Building Energy Modeling: the Long-Term Evolution of Building Energy Consumption in China and India and the Influence of Socioeconomic and Climate Change on Heating and Cooling Demands

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Presentation Outline

- Modeling Building Energy Use
- The Long-term Evolution of China’s Building Energy Use
- The Long-term Evolution of India’s Building Energy Use
- Population Weighted HDD/CDD
- Coupling Climate Change and Population Migration with Building Energy Use
- Assessing the Long-term Impact of China Building Code
Modeling Building Energy Use:
Overview of Building Energy Use in China

Note:
190 million households in urban
183 million households in rural in 2005
Modeling Challenges

1. How should urban/rural population change over time?
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2. How to build a reasonable floor space expansion model?
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2. How to build a reasonable floor space expansion model?

3a. How should energy service demands per unit of floor space vary with income and prices?
Modeling Challenges

1. How should urban/rural population change over time?

2. How to build a reasonable floor space expansion model?

3a. How should energy service demands per unit of floor space vary with income and prices?

3b. How to define urban/rural preferences for individual energy service demands and fuels?
Modeling Urbanization in China
Urbanization in China

- **We specify a relationship between urbanization rate and total income**
  Based on parameters obtained by regressing data from national statistics and UN urbanization prospect (by 2050)
- **Urbanization mostly occurring between 2005-2050 and ultimately reaching 80% in China by the end of the century.**
Demand for Floor space
The approach to Floor Space Expansion

This is a very idealized approach that has some weaknesses when applied to floorspace.

- Urban / rural/commercial floor space expansion is not inter-related.
- Households’ preferences for floor space depends only on where they are currently located.
- There is no noticeable lag in market adjustment to price and income changes.
- Steady decline in household size is not an important factor.
- There is no sizeable technical changes in building floorspace service production.

\[
\text{Demand}_t = k_D P_t^{\varepsilon_D} I_t^{\varepsilon_I} \quad \text{Supply}_t = k_S P_t^{\varepsilon_S}
\]

Floor space price [$ / m^2$]

Floor space per capita [m$^2$ per capita]
International Comparison of Residential Building Floor Space

Per capita residential floor space for selected countries (1990-2004, IEA) vs. our projections for China (2005-2095)
Demand for Building Services
Modeling the Change in Service Demands

Demand for Space Heating Service [GJ-output/m²]:

\[
Q_{H,t} = k_H \cdot (HDD_t \cdot ShellEff_t \cdot SurfaceRatio_t - \lambda_H InternalGain_t) \cdot 1 - \exp\left(- \ln 2 \cdot \left(\frac{Y_t}{P_{H,t}}\right)\right)
\]

Space Heating Requirement (satiated demand)  
Economic Behavior

Demand for Space Cooling Service [GJ-output/m²]:

\[
Q_{C,t} = k_C \cdot (CDD_t \cdot ShellEff_t \cdot SurfaceRatio_t + \lambda_C InternalGain_t) \cdot 1 - \exp\left(- \ln 2 \cdot \left(\frac{Y_t}{P_{C,t}}\right)\right)
\]

Space Cooling Requirement (satiated demand)  
Economic Behavior

Demand for Other Services (water heating & cooking, lighting, other appliances):

\[
Q_t = k_i \cdot q_i \left[1 - \exp\left(- \ln \frac{2}{\alpha_i} \cdot \left(\frac{Y_t}{P_t}\right)\right)\right]
\]
How to Represent the Income Effects on Demands: The Case of Chinese Residential Buildings

Projected expansion of energy services per unit of floorspace indexed to their satiation levels (2005-2095)

- Urban Residential Buildings
- Rural Residential Buildings

This shows how households would allocate their income into different energy services, given that these services have their own satiation points.
How to Model Traditional Biomass?

► In 2005, traditional biomass (TB) accounted for 84% and 73% of energy used by rural households in China and India, respectively.

► Traditional biomass use in rural areas is assumed to be gradually phased out (No market price but potentially huge non-market price).

► **Full cost of TB-delivered energy service**

\[
\text{Full cost of TB-delivered energy service} = \text{capital cost of TB-using equipment} + \text{time cost of collecting TB}
\]
The Long-Term Evolution of China’s Building Energy Use
Residential Building Energy Use in China

The three competing drivers:
Income growth, fuel substitution, and technology improvement

Residential Energy Use per Unit of Floorspace
: International Comparison

Source: Our model calculation, Database for Energy efficiency indicators in Europe, US Building Energy Databook, and OECD stat extracts
China’s Residential Building Energy Use per Unit of Floorspace by Service

- Urban and rural energy use patterns are different because of their differences in
  1. Fuel options and associated technology efficiencies
  2. Urban-to-rural income gap
  3. Preferences for energy services
How would building fuel consumption change over time?

- Fast electrification even in the baseline scenario
• How would building fuel consumption change over time?
• How might fuel consumption respond to advanced tech programs?

- Fast electrification even in the baseline scenario
- Advanced technologies substantially reduces total final energy.
- But, they have nearly no influence on fuel shares

*Faster improvement in assumed technical efficiencies than the baseline scenarios with the rate depending on the maturity of the technologies*
• How would building fuel consumption change over time?
• How would it respond to a carbon price?

- A carbon tax policy reduces total final energy, but not substantially.
- The tax policy induces the change in fuel shares: more use of electricity and gas, and less use of coal and district heat.
• Why is fuel switching pronounced under a carbon tax policy?

- The prices of more carbon-intensive fuels (coal, oil, and biomass) rise faster than the prices of other fuels (electricity and gas).
- Fuel switching is more attractive under the policy case than the regulatory approach.

* Global carbon tax pathway achieving 550ppm CO₂ by 20100.
• What would be the impact of a carbon policy on building electrification?

- The majority of electrification in China occurs simply because of the income-driven growth in services that use electricity.
- Price-induced electrification exists in a meaningful way well past mid-century, when carbon prices become very high.
• How would fuel consumption change in urban residential buildings?
• How would it respond to a carbon price?

The carbon policy substantially reduces the use of district heat and coal for space heating, while increasing the use of coal gas.
• How would fuel consumption change in rural residential buildings?
• How would it respond to a carbon price?

- Service intensification interacts with rapid fuel switching away from traditional biomass, resulting in decreased intensity of energy consumption in rural buildings.

- Price effects from the carbon policy push to extend the use of traditional bio-energy.
The Long-Term Evolution of India’s Building Energy Use
India Buildings’ Energy Consumption (2005)

- **Urban**: 1.15 EJ
  - Cooking: 76.3%
  - Appliance: 11.0%
  - Lighting: 9.9%
  - Cooling: 2.6%
  - Heating: 0.1%

- **Rural**: 5.41 EJ
  - Cooking: 93.9%
  - Appliance: 1.8%
  - Lighting: 4.2%
  - Cooling: 0.1%
  - Heating: 0.0%

- **Commercial**:
  - Cooking: 70.5%
  - Appliance: 3.5%
  - Lighting: 8.8%
  - Cooling: 16.8%
  - Heating: 0.4%

Legend:
- TradBiomass
- Refined Liquids
- Gas
- Electricity
- Coal
Final energy consumption by Indian buildings

- Very fast electrification:
  - rapid expansion of cooling, appliances, and lighting
- Non-electricity fuel (LPG and coal) used mainly for cooking
Electrification in Indian Buildings

- Similar to China buildings, the majority of electrification in India occurs simply because of the income-driven growth in electricity-using services, such as cooling, appliances, and lighting.
- Price-induced electrification is very small.
Population Weighted HDD/CDD
Method of Population Weighted HDD/CDD

- Overview of HDD/CDD
- Scenarios Design
- Method
  - Monthly and annual HDD/CDD
  - Population weighted HDD/CDD
- Summary
Overview of HDD/CDD
What are HDD and CDD?

- Degree-days are essentially the summation of temperature differences from a human comfort level over time. They capture both extremity and duration of outdoor temperatures.

- Heating degree day (HDD) and cooling degree day (CDD) are measured in “degree-days” below (HDD) or above (CDD) the set point.

- In general, a “set point” of 18°C is used for calculating HDD and CDD.

- Population weighted HDD/CDD can help understand the aggregated requirement of heating and cooling service across a country or region with heterogeneously distributed population.
Scenarios Design:

For Future HDD/CDD
Scenarios design

* Reference represented by SRES A2 emissions pathway; 550 ppmv scenario represented by the SRES B1 scenario
Two Emissions Scenarios

- **A2 Emissions (“Reference”)**
  - High emissions pathway in IPCC SRES scenarios
  - Corresponding to Reference Scenario in GCAM

- **B1 Emissions (“550ppm”)**
  - Low emissions pathway in IPCC SRES scenarios
  - Corresponding to 550ppm stabilization scenario in GCAM
Three Climate Models

- **CCSM (#15)**
  - National Center for Atmospheric Research, USA (Collins et al., 2006)

- **GISS (#7)**
  - NASA/Goddard Institute for Space Studies, USA (Russell et al., 2000)

- **Hadley (#16)**
  - Hadley Centre for Climate Prediction and Research/ Met Office, UK (Gordon et al., 2000)

The three climate models were chosen to represent a range of temperature outcomes.

Three population distribution scenarios (A2r, B1, Fixed)

<table>
<thead>
<tr>
<th></th>
<th>A2r</th>
<th>B1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population size</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Demographic transition</td>
<td>Delayed and slow</td>
<td>Rapid</td>
</tr>
<tr>
<td>Long-term fertility levels</td>
<td>Near or below replacement</td>
<td>Well below replacement</td>
</tr>
<tr>
<td><strong>Urbanization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urbanization rates</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Megacity growth</td>
<td>High</td>
<td>Low (constrained)</td>
</tr>
<tr>
<td>Urban–rural gradient</td>
<td>Medium–high</td>
<td>Converging to zero</td>
</tr>
<tr>
<td><strong>Income</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Income growth</td>
<td>Medium–low</td>
<td>High</td>
</tr>
<tr>
<td>Income convergence</td>
<td>Very low (initially diverging)</td>
<td>Very rapid</td>
</tr>
<tr>
<td>Domestic/international price differences (for PPPs)</td>
<td>Initially persistent, slow convergence after 2040</td>
<td>Rapid convergence</td>
</tr>
</tbody>
</table>

*Note that this is only the population distribution. We are using a single population scenario for GCAM analyses*

Fixed scenario: we maintain the year 2000 population distribution.

Source: A. Grübler et al. / Technological Forecasting & Social Change 74 (2007) 980–1029
Step 1:

Annual HDD/CDD Estimation
HDD/CDD Calculation

Heating Degree Day (HDD)

\[ HDD_{Month} = \sum_{day=1}^{m} (18 - T_c) \]

\[ HDD_y = \sum_{Month=1}^{12} HDD_{Month} \]

Cooling Degree Day (CDD)

\[ CDD_{Month} = \sum_{day=1}^{m} (T_c - 18) \]

\[ CDD_y = \sum_{Month=1}^{12} CDD_{Month} \]
Monthly mean temperature (0.5\(^\circ\), 2000-2099)

- Monthly mean temperature data does not fully capture the variation in daily mean temperature.
- An improvement is needed for annual HDD/CDD estimation.
Variance of Daily Temperature (historical daily data 1950-1999)

- Observationally-derived baseline data

- Source: Globally Downscaled Climate Data at http://www.engr.scu.edu/~emaurer/global_data/
Standard Deviation / Variance (seasonal trend removed)

Example

\[ 6_{\text{month} i} = \sqrt{\frac{\sum_{\text{day}=1}^{n}(T_{\text{day}} - \bar{T}_i)^2}{n - 1}} \]
Monthly and Annual HDD/CDD

\[
\begin{align*}
HDD_m &= \sum_{T=T_m-36_m}^{T=T_m+36_m} (18 - T) f(T) \Delta TD_m & \text{if } T < 18 \\
CDD_m &= \sum_{T=T_m-36_m}^{T=T_m+36_m} (T - 18) f(T) \Delta TD_m & \text{if } T > 18
\end{align*}
\]

\[
\begin{align*}
HDD_y &= \sum_{m=1}^{12} HDD_m \\
CDD_y &= \sum_{m=1}^{12} CDD_m
\end{align*}
\]
Annual HDD 2000-2099 (Ref & CCSM)
Annual HDD 2000-2099 (Ref & CCSM)
Step 2:
Weighting HDD and CDD by Population
Population Data from IIASA

- We are focusing on distribution of population – not on totals.
- 3 distribution scenarios
- 0.5 degree spatial resolution (same as temperature data)

Population (1990-2100) 10-year Step

- A2r
- B1
- Fixed
IIASA Population Downscaling Method

- 4 steps to downscaling
  - 11 regions -> 185 countries -> sub-national (urban & rural) -> grid

- Urban and rural population was disaggregated at national level

- Gravity type model was applied on urban population
Change in Population Distribution (A2r)
Population Weighted HDD/CDD

\[ HDD_i = \frac{\sum_j HDD_{i,j} P_{i,j}}{\sum_j P_{i,j}} \]

\[ CDD_i = \frac{\sum_j CDD_{i,j} P_{i,j}}{\sum_j P_{i,j}} \]

- \( HDD_i \): Heating degree day in GCAM region \( i \)
- \( CDD_i \): Cooling degree day in GCAM region \( i \)
- \( HDD_{i,j} \): Heating degree day of cell \( j \) in GCAM region \( i \)
- \( P_{i,j} \): Annual population of cell \( j \) in GCAM region \( i \)
Population Weighted HDD 2000-2100 (CCSM-ref-A2r)
Population Weighted HDD 2000-2100 (CCSM-ref-A2r)
Results
Global Population Weighted CDD

Ref emissions scenario

550 ppm emissions scenario
Regional HDD/CDD

Global map of GCAM regions
Emission Scenarios (Ref & 550ppm) based on CCSM & A2r pop

- **USA HDD**
- **China HDD**
- **USA CDD**
- **China CDD**
Climate Models (CCSM, GISS, & Hadley) based on ref and A2r pop

USA HDD

China HDD

USA CDD

China CDD
Population Scenarios (A2r, B1 & Fixed)
based on CCSM and ref
Summary of population weighted HDD/CDD

- **Emissions**: Emission scenarios have important impact on population weighted HDD/CDD, and the difference between emission scenarios increases in mid century.

- **Climate models**: HDD/CDD from different climate models have similar trend, and CCSM generally has medium estimation of HDD/CDD.

- **Population migration**: The population migration has different impact on population weighted HDD/CDD in different level and in different regions. At global level, population may increase in “less-cold” areas. At regional level, population migration shows different impacts (e.g. China and USA).
Coupling Climate Change and Population Migration with Building Energy Use
Implementation of Emissions Scenarios in GCAM

- **Reference scenario: SRES A2 emissions path**
  - No climate mitigation policy, business-as-usual

- **550ppm stabilization scenario: SRES B1 emissions path**
  - 3 emissions trading markets (China, U.S., and ROW) ensuring 550ppm global emissions path.
  - China emissions pathways do not vary across climate and migration scenarios to enable comparison of energy consumption in the buildings sector.
In the reference scenario, climate change lowers US buildings’ final energy by 6% or less.

Stabilization policy reduces the shifts in building energy use.
In the reference scenario, climate change lowers China buildings’ final energy by 6% or less.

Stabilization policy reduces the shifts in building energy use.
Less heating energy use & more cooling energy use with climate change

Migration decreases heating energy use but increases cooling energy use:

Urban growth and its spillover concentrated in ‘less-cold’ eastern areas
US Building Energy Use by Fuel

* The left figure shows ‘Ref-Fix’ case and the right figure shows ‘CCSM-Ref-Fix’ case.
China Building Energy Use by Fuel

* The left figure shows ‘Ref-Fix’ case and the right figure shows ‘CCSM-Ref-Fix’ case.
Less use of direct fossil fuels (coal, oil, gas, and biomass), less use of district heat, and more use of electricity in the buildings sector.

Regardless of emissions scenarios, reductions in building energy use are distributed across various fossil fuels.
Less use of direct fossil fuels (gas, oil, and biomass) and more use of electricity

Regardless of emissions scenarios, reduction in gas consumption accounts for the majority of the decrease in building energy use.
Climate change will decarbonize the buildings sector, and the effect is more pronounced in China than in the U.S.

In terms of total emissions (including power sector emissions), global climate change virtually has no effect on the sector’s emissions.
Assessing the Long-term Impact of China Building Codes
### Table 3.3.1: Different Regions and Basic Requirements

<table>
<thead>
<tr>
<th>Region</th>
<th>Climate Type</th>
<th>Basic Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>I A</td>
<td>Hot Summer</td>
<td>-</td>
</tr>
<tr>
<td>I B</td>
<td>Cold Winter</td>
<td>-</td>
</tr>
<tr>
<td>I C</td>
<td>Cold Winter</td>
<td>-</td>
</tr>
<tr>
<td>I D</td>
<td>Cold Winter</td>
<td>-</td>
</tr>
<tr>
<td>II A</td>
<td>Hot Summer</td>
<td>-</td>
</tr>
<tr>
<td>II B</td>
<td>Cold Winter</td>
<td>-</td>
</tr>
<tr>
<td>II C</td>
<td>Cold Winter</td>
<td>-</td>
</tr>
<tr>
<td>III A</td>
<td>Winter</td>
<td>-</td>
</tr>
<tr>
<td>III B</td>
<td>Winter</td>
<td>-</td>
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<tr>
<td>III C</td>
<td>Winter</td>
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<td>IV A</td>
<td>Winter</td>
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<td>IV B</td>
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<td>IV C</td>
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<td>V A</td>
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<td>V B</td>
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<td>-</td>
</tr>
<tr>
<td>V C</td>
<td>Winter</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Figure

- "Cold" regions include: Hot Summer, Cold Winter, Cold.
- "Severe Cold" regions include: Hot Summer, Cold Winter, Cold.
- "Temperate" regions include: Hot Summer, Cold Winter, Cold.
- "Hot Summer, Cold Winter" regions include: Hot Summer, Cold Winter, Cold.
- "Hot Summer, Cold" regions include: Hot Summer, Cold Winter, Cold.

Note: The figure shows the climate distribution across China with different colors indicating various climate zones.
The Twelve Buildings Sectors

China

- Cold
  - Urban Residential
  - Rural Residential
  - Commercial

- Hot Summer Cold Winter
  - Urban Residential
  - Rural Residential
  - Commercial

- Hot Summer Warm Winter
  - Urban Residential
  - Rural Residential
  - Commercial

- Severe Cold
  - Urban Residential
  - Rural Residential
  - Commercial

9 Provinces: Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, Tibet, Shaanxi, Gansu

9 Provinces: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan

6 Provinces & 2 countries: Fujian, Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Cambodia, Vietnam

6 Provinces & 2 countries: Inner Mongolia, Jilin, Heilongjiang, Qinghai, Xinjiang, Liaoning, Mongolia, DPRK
Modeling Overview

- **Building Stock Model**
  - Assumptions about future building codes, compliance, and building retrofit

- **Global Change Assessment Model (GCAM)**
  - Base-year energy consumption by fuel and service

- **Historical info:**
  - Construction
  - Building types
  - Codes/standards
  - U value

- **Climate Change Impact:**
  - Heating/Cooling Degree Days by Sub-Region

- **Building Energy Results**
Building Energy Consumption: The Three Building Shell Efficiency Scenarios (Preliminary Results)

- We constructed a building stock model that specifies building construction, building code development and enforcement, and retrofits and retirement. Based on this, three distinct shell efficiency scenarios were developed.
- The improvement in building envelope is likely to have a sizeable impact on total building energy consumption in China.
- The impact varies across climate regions in China.
Current and Future Research

► Current
  ◆ Development of a Global Building Model
  ◆ Multi-model Detailed assessment of US Building Sector:
    Linking to BEND and WRF in Richland

► Future
  ◆ Development of a population migration model linked to income distribution and climate condition
  ◆ Climate feedback and downscaling