Creating a Virtual Utility District: Assessing Quality and Building Energy Impacts of Microclimate Simulations

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• Career
  – 2009+ Oak Ridge National Laboratory, R&D staff
    • ETSD, Building Technology Research & Integration Center (BTRIC), Building Envelope & Urban Systems Research Group (BEUSR)
  – 2012+ The University of Tennessee, Joint Faculty

• Education

• Professional Involvement
  – AEE, Lifetime Member, Certified Energy Manager, Certified Measurement & Verification Professional
  – PMI, Member, Project Management Professional
  – IEEE, Senior Member
  – ASHRAE, defines international building codes
    • TC1.5, Computer Applications, Voting member and officer
    • TC4.7, Energy Calculations, Voting member and officer
    • TC4.2, Climatic Information, Voting member and officer
    • SSPC169, Weather Data for Building Design Standards (24% of page count of building code), Voting member
    • SSPC140 and ASHRAE Guideline 14 involvement
Energy Consumption and Production

U.S. Energy Consumption by Sector

- Transportation 25%
- Residential 26%
- Industrial 30%
- Commercial 19%

45% Buildings consume 73% of the nation’s electricity


124 million U.S. buildings
$395 billion/yr energy bills

Goal of the DOE Building Technologies Office:
45% energy reduction per sq. ft. by 2030 compared to 2010 baseline

Building Energy Modeling – building descriptions + weather = estimated building energy consumption

- $9B/yr – ESCO; $7B/yr – utility EE
- $14B/yr – DR management systems

0.3% modified, BEM < 10% of those
Climate and U.S. Buildings
ASHRAE Climate Zones

- Based on weather stations, most w/ 18+ yrs of quality data (1961-1990)

Updated every 4 years (2021)

Climate Zone 0 (extremely hot):
10,800 < CDD 50°F
Int’l Energy Conservation Code (IECC) adopts for 2018 code
Redefine CZs using model data

• Resolution: 2 km x 2 km grid cells
• Extent: Continental United States
• Present Conditions (1950-2000): WorldClim
• Future conditions (2050, 2100): PCM and Hadley GCMs; for multiple scenarios (IPCC AR4 A1FI, B1)

1. Precipitation during the hottest quarter
2. Precipitation during the coldest quarter
3. Precipitation during the driest quarter
4. Precipitation during the wettest quarter
5. Ratio of precipitation to potential evapotranspiration
6. Temperature during the coldest quarter
7. Temperature during the hottest quarter
8. Sum of monthly $T_{avg}$ where $T_{avg}$ $\geq$ 5 deg C
9. Integer number of consecutive months where $T_{avg}$ $\geq$ 5 deg C (Length of potential growing season)
10. Solar interception
11. Day/night diurnal temperature difference
12. Elevation

• 12 energy-related variables
  • Temperature
  • Humidity
  • Radiation
  • Elevation
Building-adjusted CZ improvement

- What other (e.g. political) variables should be included?
- How could the nation's energy security and critical infrastructure resiliency be improved by incorporating future scenarios into the built environment?
- How much energy and $ could be saved by having a forward-looking climate-aware building code?
Climate Change Impacts
Why Urban Microclimate?

• Rode et al., “Cities and energy: urban morphology and residential heat-energy demand”
  • Neighborhood scale (500m x 500m), residential building type, density (ratio of total floor area to the total grid cell area), building height, surface-to-volume ratio and open space ratio (ratio between unbuilt area and total grid cell area) in cities (urban morphology) all significantly impact heat-energy demand for northern latitude (41-53°N) European cities.
  • Differences in building topographies (compact urban block, detached housing, high rise apartments and slab housing) represented among 100 different blocks in the four cities of London, Paris, Berlin and Istanbul showed significant per-city heat-energy use savings
    • 11% to 73% heat energy savings from least to most efficient urban topography
    • 54 to 83% heat energy savings for different building densities (as defined by the sum of the areas of all building floors to that of the sample block area)
Case Study: WRF+EnergyPlus at ORNL

- Weather Research Forecast model (WRF) with site-specific boundary conditions and urban canopy layer for interaction with building geometry
- WRF 3 nested domains to go from 4km² to 270-meters to 90-meters (breaking at 1km²)
- WRF simulation gives multiple weather files for each building
- Weather file couples WRF output to building input
- Future work will couple this with the surface heat transfer coefficients for tighter coupling at each timestep
Empirical Validation of WRF

- Daily, monthly, annual statistical characterization
  - Frequency distribution
  - Linear regression
  - ASHRAE Typical Meteorological Year (TMY)
- Whole building energy analysis
- Summary and comparison

90m horizontal resolution, hourly output

270m horizontal resolution, monthly averages

270m horizontal resolution, 2015 annual summary
Microclimate impact on building loads

Medium Office

Efficient Residence

HERS BESTEST L100A

Heating Load - Building 1

Heating Load - Building 2

Heating Load - Building 3

Cooling Load - Building 1

Cooling Load - Building 2

Cooling Load - Building 3
Microclimate – 5% ($4k/yr) energy difference

Hourly heating and cooling loads

Building 1 - Energy Consumption

Baseline and Individual Weather Parameter Swap

Annual Energy Cost ($)

Baseline and Individual Weather Parameter Swap
Chicago

- Urban planning for redevelopment of an area south of the Chicago loop
- Microclimate impacts on downtown Chicago, electrical planning, transportation
Urban Microclimate

- Physical elements and relationships identified, subsetted, recombined for new morphology
- Converted to binary format for WRF

<table>
<thead>
<tr>
<th>No. of Bldgs</th>
<th>Area ($m^2$)</th>
<th>Elec (GJ)</th>
<th>Gas (GJ)</th>
<th>EUI elec ($GJ/m^2$)</th>
<th>EUI gas ($GJ/m^2$)</th>
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</thead>
<tbody>
<tr>
<td>NoMorph</td>
<td>334</td>
<td>19,924,975</td>
<td>5,587,504</td>
<td>3,728,528</td>
<td>0.2804</td>
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<tr>
<td>Morph1</td>
<td>361</td>
<td>20,892,217</td>
<td>6,025,625</td>
<td>4,754,649</td>
<td>0.2884</td>
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<tr>
<td>Morph2</td>
<td>355</td>
<td>22,996,771</td>
<td>6,414,792</td>
<td>4,989,149</td>
<td>0.2789</td>
</tr>
</tbody>
</table>

Best EUI: High Density

- High density building parcel
- Low density, more spread building parcel

Low-rise residential

Chicago Loop with undeveloped parcel

Moderate density building parcel
Model America 2020 – calibrated BEM for every U.S. building

- Input Data
  - LandScan Population Model
- Material Analysis via Thermal/IR
- 3D Energy Model Creation
- Autotune Model Calibration
- Calibrated Energy Model

Benchm... Reduce Offset

Benchmarking

Download BEM via your street address

LIDAR   StreetView   Databases
Acknowledgements

• U.S. Department of Energy
• National Nuclear Security Administration
• Oak Ridge National Laboratory
• Building Technologies Office
• Office of Electricity
Data Sources

- Database and image sources for urban model generation
  - Satellite and airborne imagery
  - Cartographic data
  - Ground level images
  - Elevation data
  - Building information databases
  - 3D building model databases
Manual Segmentation of DC
Automatic Road Extraction
Algorithm: Deep Learning extended and using GPUs for fast building footprint and area extraction over large geographical areas.

Multi-company Competition Precision/Recall – 30/35; Current Precision/Recall – 60+/60+
Automatic Building Footprint Extraction

- Portland, OR (25,393 m²)
  Imagery: June – July 2012
  Lidar: September 2010

- Frankfort, KY (14,801 m²)
  Imagery: June 2012
  Lidar: June 2011

- Part of Knox County, TN (18,527 m²)
  Imagery: June 2012
  Lidar: October 2014

- 220,005 NAIP images
- 1 meter multispectral
- 2012-2014
- 5.8 TB compressed
- 9.8 trillion pixels
Processing Street-Level Imagery

3D Building Model Generation
Prototype Buildings

- Small Office
- Medium Office
- Large Office
- Warehouse
- Strip Mall Retail
- Standalone Retail
- Primary School
- Secondary School
- Outpatient Healthcare
- Hospital
- Small Hotel
- Large Hotel
- Quick-service Restaurant
- Full-service Restaurant
- Mid-rise Apartment
- High-rise Apartment
Prototype and Reference Building Updates

- 70, 80 → 90% of U.S. commercial floor space
- 16 types, 16 climate zones, 3 vintages = 768 buildings
  - 17-19+ types, 16-17 climate zones, 5-16+ vintages = 1,360-5,168 models
- ~3,000 avg. parameters per building
  - Square footage, HVAC layout, infiltration (i.e. airflow)
  - Construction (e.g. wall, layers of envelope)
  - Material properties (ASHRAE Handbook of Fundamentals)
  - Equipment and occupancy schedules

### Physical Properties of Materials

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Specific Heat, Btu/lb°F</th>
<th>Density, lb/ft³</th>
<th>Thermal Conductivity, Btu·h·ft⁻¹°F⁻¹</th>
<th>Emissivity Ratio</th>
<th>Surface Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (alloy 1100)</td>
<td>0.214⁴</td>
<td>171⁴</td>
<td>128⁴</td>
<td>0.09⁴</td>
<td>Commercial sheet</td>
</tr>
<tr>
<td>Aluminum bronze (76% Cu, 22% Zn, 2% Al)</td>
<td>0.09⁴</td>
<td>517⁴</td>
<td>58⁴</td>
<td>0.20⁴</td>
<td>Heavily oxidized</td>
</tr>
<tr>
<td>Asbestos: Fiber</td>
<td>0.25⁴</td>
<td>150⁴</td>
<td>0.907⁴</td>
<td>0.041⁴</td>
<td>(122)</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.20⁴</td>
<td>36⁴</td>
<td>0.02⁴</td>
<td>0.93⁴</td>
<td>“Paper”</td>
</tr>
<tr>
<td>Ashes, wood</td>
<td>0.20⁴</td>
<td>40⁴</td>
<td>0.041⁴</td>
<td>0.93⁴</td>
<td>“Paper”</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0.22⁴</td>
<td>133⁴</td>
<td>0.49⁴</td>
<td>0.93⁴</td>
<td>“Paper”</td>
</tr>
<tr>
<td>Bakelite</td>
<td>0.35⁴</td>
<td>81⁴</td>
<td>9.7⁴</td>
<td>0.93⁴</td>
<td>“Paper”</td>
</tr>
<tr>
<td>Bell metal</td>
<td>0.086⁴ (122)</td>
<td></td>
<td></td>
<td>0.93⁴</td>
<td></td>
</tr>
<tr>
<td>Bismuth tin</td>
<td>0.086⁴</td>
<td>123⁴</td>
<td>0.4⁴</td>
<td>0.93⁴</td>
<td></td>
</tr>
<tr>
<td>Brick, building</td>
<td>0.2⁴</td>
<td>129⁴</td>
<td>37.6⁴</td>
<td>0.4⁴</td>
<td></td>
</tr>
</tbody>
</table>
AutoBEM – Automatic Building detection and Energy Model creation

• 19 underlying Intellectual Properties (granted or in process)
  • Range from classified to open-source
  • AutoBEM-LiDAR
  • AutoBEM-Aerial – world’s best building footprint extractor
  • AutoBEM-Street
  • AutoBEM-3D DB
  • AutoBEM-Type
  • AutBEM-Gen – world’s fastest BEM creator
  • AutoSIM – world’s fastest buildings simulator
  • AutoDoEGen
  • AutoSTAT
  • Autotune – world’s best calibration algorithm
AutoBEM – ongoing work

- AutoBEM-Aerial/HVAC
- AutoBEM-Aerial/Chiller
- AutoBEM-scrape
The University of Tennessee (2 days)
Chattanooga, TN (100,000+ buildings)
The AutoBEM technology “axe”

135,481 building models have been created and matched to EPB’s PremiseID
Limitations: limited building types, not calibrated, will improve quarterly
QA/QC: will show how close our simulations are to 15-min data

1.9 million EnergyPlus building energy models using AutoBEM technology, Titan, cloud, and local servers to produce and analyze 10.7 TB of simulation data.

1. Generate baseline building – OpenStudio (1.5-3h Amazon, 30h internal)
2. Run ECM measures – OS Measure (30 mins AWS, 2h internal), Custom (1m AWS, 5m intl.)
3. Copy data to Titan – 1 min (1.2GB tar.gz)
4. Submit to Titan – 0-2 hours in queue
5. EnergyPlus simulation time – 30-45 mins (5mins/sim = 1.4 years to simulate EPB on 1 core)
6. Data transfer – 40 mins (160GB tar.gz)
7. Uncompress – 10-15 mins
8. Reformat data – 20-30 mins
9. Analysis – 5-10 mins

Time for creation, annual simulation, and analyzing “all” EPB buildings
6.5 hours (6.1h – 36.5h)
1a – Peak contribution percentile by type

- Building ID
- Area (m²)
- Number of Floors
- **Color:** Energy Use Intensity (kWh/m²) by building type
- Min/Avg/Max by building type
Virtual EPB – interactive results

<table>
<thead>
<tr>
<th>ID</th>
<th>60246</th>
</tr>
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<tbody>
<tr>
<td>DOE Building Type</td>
<td>Small Office</td>
</tr>
<tr>
<td>Num Floors</td>
<td>3</td>
</tr>
<tr>
<td>Percentile</td>
<td>87.70%</td>
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<tr>
<td>Estimated wholesale vs retail cost</td>
<td>$9797.07</td>
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<tr>
<td>CO2 emissions</td>
<td>222052.32 lbs/year</td>
</tr>
<tr>
<td>Smart Thermostat - 4F cost savings</td>
<td>$1316.61</td>
</tr>
<tr>
<td>Smart Thermostat - 8F cost savings</td>
<td>$2325.84</td>
</tr>
<tr>
<td>TMY-&gt;AMY Smart Thermostat - 4F cost savings</td>
<td>$204.99</td>
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<tr>
<td>TMY-&gt;AMY Smart Thermostat - 8F cost savings</td>
<td>$103.41</td>
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<tr>
<td>HVAC Efficiency ECM</td>
<td>$1291.79</td>
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<tr>
<td>Gas HVAC ECM</td>
<td>$4276.69</td>
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<tr>
<td>Gas Water Heater ECM</td>
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<td>Heat Pump Water Heater ECM</td>
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<td>Insulation ECM</td>
<td>$736.27</td>
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<tr>
<td>Infiltration ECM</td>
<td>$1577.50</td>
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<tr>
<td>Lighting ECM</td>
<td>$2898.95</td>
</tr>
</tbody>
</table>
Discussion

Joshua New, Ph.D., CEM, PMP, CMVP
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HPC Tools for Modeling and Simulation
Capturing building energy consumption