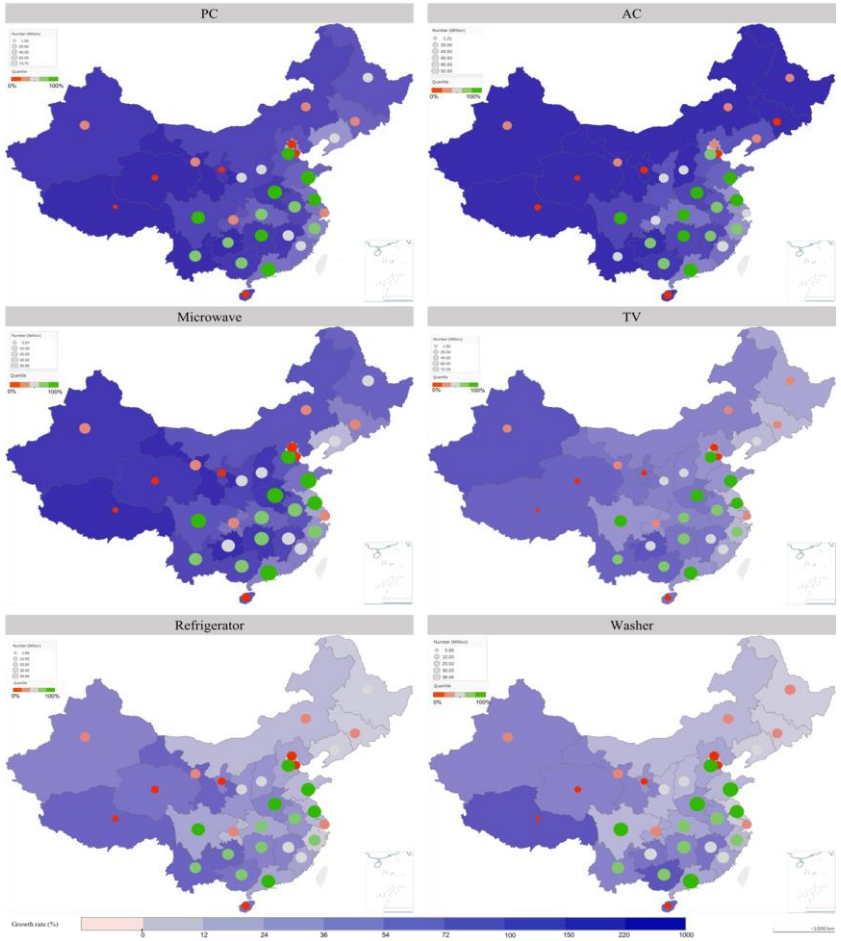


Total Ownership of Electric Appliances

- Increase in the number of PC and AC units will be higher
- Appliance will reach a peak during the period

- Higher growth rates in Central and Western China
- Most will be owned by urban households in Eastern China

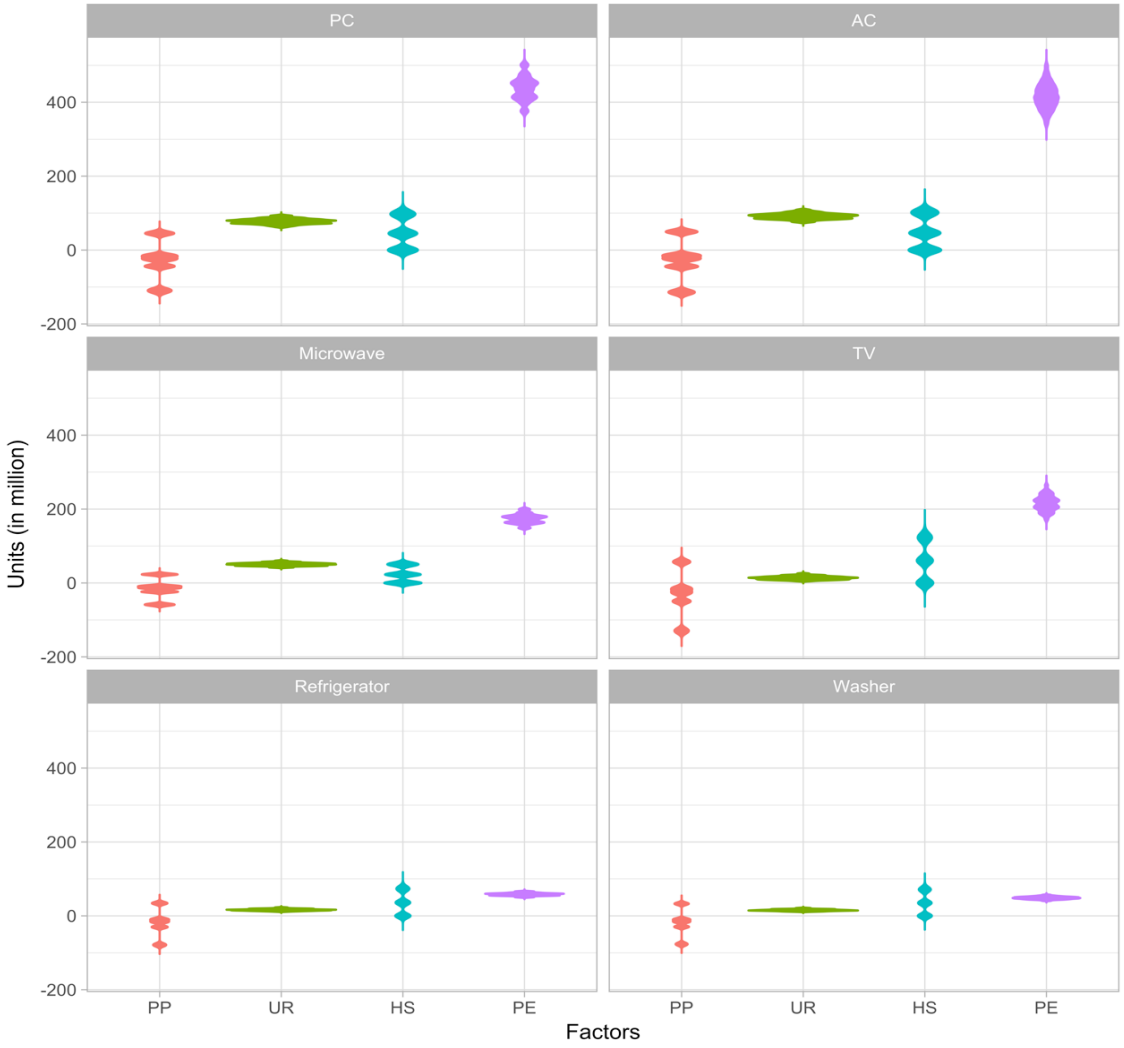




Impact of Each Driver to Adoption of Appliances

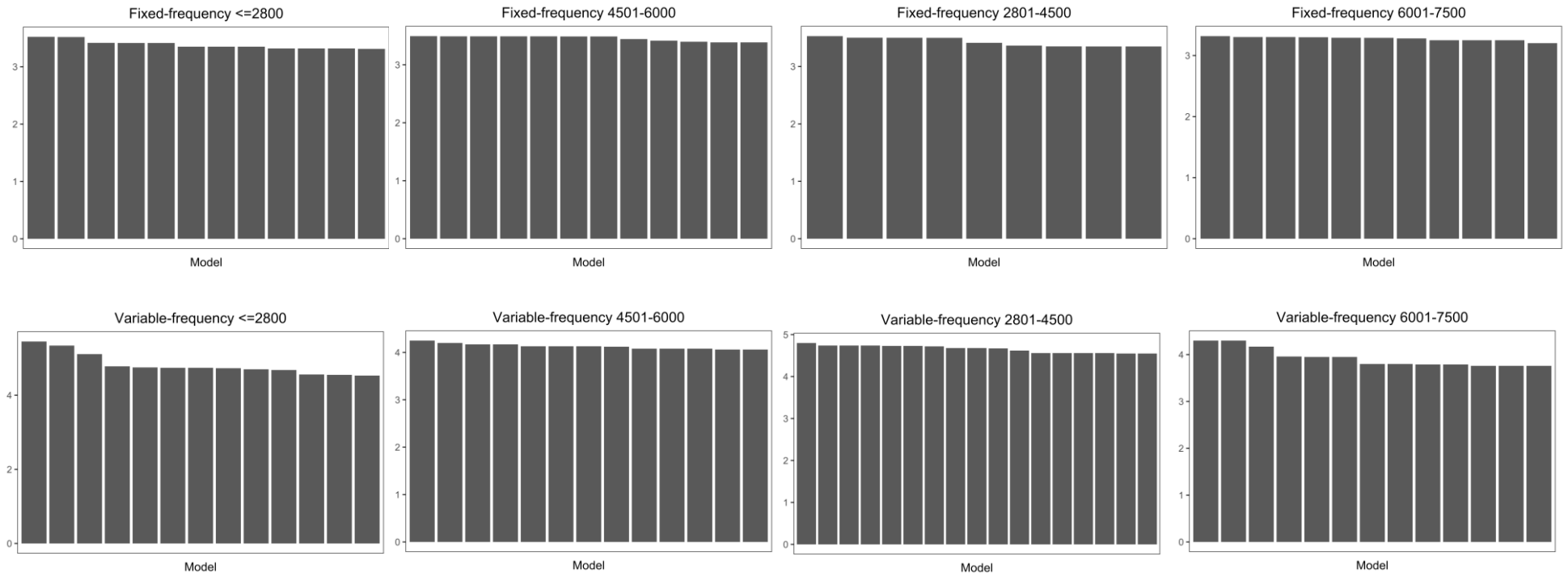
Effects of population, urbanization, household size, and income on electric appliance adoption

- Positive effect: Urbanization, household downsizing, and penetration growth
  - Growth of penetration (higher income) contributes the most
- Possible negative effect: Population change
  - Low total fertility rate is the reason



Energy Performance of Major Electric Appliances

Energy performances of many models: Segment by technology and volume



Take AC as an example

Category	Fixed-frequency	Variable-frequency
<=2800	12.5	8.8
2801-4500	13.3	9.4
4501-6000	7.0	4.9
>=6001	25.8	18.2

Market share of each category

- Normalized Ali 1688 purchasing index

Energy Performance of Major Electric Appliances

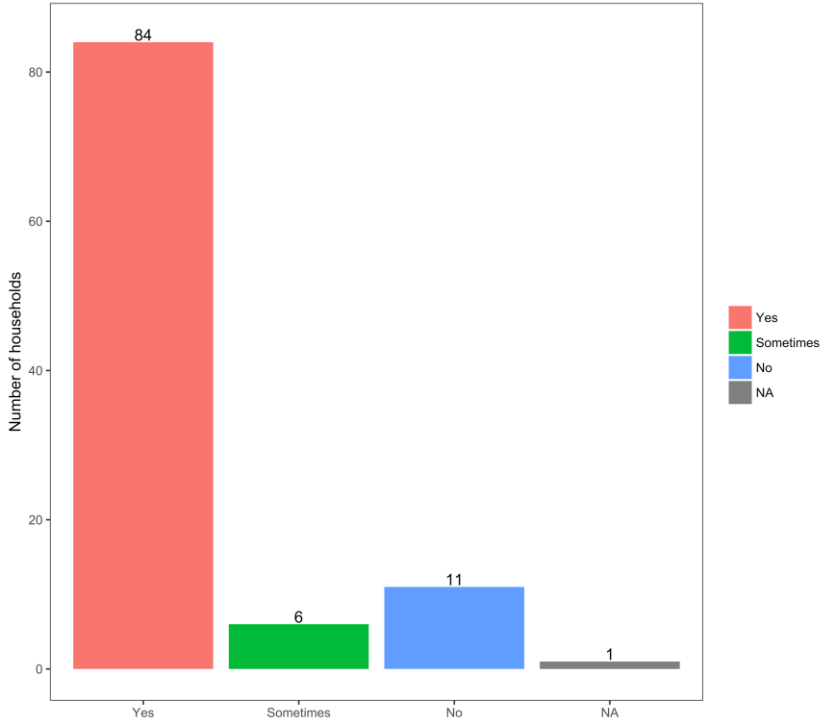
End-use	Electric appliance	Indicator	Unit	Low	Middle	High
Space cooling	Air conditioning system	Energy consumption efficiency	Wh/Wh	3.77	3.89	4.08
		Cooling power	W	1288	1379	1453
	Fan	Name plate power	W	80	63	55
Water heating	Water heating equipment	Standing loss per 24 hours	KWh	0.60	0.55	0.50
		Hot water output rate	%	0.80	0.85	0.90
		Name plate power	W	3000	3000	3000
Kitchen appliance	Induction Cooker	Operating mode power	W	2000	2100	2200
		Off mode power	W	1	1	1
	Rice cooker	Operating mode power	W	1425	896	645
		Heat-preserving mode power	W	75	61	50
	Microwave Oven	Operating mode power	W	1075	954	850
		Off mode power	W	1	1	1
	Cook Vent	Name plate power	W	224	100	50
Food preserving	Refrigerator	Annual electricity consumption	KWh	158	143	105
Clothes Washing	Clothes washing machine	Electricity consumption per cycle	KWh/time	0.72	0.61	0.55
TV watching	Television	Operating mode power	W	119	90	66
		Off mode power	W	0.5	0.5	0.5
	TV receiver	Operating mode power	W	4.4	4.2	3.6
		Off mode power	W	0.8	0.6	0.4
PC playing	Laptop and desktop	Operating mode power	W	163	130	113
		Standby mode power	W	4.1	3.3	2.7
		Off mode power	W	2.7	2.1	1.8
Lighting	Lightbulbs	Energy consumption per hour (Workday)	W	350.85	173.14	74.64
		Energy consumption per hour (Weekend)	Unit	372.81	184.30	78.88

Typical Usage Archetypes of Each End-use

Survey Instruments

- Residential survey in 124 households, covers all districts in Beijing city (summer 2017)

Take washing machine as an example



Survey ID | Times | Frequency | Weekly Schedule | Hourly Schedule

ID	Times	Frequency	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	0	1	2	..	21	22	23
1	1	1	1			1	1	1	1	0	0	0			1	0
2	3	2				0	1	1	0	0	0	0			1	0
…	1	1				1	1	1	1	0	0	0			1	0
83	4	2	0			1	0	0	1	0	0	0			1	0
84	1	1	1	1	1	1	1	1	1	0	0	0	…	1	1	0

daily =1
weekly=2
monthly=3
seasonally=4
annually=5
never=6

Yes =1
No=0

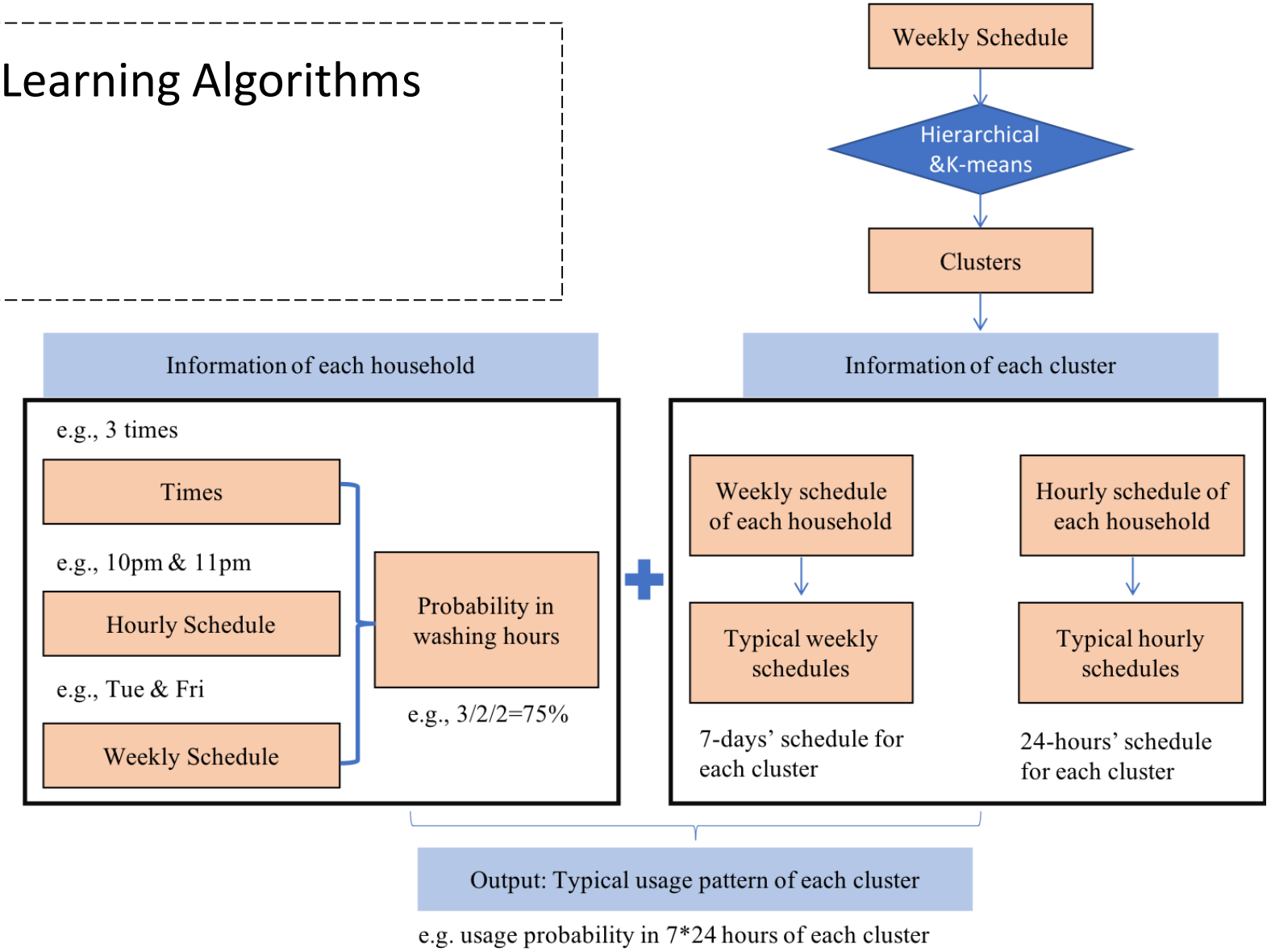
Typical Usage Archetypes of Each End-use

Non-supervised Machine Learning Algorithms

- Hierarchical clustering
- K-means clustering

Take washing machine as an example

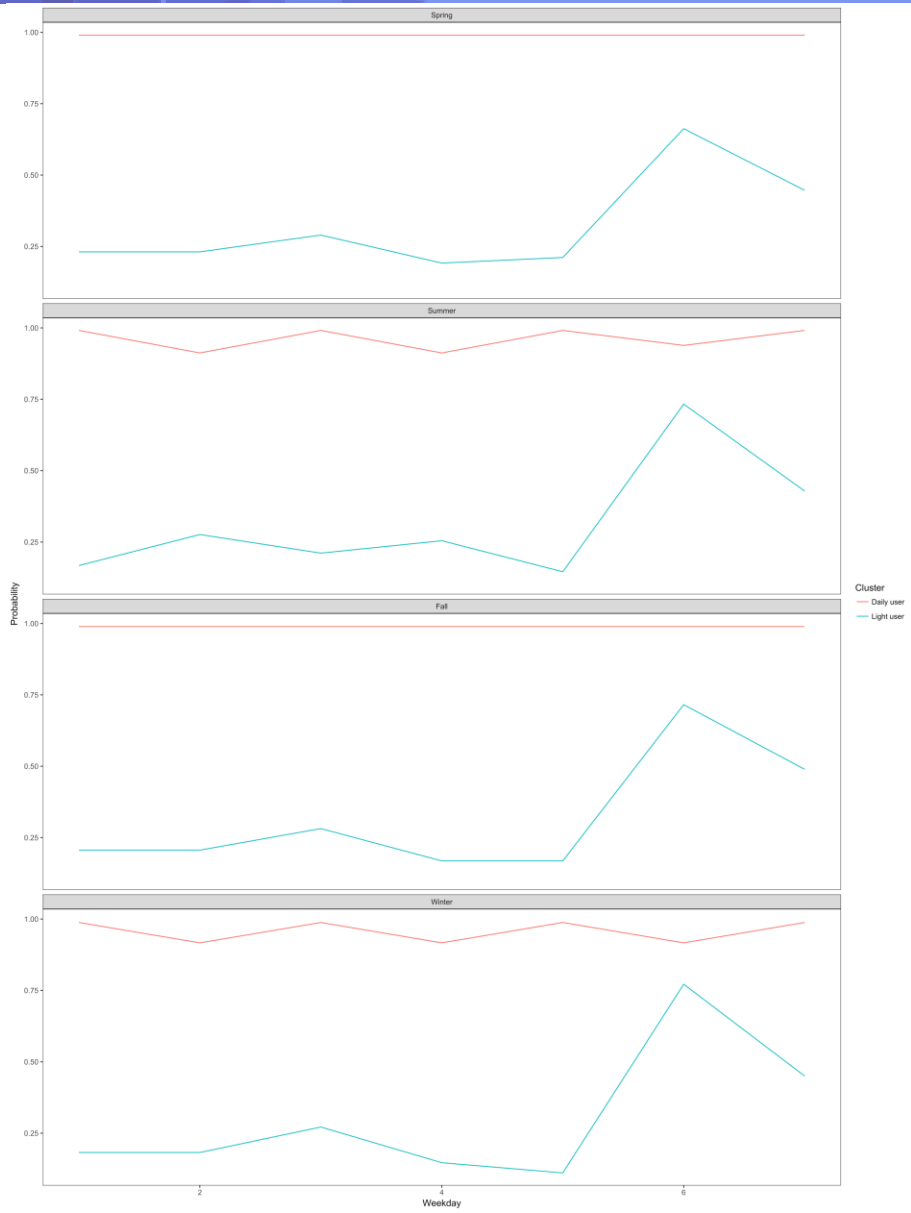
Usage archetypes in each season

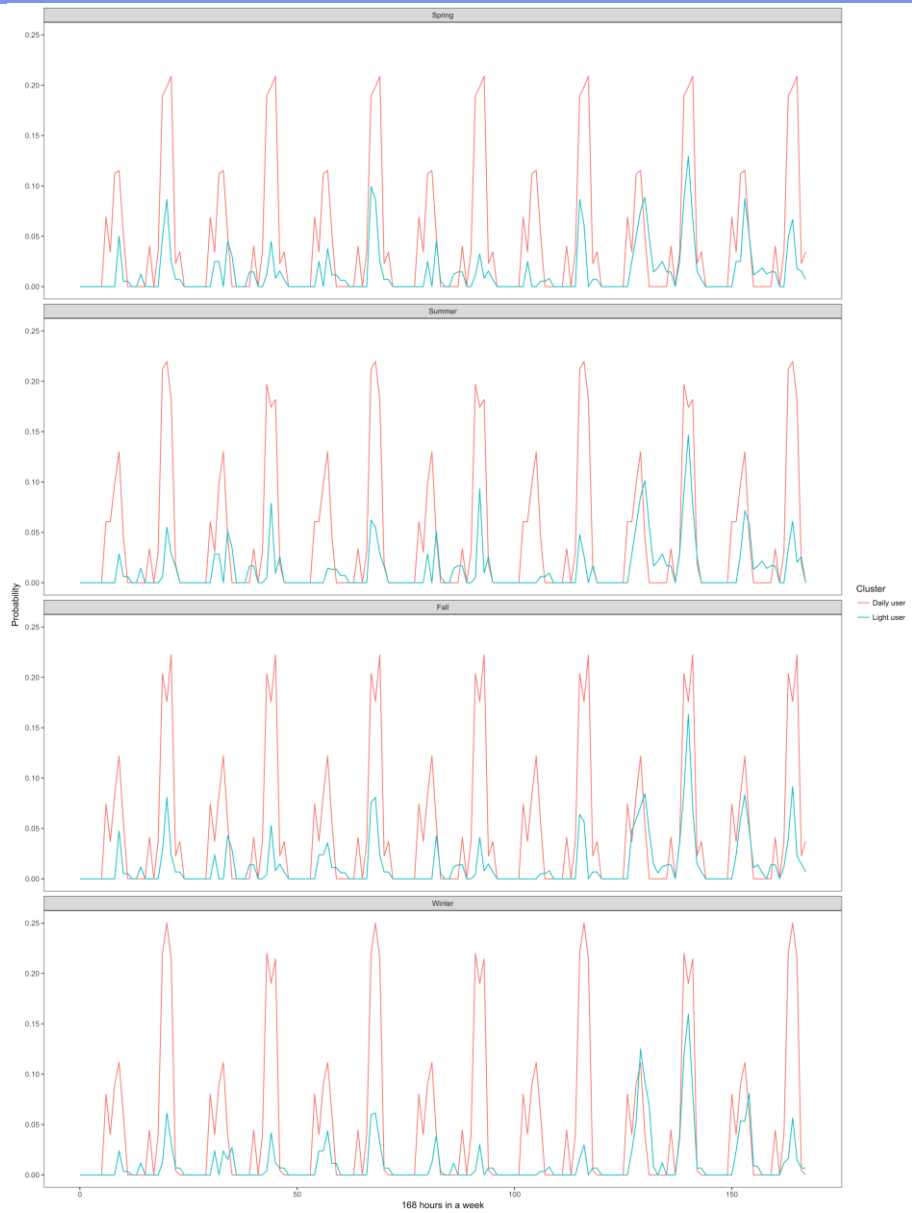


Typical Usage Archetypes of Each End-use

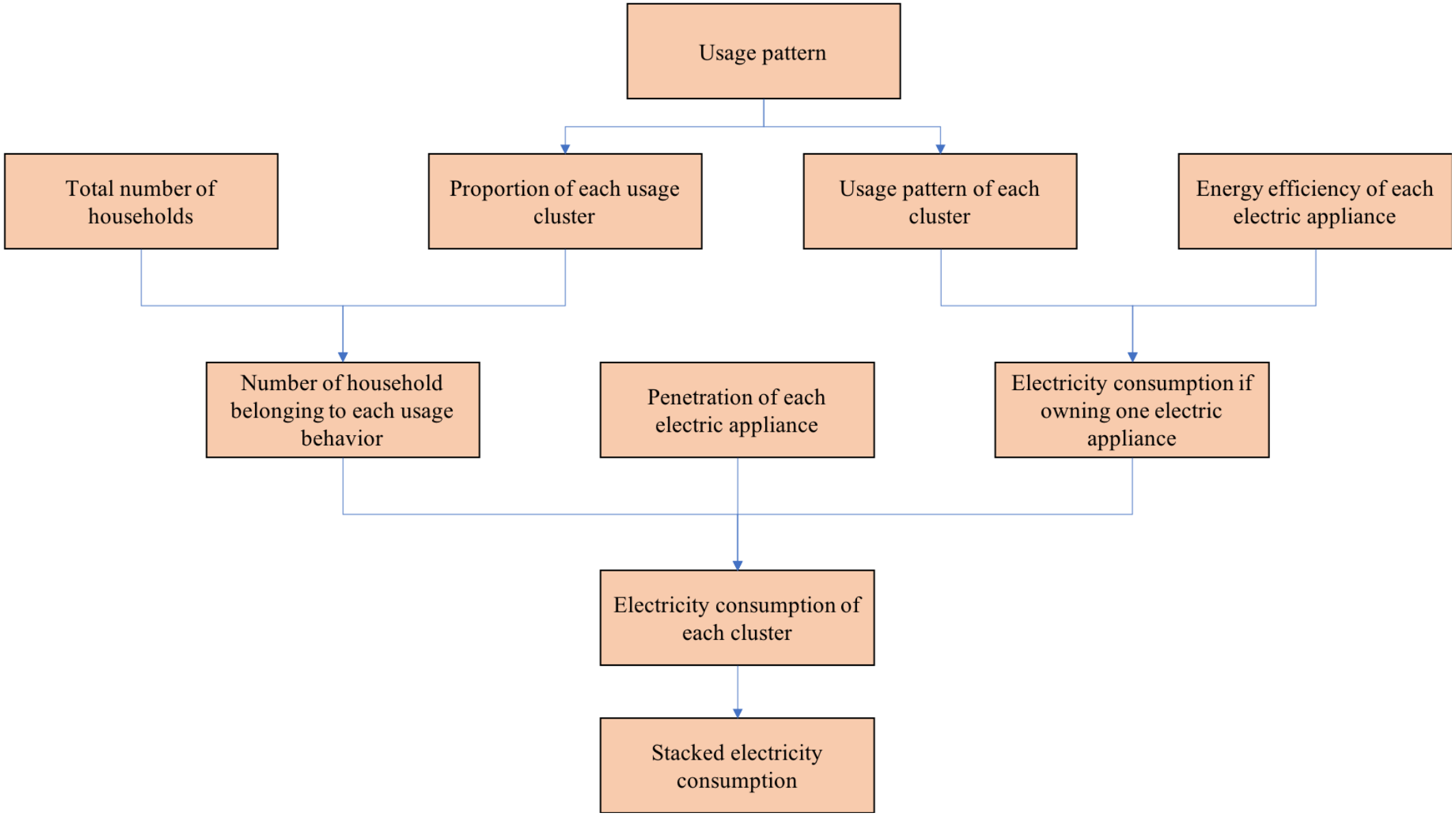
- Two types of households
  - Every single day
  - Every other day
- Two-peak shape
  - Morning (6-10am)
  - Evening (7-9pm)

Cluster	Daily user	Light user
Spring	36.9	63.1
Summer	39.3	60.7
Fall	45.2	54.8
Winter	33.3	66.7



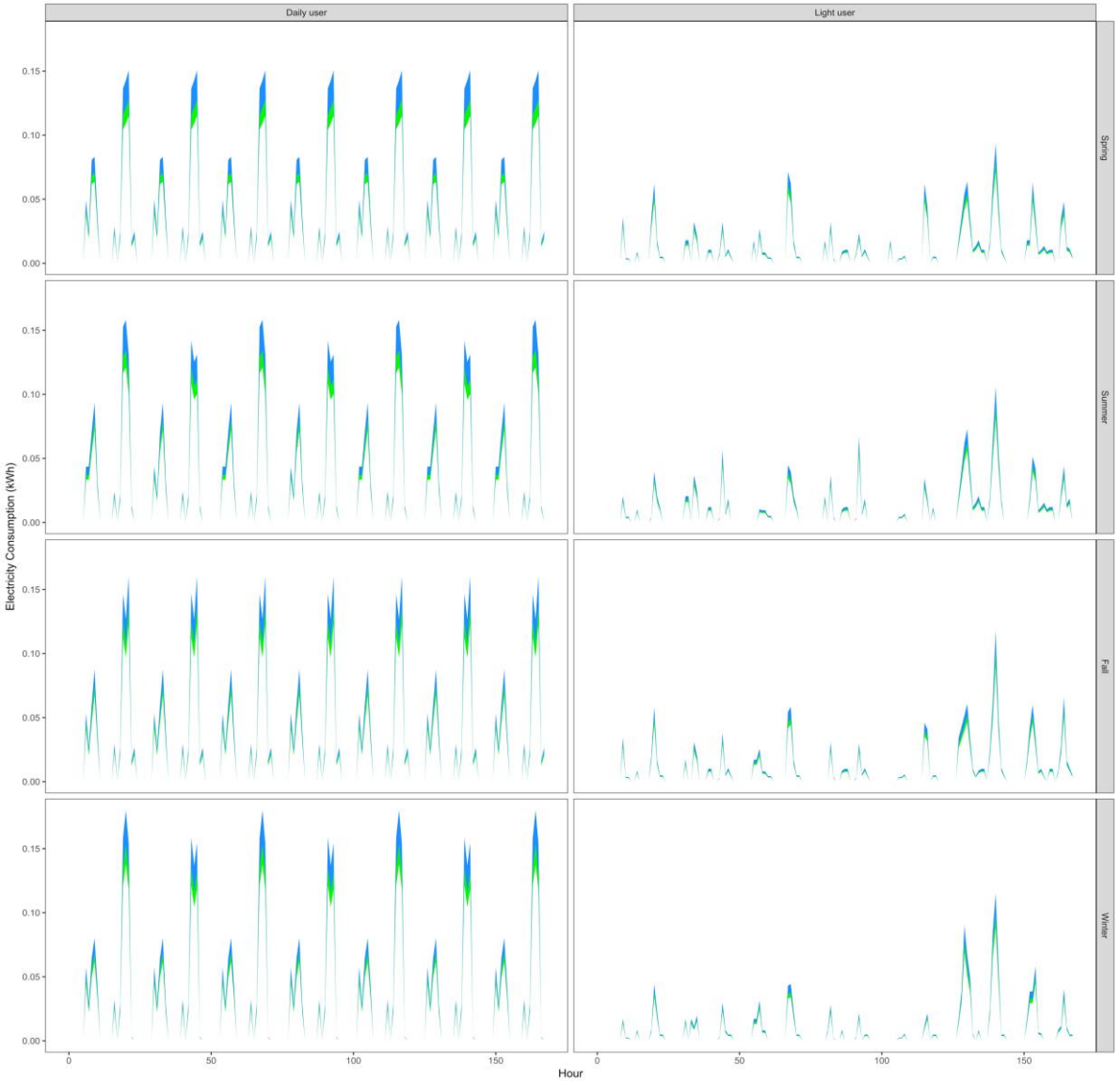


Residential Electricity Demand: Bottom-up Method

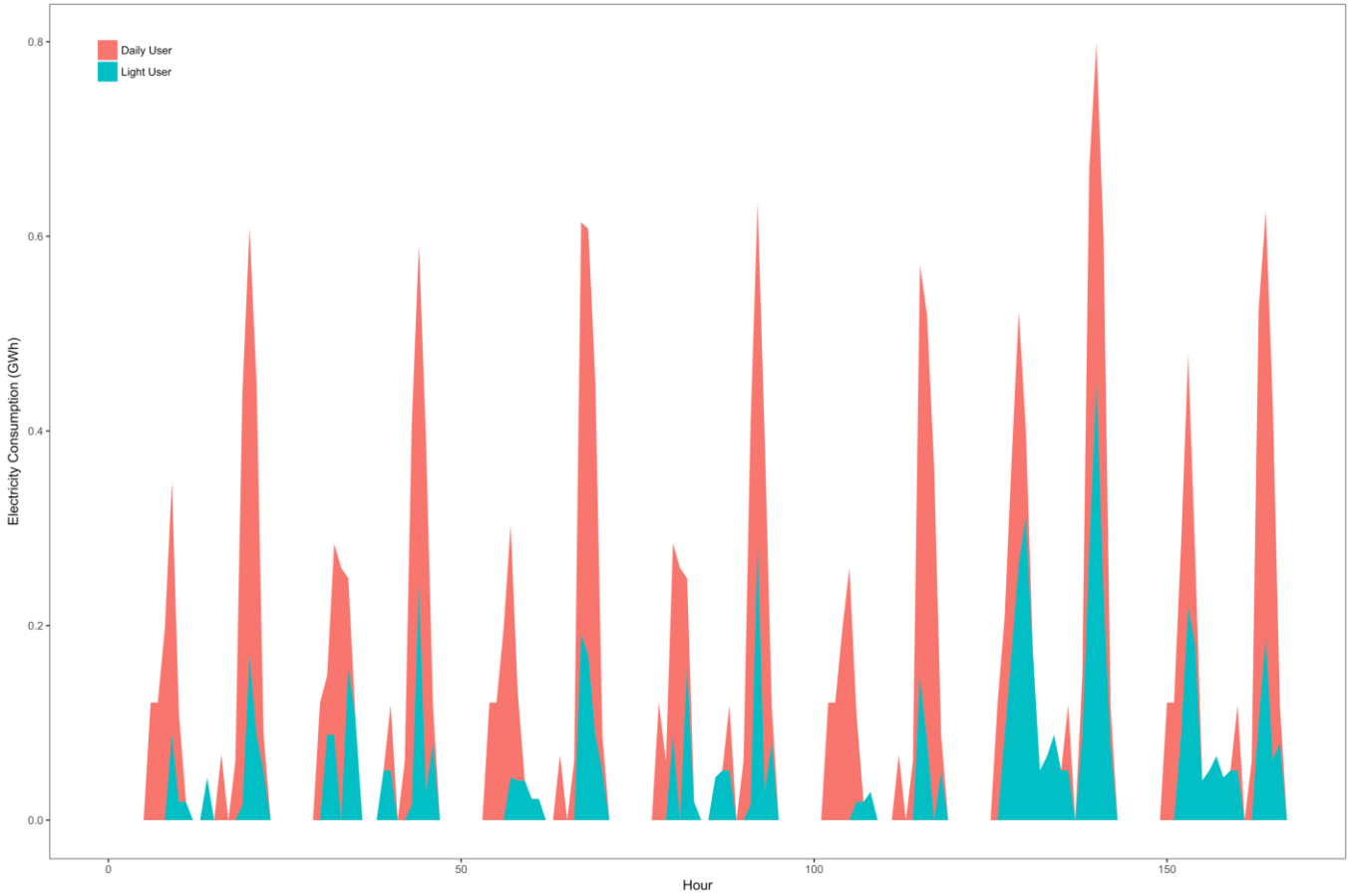


Electricity Demand of Each Usage Archetype

Electricity consumption of one typical clothes washing machine



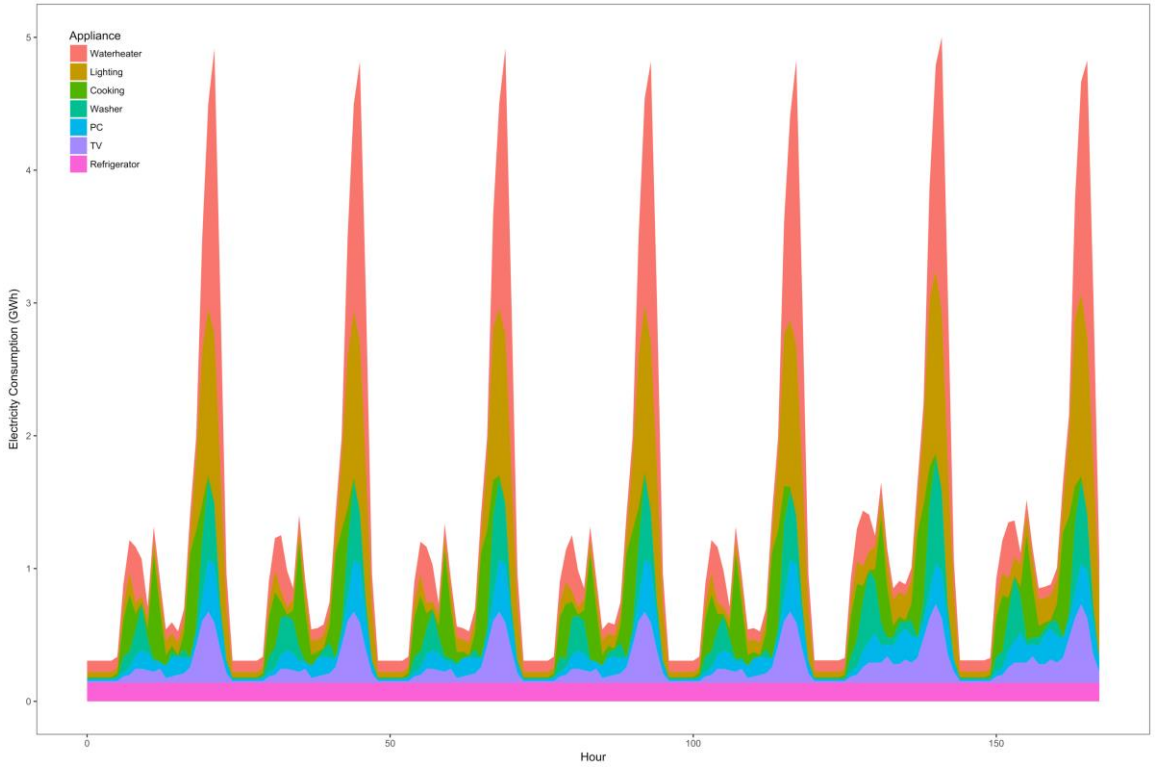
Electricity consumption for clothes washing in summer under the middle level of energy performance in Beijing

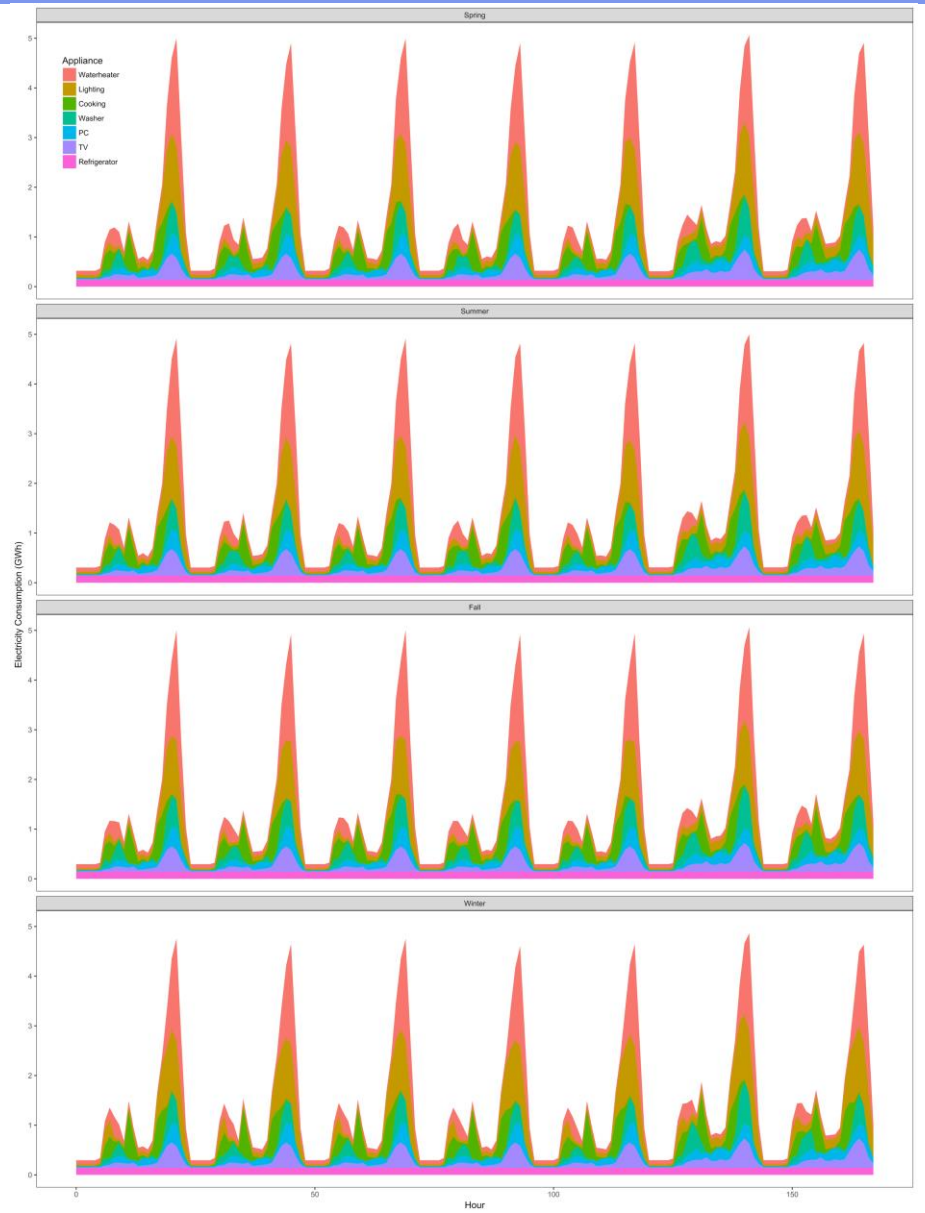


Residential Electricity Demand: Bottom-up Results

	Appliance	Spring	Summer	Fall	Winter	Total
Weekly	Air conditioner	-	-	-	-	4427.3
	Water heater	59.7	60.3	59.7	57.1	3078.6
	Lighting	56.6	52.4	49.4	58.0	2813.3
	Cooking	30.1	30.1	30.4	31.9	1593.4
	Washer	22.1	21.7	24.1	19.8	1139.5
	PC	19.8	19.9	19.8	19.8	1032.0
	TV	22.8	23.2	22.7	22.7	1188.3
	Refrigerator	23.5	23.5	23.5	23.5	1223.0
Seasonal		3051.2	7431.7 [a]	2986.4	3026.1	16495.5

- Peak of demand
  - Space cooling
  - Water heating
  - Lighting





Outline

1 Background and Objectives

2 Modeling Framework

3 Methods, Data and Results

4 Future Work

Future Works

- To expand samples/household surveys
  - Pilot surveys -> ~ 1000 surveys
  - Understanding the behavior, attitudes, and beliefs of residential users

- To validate results by comparing with metering information
  - Understanding the performance of bottom-up model
  - Calibrating the bottom-up results

THANKS!