Combining Measurements and Models to Predict the Impacts of Climate Change and Weatherization on Indoor Air Quality and Chronic Health Effects in U.S. Residences

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Importance of residential indoor environments

- People spend the majority of their time **at home** (~69%)

  Klepeis et al. **2001** *J Exp Anal Environ Epidem* 11:231-252

- The cumulative chronic health impacts from inhalation of indoor air pollutants in residences has been estimated to be between 400 and 1100 disability-adjusted life-years (DALYs) per 100,000 persons
  - Between **5-14% of the** annual non-communicable, non-psychiatric **disease burden** in the US (excludes radon and secondhand smoke)

  Logue et al. **2012** *Environ Health Perspect* 120:216-222

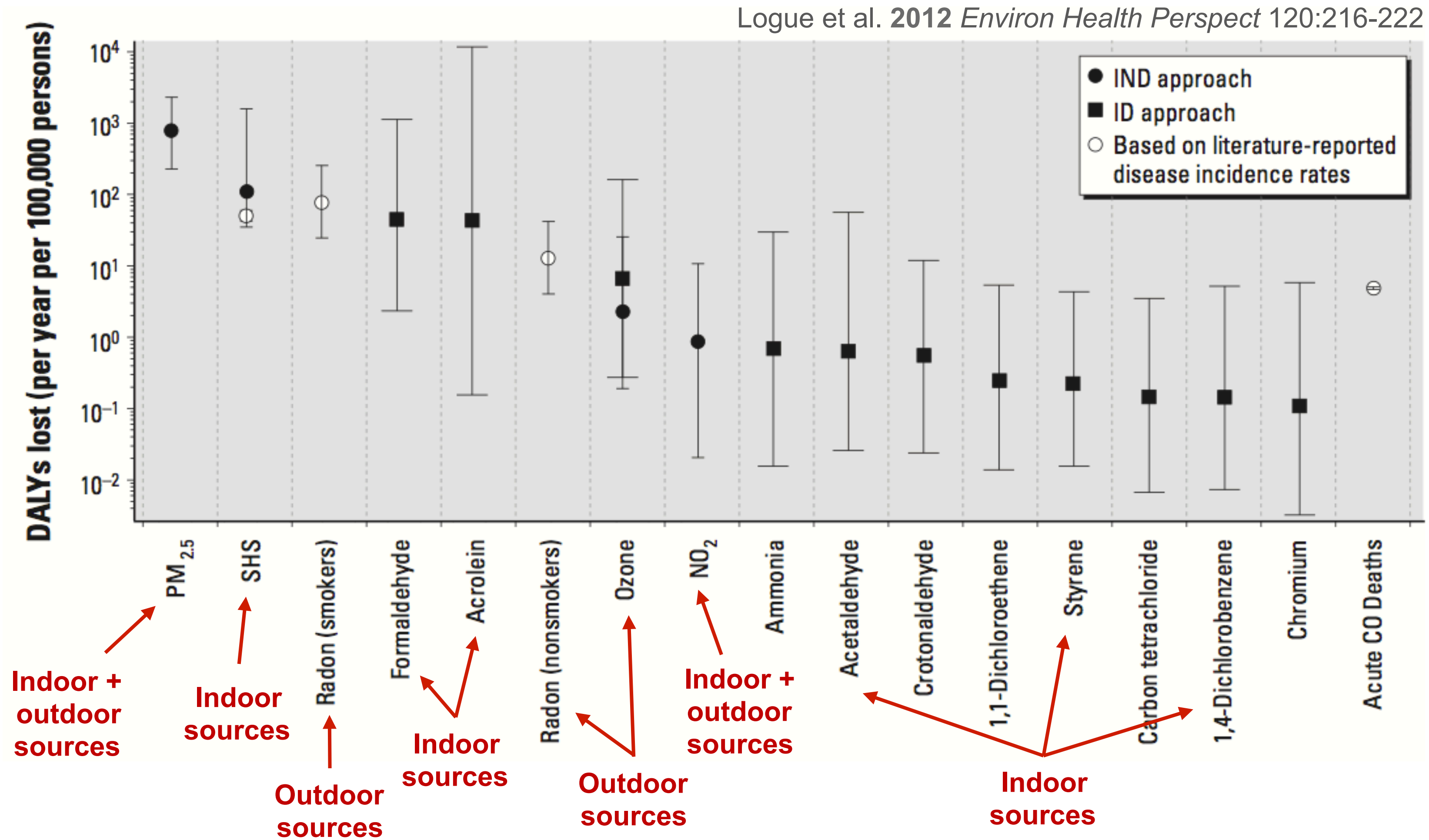
- Cumulative lifetime **cancer risk** from exposure to several hazardous indoor air pollutants ranges between **1-10 excess cases per 10,000 people**

  Wallace et al. **1991** *Environ Health Perspect* 95:7-13
  Sax et al. **2006** *Environ Health Perspect* 114:1558-1566
  Hun et al. **2009** *Environ Health Perspect* 117:1925-1931

Residential indoor air and **chronic health outcomes**

Likely the **most harmful indoor air pollutants** inside residences:

Logue et al. **2012** *Environ Health Perspect* 120:216-222



Climate change, the indoor environment, and health

- Climate change is expected to influence indoor pollutant exposures in a number of **direct** and **indirect** ways

Nazaroff **2013** *Environ Res Lett* 8:015022

1) Changes in concentrations of outdoor pollutants → Changes in indoor **concentrations** of pollutants of **outdoor origin**

2) Buildings are operated differently (intentionally or unintentionally) → Changes in ventilation rates or HVAC operation alter indoor **concentrations** of pollutants of **both indoor and outdoor origin**

3) People alter their activities (e.g., time spent indoors) → Changes in indoor **exposures** to pollutants of **both indoor and outdoor origin**

EPA STAR: Impacts of climate change on indoor air

“Combining measurements and models to predict the impacts of climate change and weatherization on indoor air quality and chronic health effects in U.S. residences”

Objectives:

- To use a combination of **field measurements** and a **nationally representative set of dynamic residential indoor air quality models** to predict **indoor exposures** and associated **chronic health effects** of several **priority pollutants** of both indoor and outdoor origin across:
  1. The current U.S. residential building stock
  2. The current U.S. residential building stock under future climate conditions in 2050 and 2080
  3. The future U.S. building stock under future climate conditions in 2050 and 2080, considering a number of climate policy scenarios that lead to widespread application of weatherization retrofits and turnover of the existing building stock to more energy efficient homes

EPA STAR: Impacts of climate change on indoor air

"Combining measurements and models to predict the impacts of climate change and weatherization on indoor air quality and chronic health effects in U.S. residences"

Research questions:

- What are the likely impacts of (a) changing meteorological conditions in future climate scenarios and (b) widespread application of weatherization retrofits on indoor air quality and chronic health effects in residential buildings across the U.S.?

Research approach:

- **Modeling** concentrations, exposures, and chronic health effects of indoor air in homes across U.S.
- **Field measurements** in homes before and after energy retrofits
  - Envelope airtightness
  - Outdoor pollutant infiltration factors and penetration factors

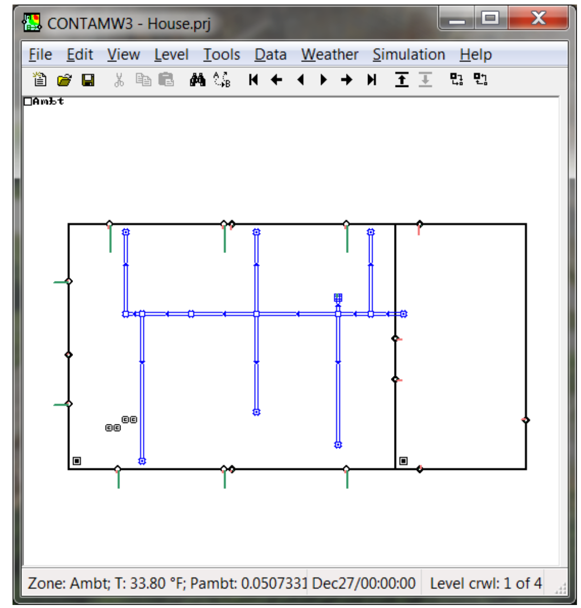
MODELING APPROACH

Modeling approach

- We originally proposed to use CONTAM and a set of 209 home models that represent approximately 80% of the U.S. housing stock

CONTAM
Multizone Airflow and Contaminant Transport Analysis Software

http://www.bfrl.nist.gov/IAQanalysis/CONTAM/



A Collection of Homes to Represent the U.S. Housing Stock

Persily et al. **2006** NISTIR 7330; Persily et al. **2010** *Indoor Air* 20:473-485

Modeling approach

- Instead, we decided to develop a custom set of **combined building energy and indoor air mass balance models** to predict hourly energy use and indoor concentrations of a number of pollutants of both indoor and outdoor origin across the U.S. residential building stock
  - Model inputs are based on the NIST 209 home database

- The custom tool can be easily automated to run a large number of simulations
  - Allows for exploring complex interactions between energy and IAQ on a scale that is large enough to evaluate changes across the building stock under various scenarios (e.g., adoption of new energy policies or IAQ standards, as well as **future climate scenarios**)

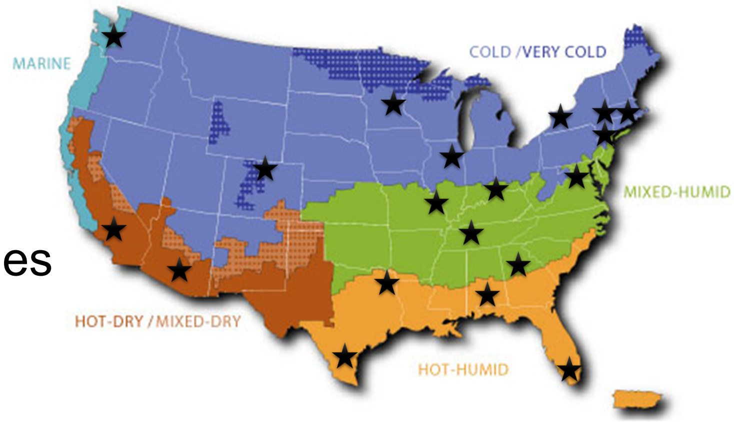
Modeling approach

The model framework combines energy simulations in BEopt and EnergyPlus with a custom hourly mass balance model for indoor pollutant simulations, written in Python

- A set of **209 dwellings** (~100 home geometries) were modeled in **19 cities** in 9 U.S. census and climate divisions that represent approximately **80%** of all U.S. residences*

Dwelling categories:

- ✓ Detached Homes
- ✓ Attached Homes
- ✓ Manufactured Homes
- ✓ Apartments



Dwelling characteristics:
Floor area, year built, number of floors, number of rooms, foundation type, whether or not they have a forced air distribution system, and presence of a garage

*Home geometries and other basic characteristics are based on the NIST CONTAM database of homes representing the U.S. building stock: http://www.bfrl.nist.gov/IAQanalysis/case%20studies/cwcase_11.htm

Persily et al. **2006** NISTIR 7330; Persily et al. **2010** *Indoor Air* 20:473-485

Building the nationally representative model set

Selecting model home characteristics:

Home characteristics were then varied by climate zone based on **4 vintages**

NIST database

Year of construction
- ✓ Before 1940
- ✓ 1940-1969
- ✓ 1970-1989
- ✓ 1990-1997

Persily et al. **2006**

Envelope airtightness
A function of both year built and house floor area
Persily et al. **2006**

Heating characteristics
- ✓ Gas furnace
- ✓ Electric furnace
- ✓ Heat pump
- ✓ Gas boiler
- ✓ Electric boiler
- ✓ Electric baseboard

Assumptions from the literature

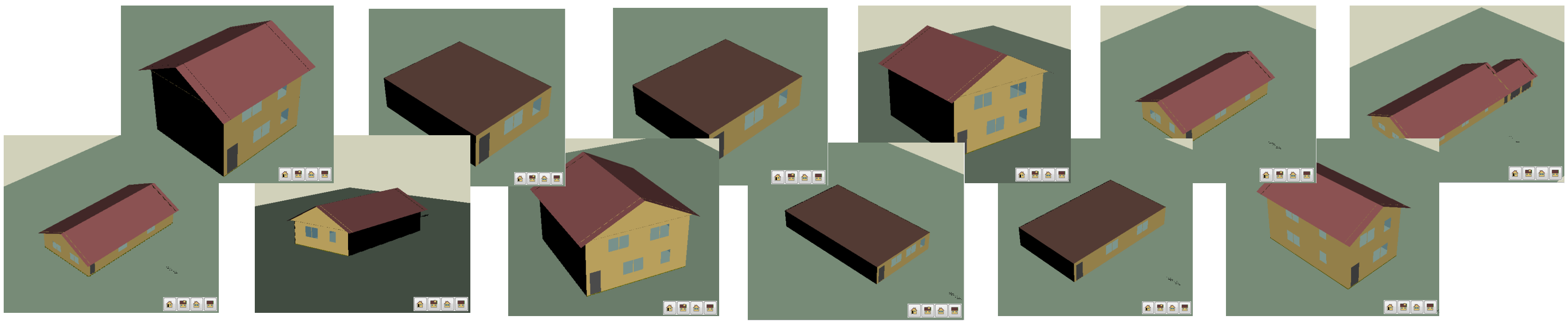
Heating and cooling thermostat set points
RECS 2009

Enclosure details
Basement, External Walls, Attic, and Windows
Huang et al. 1999, IECC 2009

Cooling characteristics
- ✓ Air conditioner
- ✓ Room conditioner

Building the nationally representative model set

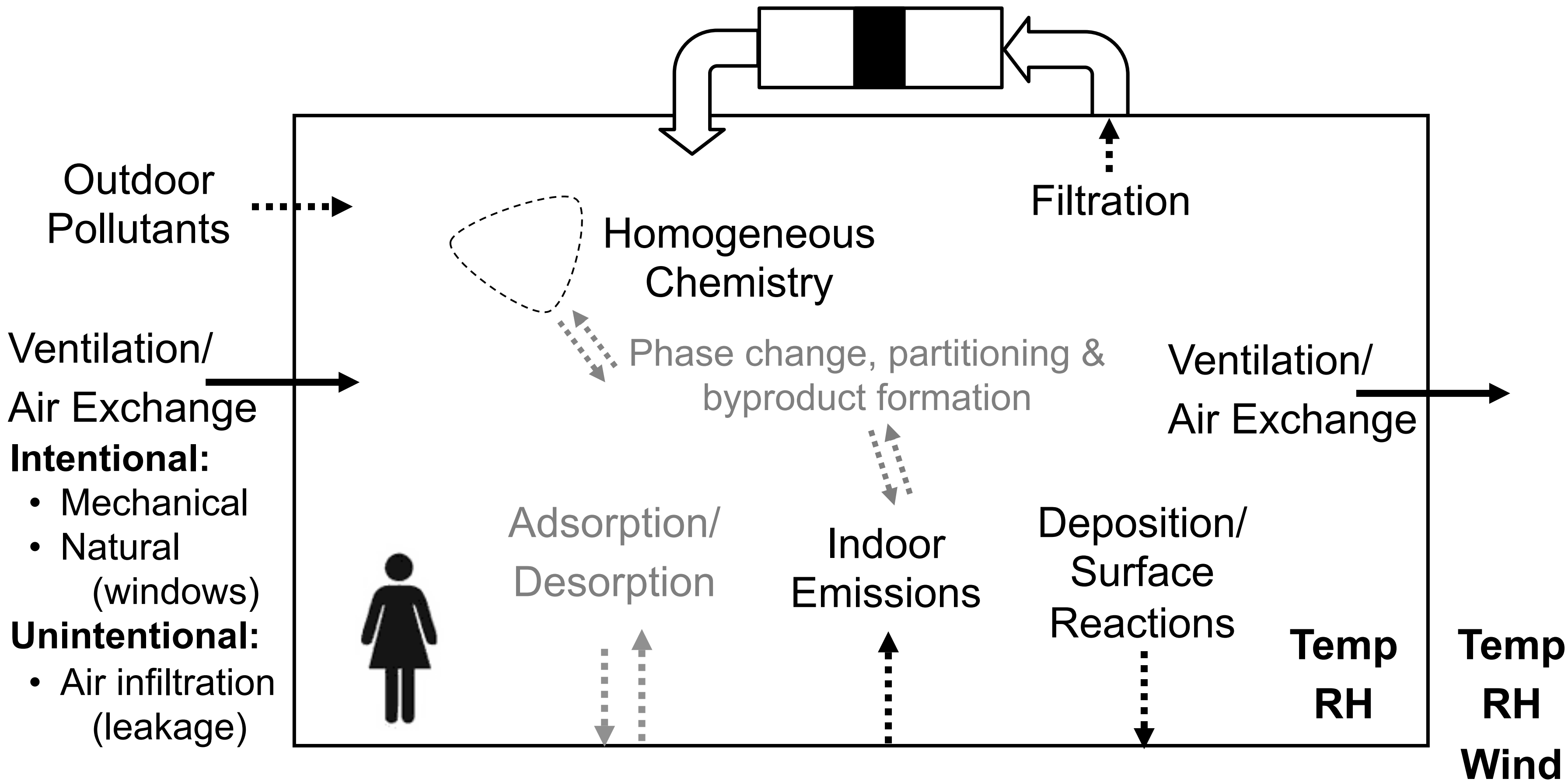
- About 100 baseline geometries of individual homes were first modeled in BEopt energy simulation software and then converted to EnergyPlus IDF input files using an automated process (explained in 2 slides)



- After energy simulations are run for each home, hourly outputs for energy use, air infiltration rates, window opening and airflows through window, and HVAC runtime are used as inputs to a custom single-zone mass balance model to predict hourly indoor concentrations of pollutants of both indoor and outdoor origin

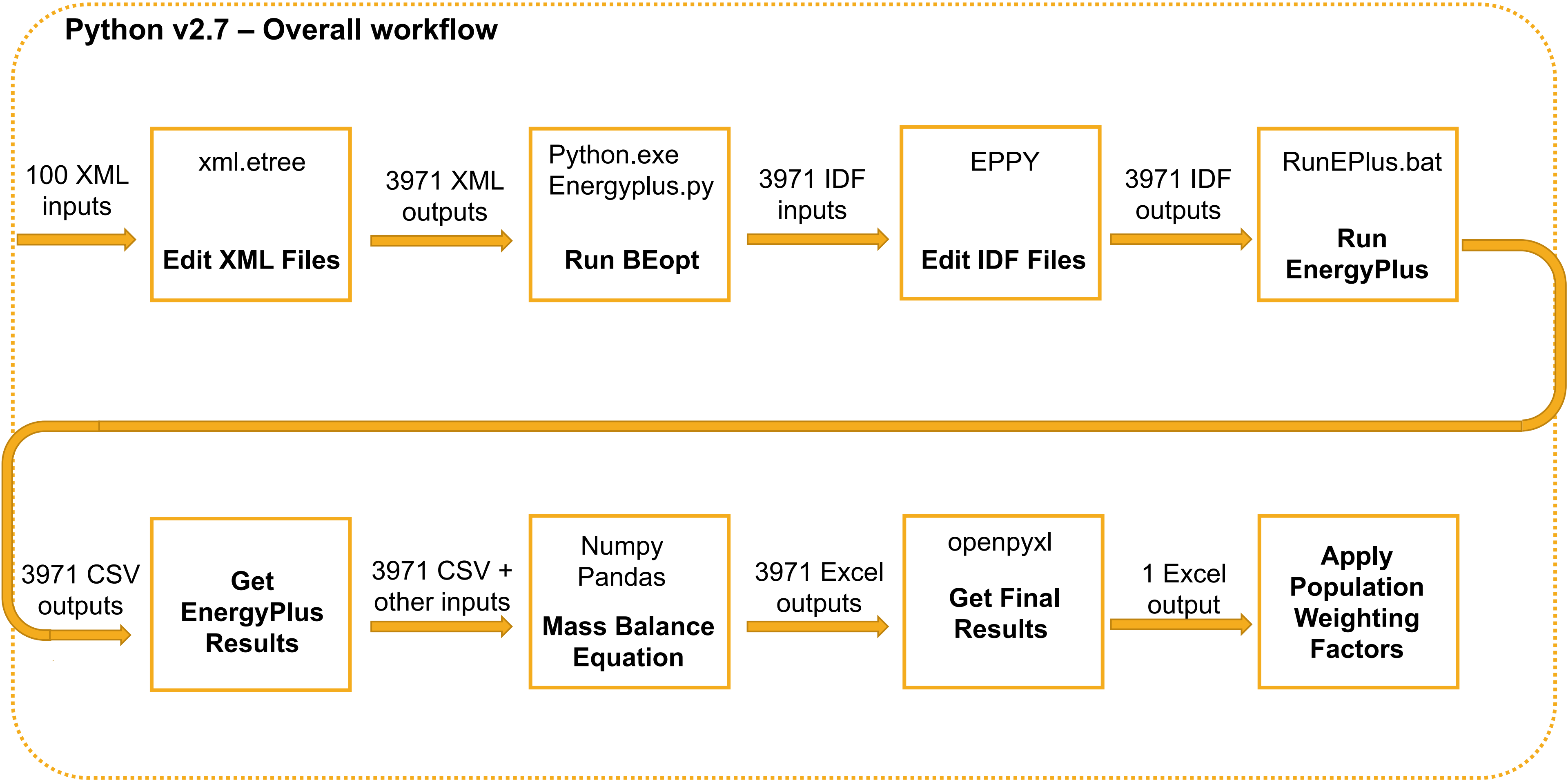
$$\frac{dC_{in}}{dt} = P\lambda_{inf}C_{out} + \frac{Q_{supply}}{V}(1-\eta_{supply})C_{out} + \frac{E}{V} - \lambda_{inf}C_{in} - \frac{Q_{exhaust}}{V}C_{in} - \beta C_{in} - f_{filt}\frac{\eta_{filt}Q_{filt}}{V}C_{in} - kC_{in}C_{j} - \frac{dC_{in}}{dt}K_{eq}\frac{A}{V}$$

Single-zone mass balance model



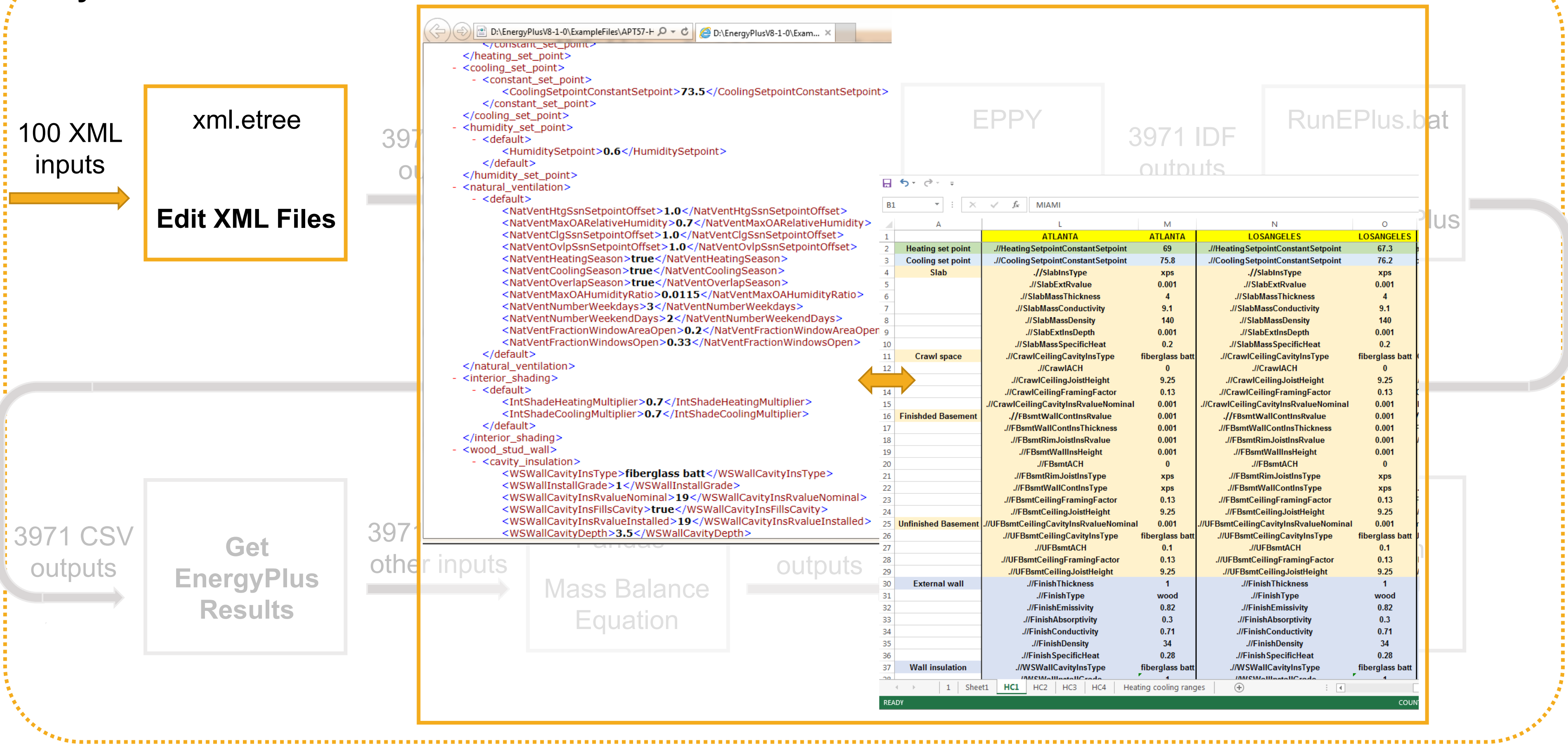
Primary pollutant classes:
(1) Particulate matter (e.g., $PM_{2.5}$ and UFPs)
(2) Non-reactive gases (e.g., several VOCs, formaldehyde)
(3) Reactive gases (e.g., O_3 and NO_2)

Simulation workflow



Simulation workflow

Python v2.7 – Overall workflow

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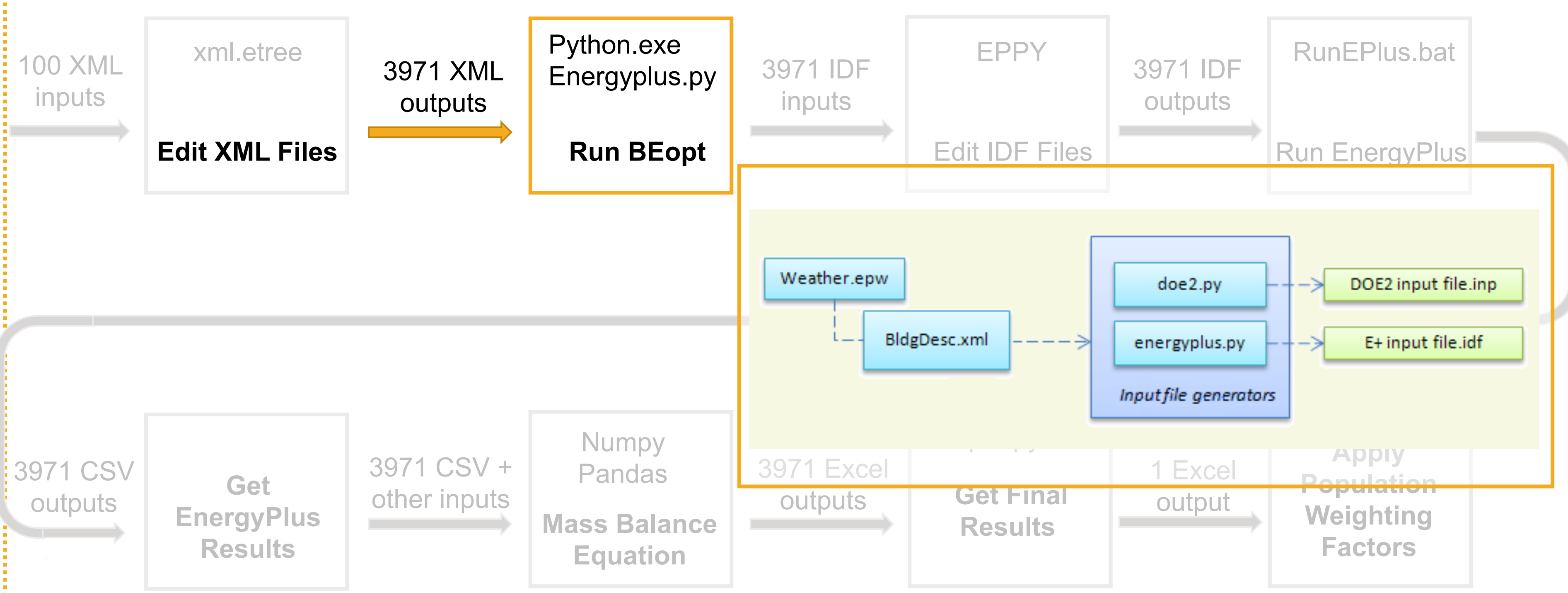
1 | Sheet1 | HC1 | HC2 | HC3 | HC4 | Heating cooling ranges

READY

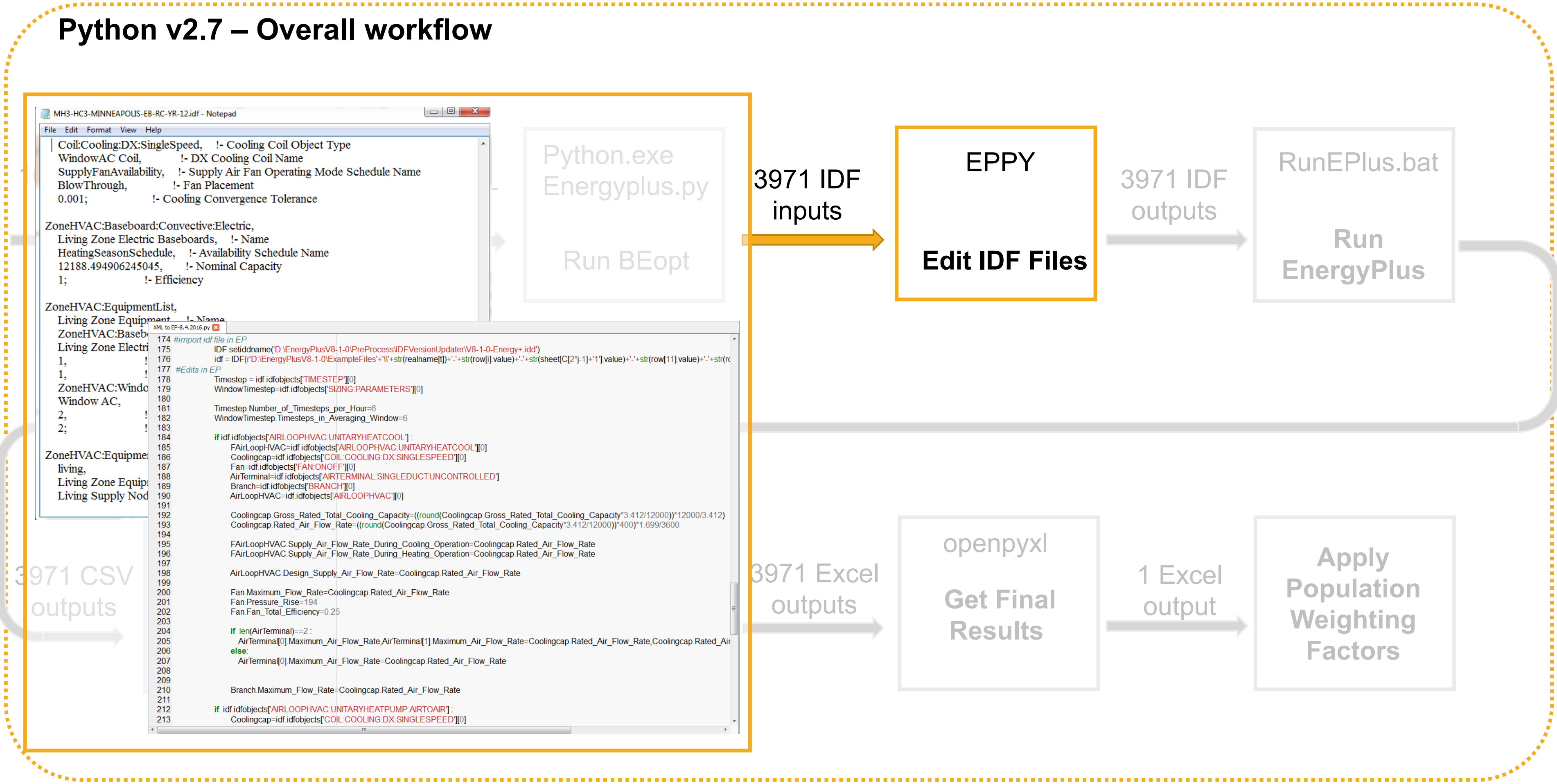
Simulation workflow

Python v2.7 – Overall workflow

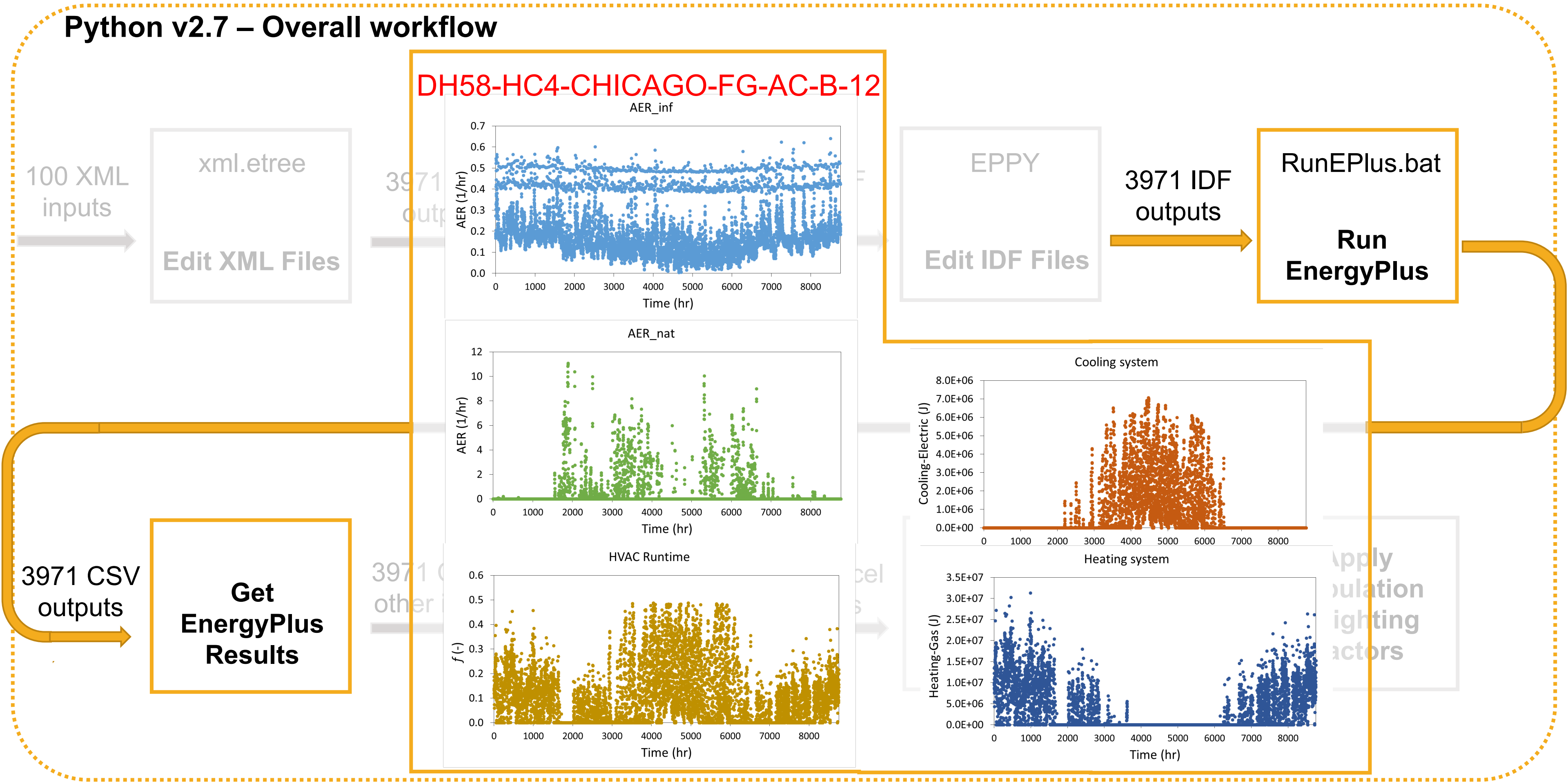


Simulation workflow

Python v2.7 – Overall workflow

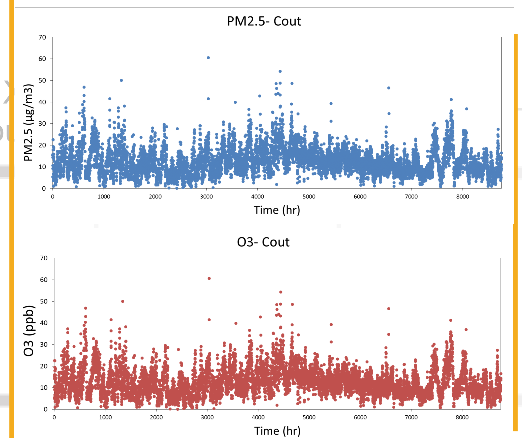


Simulation workflow



Simulation workflow

Python v2.7 – Overall workflow



Outdoor origin pollutants - EPA 2012

Default assumptions:

Parameters	$PM_{2.5}$	O_3	
P (-)	0.8	0.71	
	(Field measurements)		
η_{filt} (-)	0.38 (Field measurements)	-	
β (1/hr)	0.7 (Wallace et al 2013)	2.8 (Lee et al 1999)	
k (1/ppb-hr)	-	0.79×10^{-2}	0.19×10^{-1}
C_j (ppb)	-	0.43	2.2
		(Waring 2014)	

Default assumptions:

Emission rates (mg/hr or ppb/hr)	
$PM_{2.5}$*	67.5
Formaldehyde**	9.6
Acetaldehyde**	4
Acrolein**	0.21
1,3-Butadiene**	0.15
Benzene**	0.35
1,4-dichlorobenzene**	0.14

* Emission from cooking-1hour/day (Burke et al 2001)

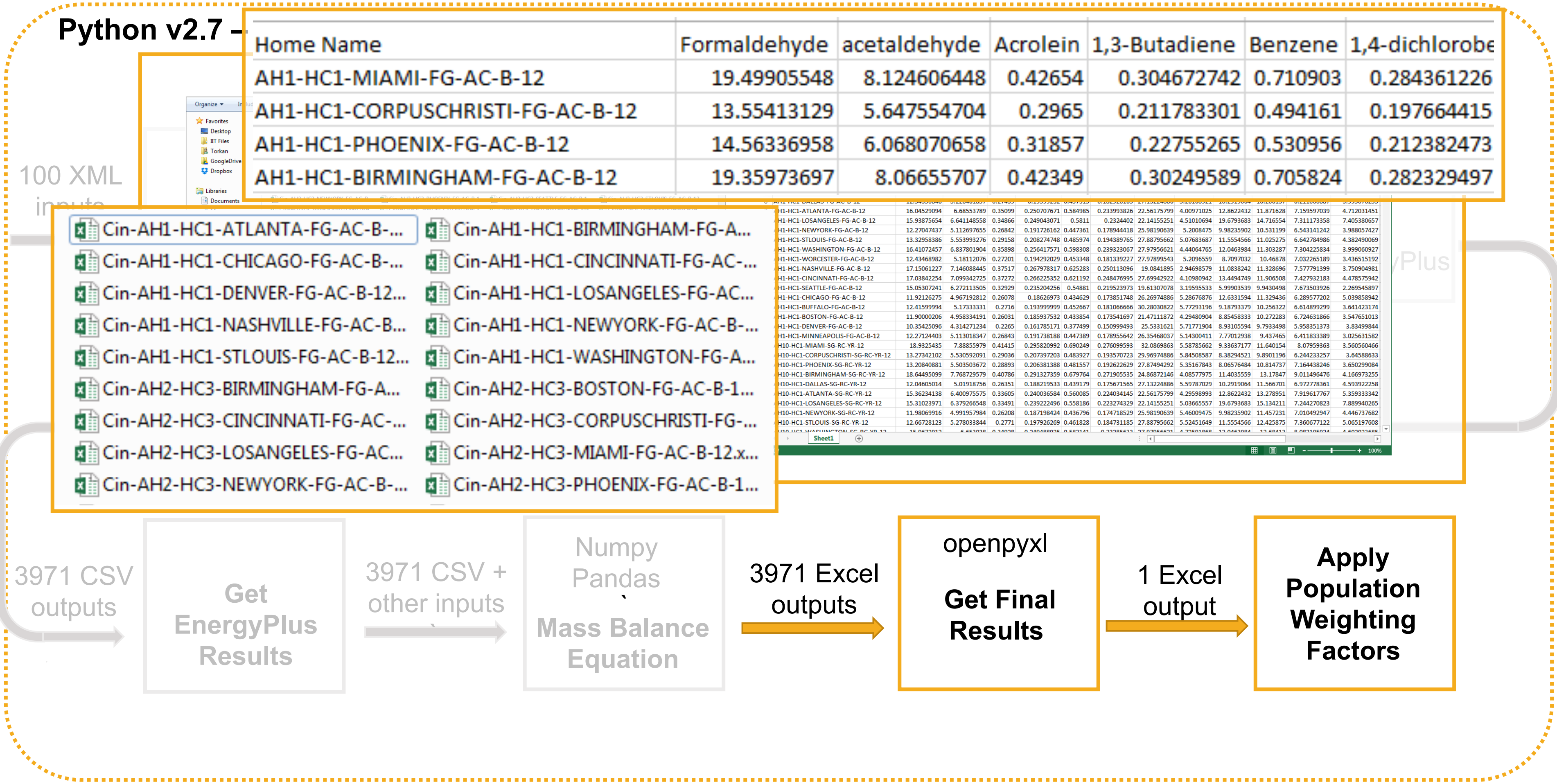
** Volume normalized emissions (Waring 2014)

3971 CSV outputs → **Get EnergyPlus Results** → 3971 CSV + other inputs → Numpy, Pandas — **Mass Balance Equation** → 3971 Excel outputs → openpyxl — **Get Final Results** → 1 Excel output → **Apply Population Weighting Factors**

Data sources:

- EPA monitoring network for hourly pollutant concentrations of outdoor origin
- Existing literature for indoor emission rates and some physical parameters (e.g., rate constants)
- Fieldwork in this project for other physical parameters (e.g., penetration factors for $PM_{2.5}$ and O_3)

Simulation workflow



Home Name	Formaldehyde	acetaldehyde	Acrolein	1,3-Butadiene	Benzene	1,4-dichlorobe
AH1-HC1-MIAMI-FG-AC-B-12	19.49905548	8.124606448	0.42654	0.304672742	0.710903	0.284361226
AH1-HC1-CORPUSCHRISTI-FG-AC-B-12	13.55413129	5.647554704	0.2965	0.211783301	0.494161	0.197664415
AH1-HC1-PHOENIX-FG-AC-B-12	14.56336958	6.068070658	0.31857	0.22755265	0.530956	0.212382473
AH1-HC1-BIRMINGHAM-FG-AC-B-12	19.35973697	8.06655707	0.42349	0.30249589	0.705824	0.282329497

Model output:

- Hourly energy use and pollutant concentrations for each model home, which can be averaged and applied across the building stock with population weighting factors
- Concentrations will eventually be linked to DALYs and CCRs to estimate impact on chronic health

Model scenarios

1. Baseline year: 2012
   – Most recent year with both actual weather data and outdoor pollutant data available when the project began

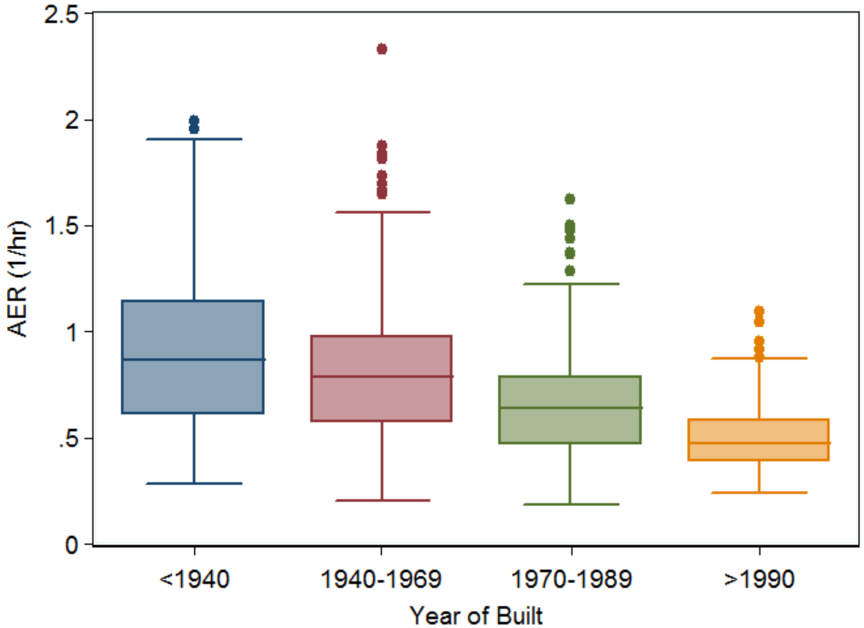
2. Future meteorological conditions: 2050 and 2080
   – Using CCWorldWeatherGen to ‘stretch’ weather files

Jentsch et al. **2008** *Energy and Buildings* 40:2148-2168; Jentsch et al. **2013** *Renewable Energy* 55:514-524

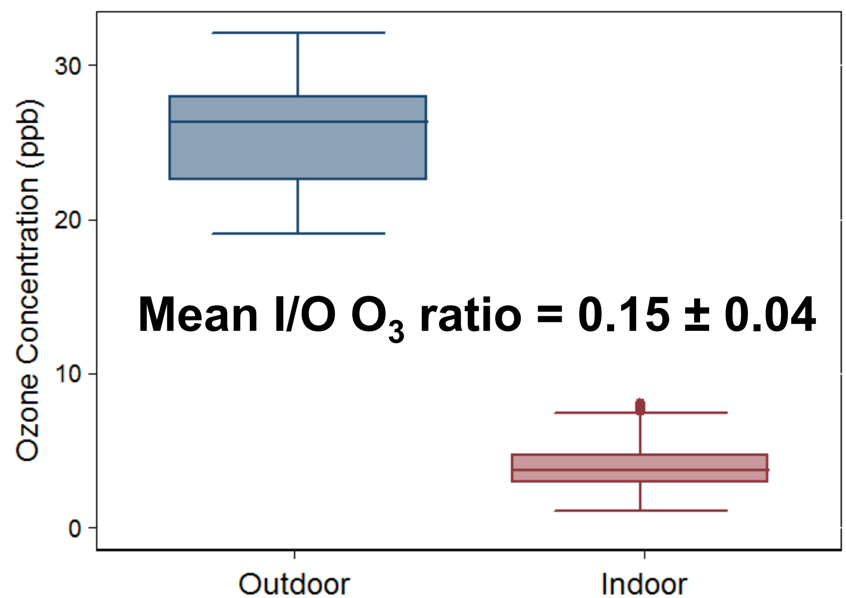
3. Future meteorological conditions + climate policy responses (e.g., widespread energy retrofits, building stock turnover): 2050 and 2080
   – Not yet simulated; informed by field work

Preliminary model results: 2012

Air exchange rates are higher in older homes

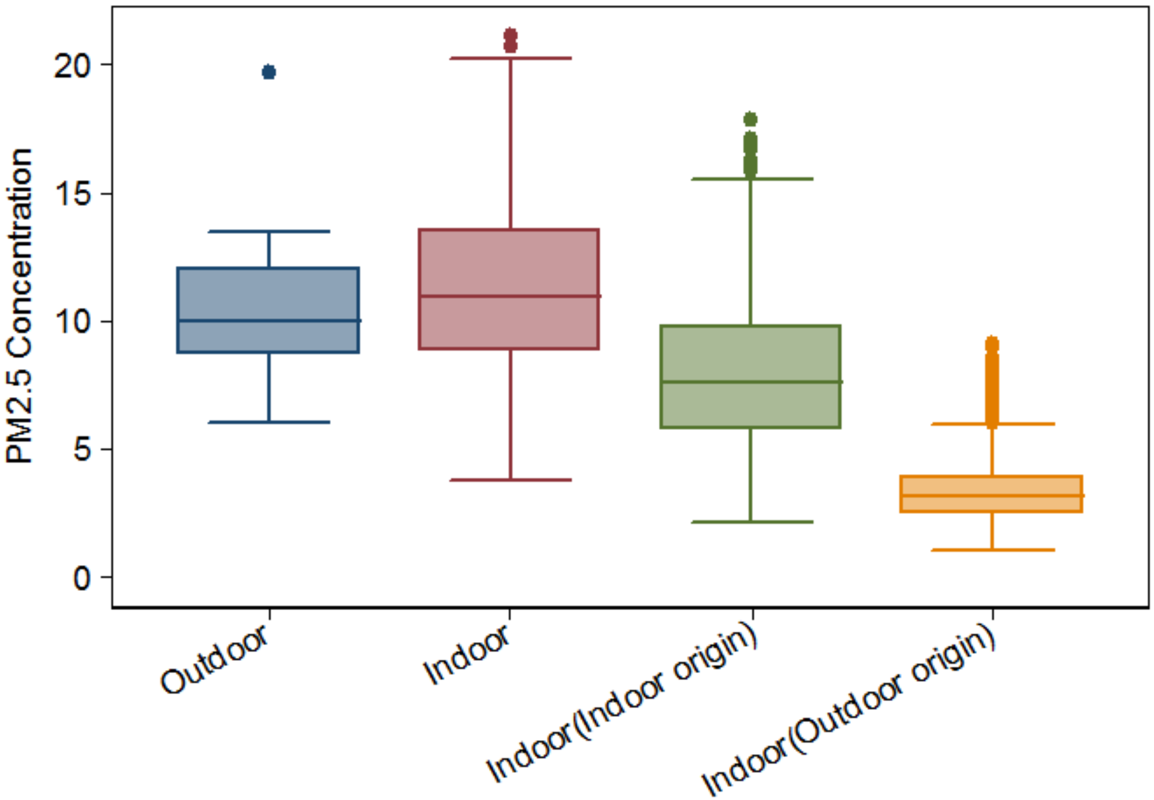


Indoor ozone concentrations are within ranges seen in the existing literature



Preliminary model results: 2012

Indoor $PM_{2.5}$ concentrations compare well to existing literature

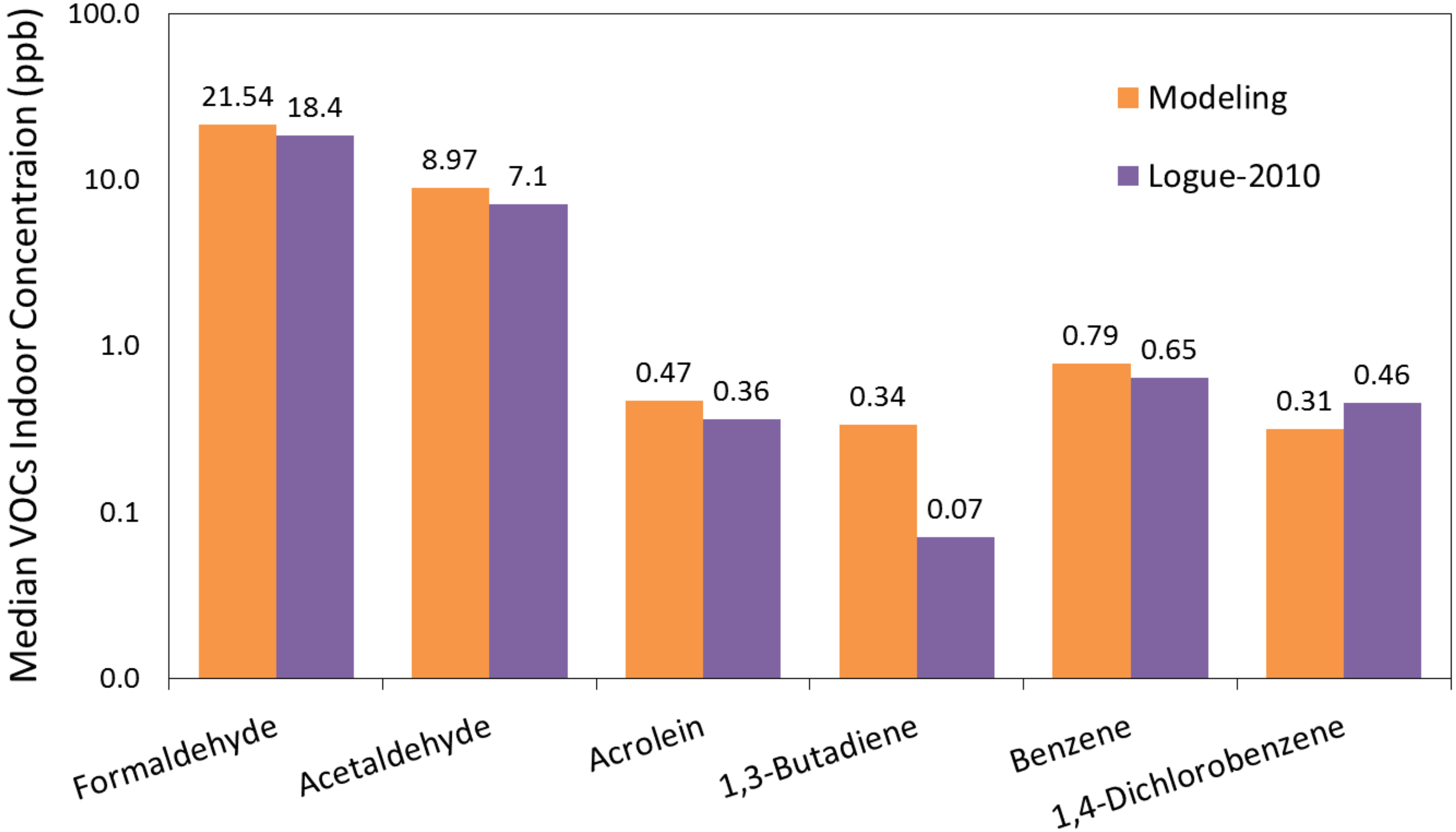


Median contributions:

- ✓ Outdoor infiltration: 4 μg/m^3
- ✓ Indoor generation: 7 μg/m^3
- ✓ Infiltration factor: 0.31

Preliminary model results: 2012

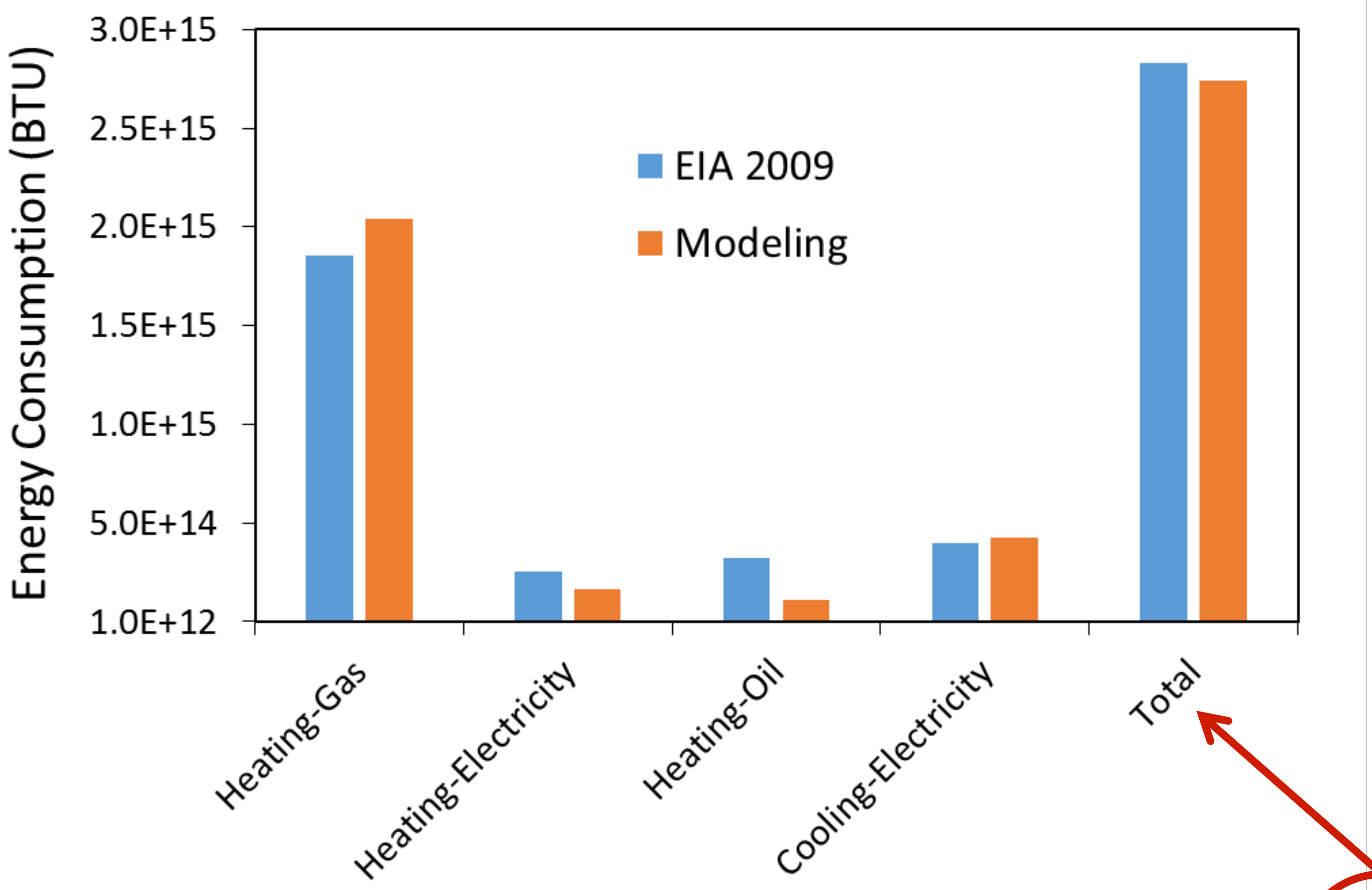
Median indoor VOC and aldehyde concentrations are similar to those reported in previous field studies



Logue et al. **2011** *Indoor Air* 21:92-109

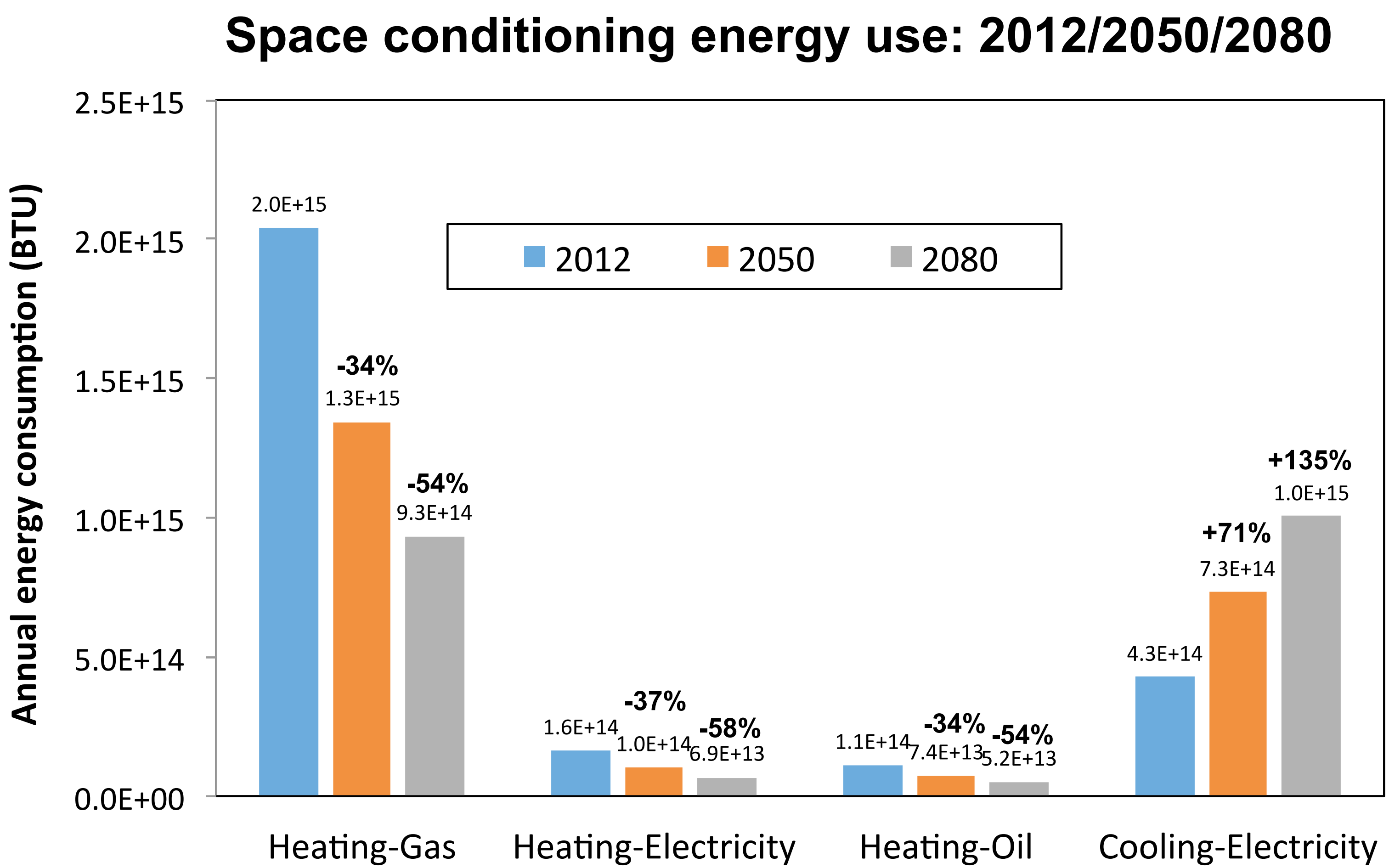
Preliminary model results: 2012

Space conditioning energy simulation results are very close to EIA data



	Heating-Gas	Heating-Electricity	Heating-Oil	Cooling-Electricity	Total
Our modeling	2.04E+15	1.63E+14	1.11E+14	4.28E+14	2.74E+15
EIA	1.90E+15	2.56E+14	2.93E+14	4.22E+14	2.83E+15
Difference	7%	-36%	-62%	1%	**-5%**

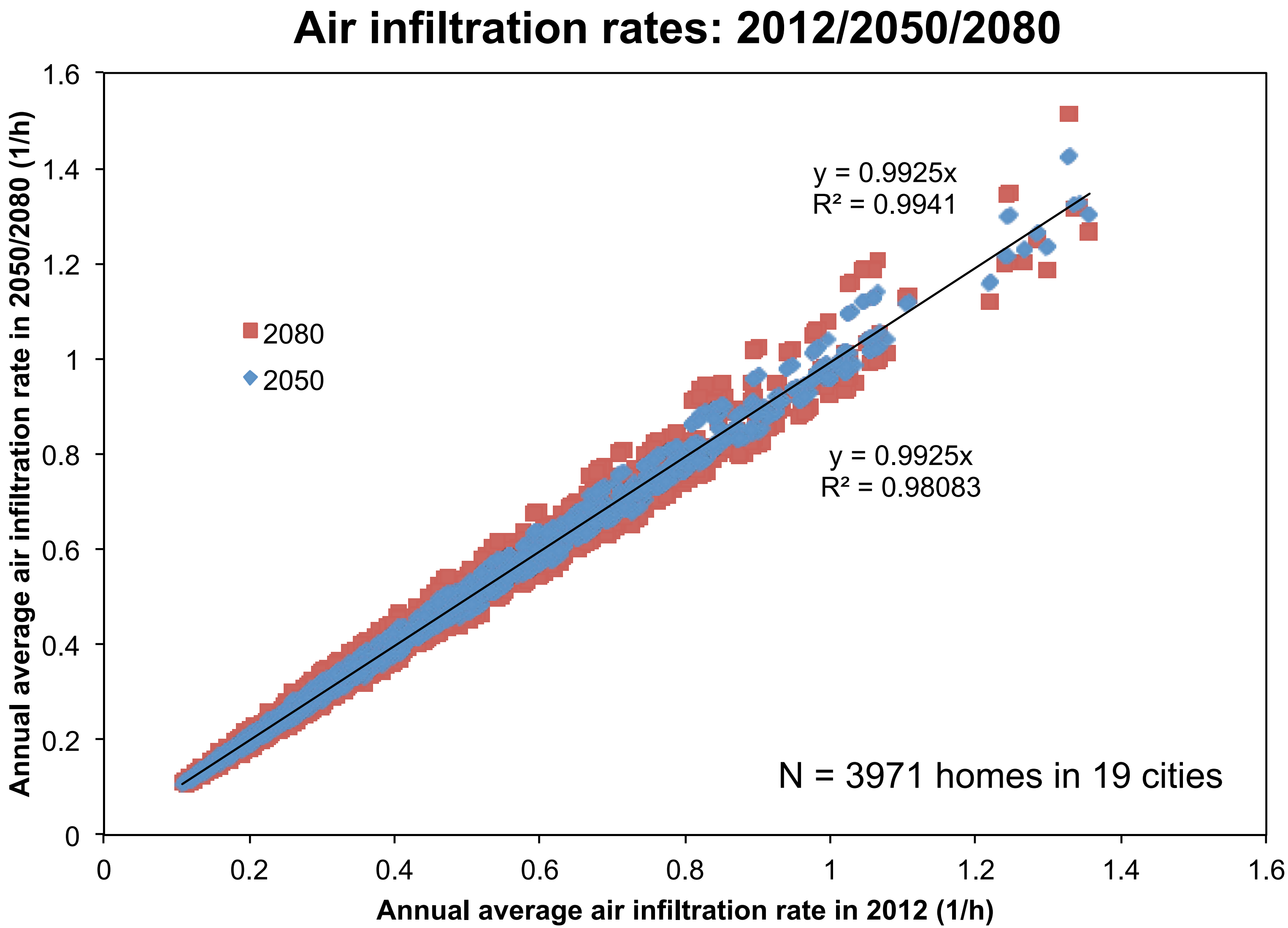
Preliminary model results: Future climate conditions



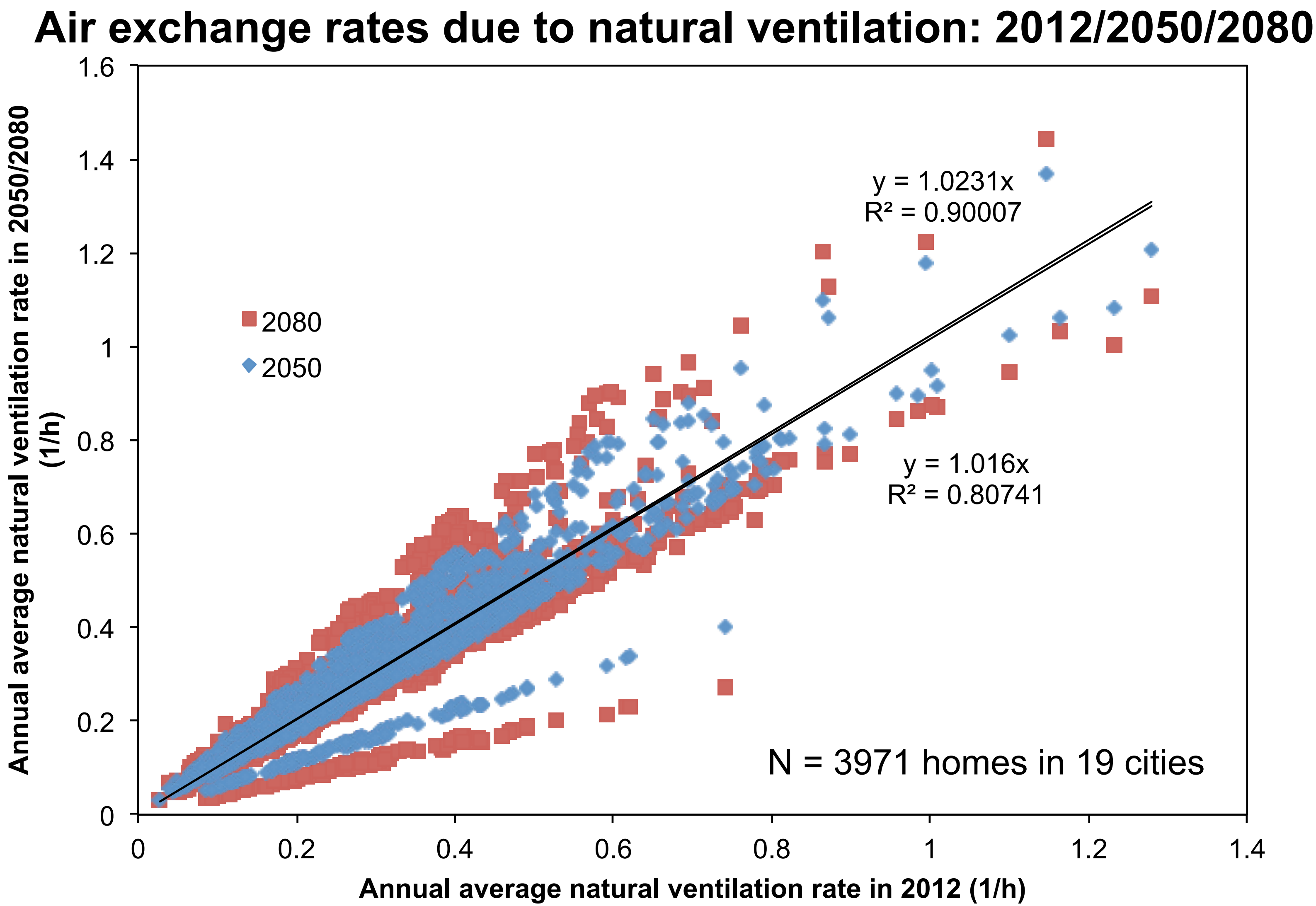
Total space conditioning site energy consumption:

2012: Baseline 2050: -18% 2080: -25%

Preliminary model results: Future climate conditions



Preliminary model results: Future climate conditions



Preliminary model results: Future climate conditions

Population weighted annual average indoor concentrations

	2050 vs. 2012	2080 vs. 2012
Formaldehyde	+0.8%	+0.8%
Acetaldehyde	+0.8%	+0.8%
Acrolein	+0.8%	+0.8%
1,3-Butadiene	+0.8%	+0.8%
Benzene	+0.8%	+0.8%
1,4-dichlorobenzene	+0.8%	+0.8%
Ozone	-1.5%	-2.6%
$PM_{2.5}$ (all sources)	-7.1%	-9.4%
$PM_{2.5}$ (indoor sources)	-7.7%	-10.3%
$PM_{2.5}$ (outdoor sources)	-5.9%	-7.6%
NO_2 (all sources)	+0.1%	+0.2%
NO_2 (indoor sources)	+0.3%	+0.2%
NO_2 (outdoor sources)	-0.2%	+0.4%

FIELD MEASUREMENTS

Field measurement approach

- **Goal:** Measure envelope airtightness, pollutant infiltration factors (F_{inf}) and, when possible, pollutant penetration factors (*P*) and deposition loss rate constants (*k*) in 30 homes before and after energy retrofits are applied
  - Focus on outdoor pollutants: UFPs, $PM_{2.5}$, BC, O_3, and NO_x
  - Help fill important data gaps in the modeling effort:
    - Initial penetration factors
    - How infiltration/penetration factors change after energy retrofits

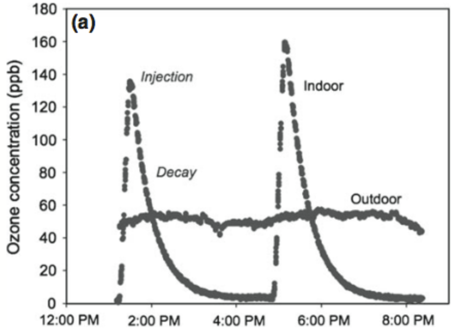
Home recruitment status:

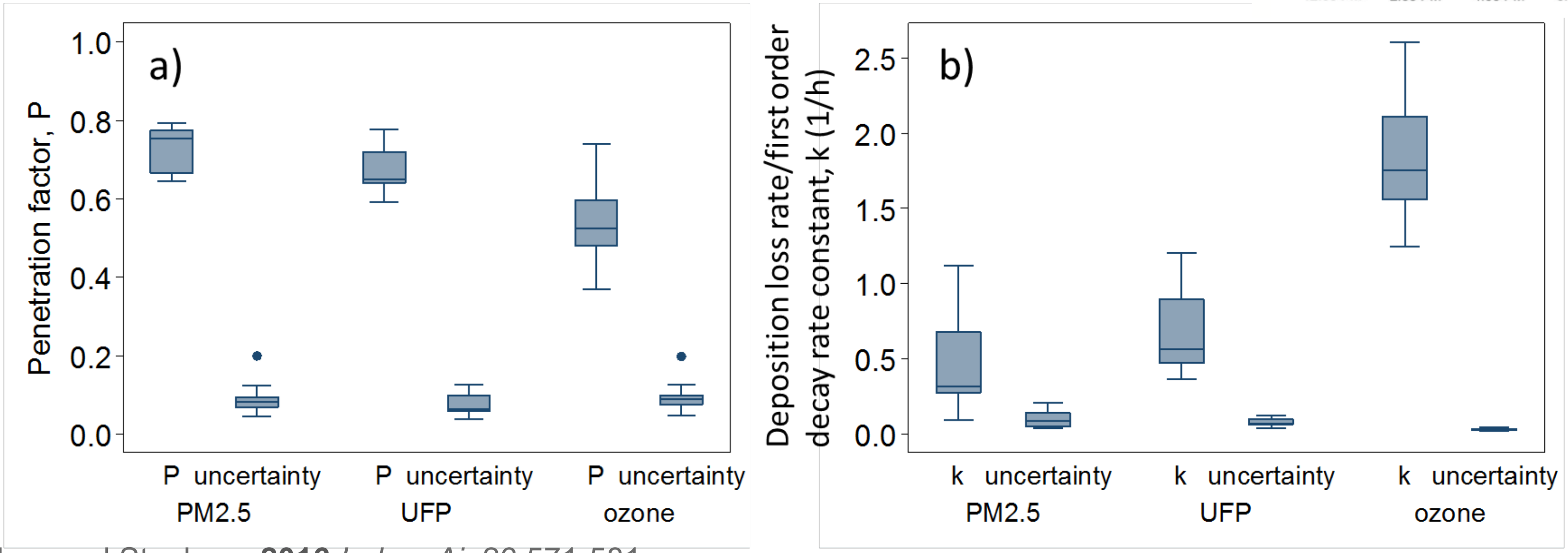
Target:	Completed to date:
30 homes pre/post retrofit	6 SF homes + 3 MF units - 1 failed MF test = 8 units pre/post retrofit complete + 5 non-retrofit MF homes = 13 tests complete

ELEVATE ENERGY
Smarter energy use for all

Field measurement approach

- We began by developing/refining penetration test methods in an unoccupied apartment unit on campus
  - Size-resolved PM (for integral measures of UFPs and $PM_{2.5}$)
  - Ozone (O_3)
  - Nitrogen oxides ($NO_x = NO + NO_2$)
    - Unable to realistically measure NO_x *P*





Ozone: Zhao and Stephens **2016** *Indoor Air* 26:571-581
PM: Zhao and Stephens **(in press)** *Indoor Air*

Field measurement approach

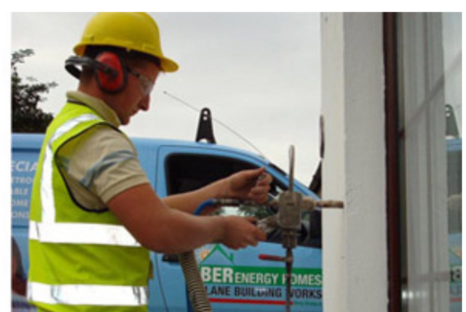
- Pre/post retrofit measurements in 6 SF + 2 MF units
  - Homes planning to undergo energy efficiency improvements

Homes built between 1894 and 1956 (avg = 1926)

Typical retrofit measures

- All homes:
  - Attic air sealing and blown-in insulation for all homes
    - Typically to R-49
    - Typically with attic hatch insulation
  - Weather stripping on doors

- Some homes:
  - Attic knee wall air sealing and insulation
  - Can light boxes
  - Crawlspace insulation and air sealing
  - Blown-in wall insulation in balloon framing wall cavities (2 homes)



Field measurements: Blower door

- Blower door tests were performed before and after retrofits
- Resulting airtightness parameters include:
  - Leakage flow at 50 Pa (CFM_{50})
  - Effective leakage area (ELA)
  - Normalized leakage (NL)
  - Air changes per hour at 50 Pa (ACH_{50})

Field measurements: Pollutant infiltration

Particles:
TSI Model 3330 Optical Particle Sizer (0.3 to 10 μm)
TSI Nanoscan SMPS (0.01 μm to ~0.2 μm)
TSI DustTrak #8534 (light scattering $PM_{2.5}$+PM_{10})
AethLabs MicroAethelometer (for BC) (not shown)

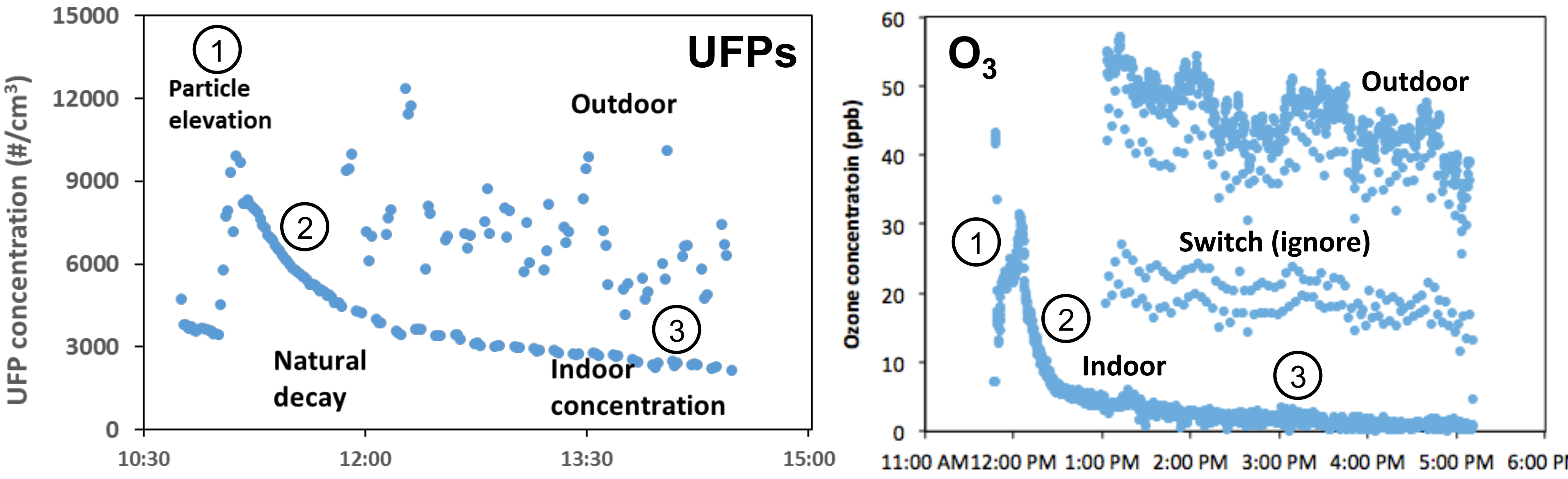
Gas-phase pollutants:
Ozone: 2B Technologies Model 211 monitor
NO_x: 2B Technologies Model 405 monitor
CO_2: PP Systems SBA-5 monitor
- CO_2 injection and decay to measure air exchange

Shinyei/GrayWolf formaldehyde monitor (indoor only)

Electronically actuated switching valves:
Stainless steel sampling lines (for PM)
Teflon sampling lines (for O_3 and NO_x)

Houses are unoccupied during testing

Example data: Pollutant infiltration

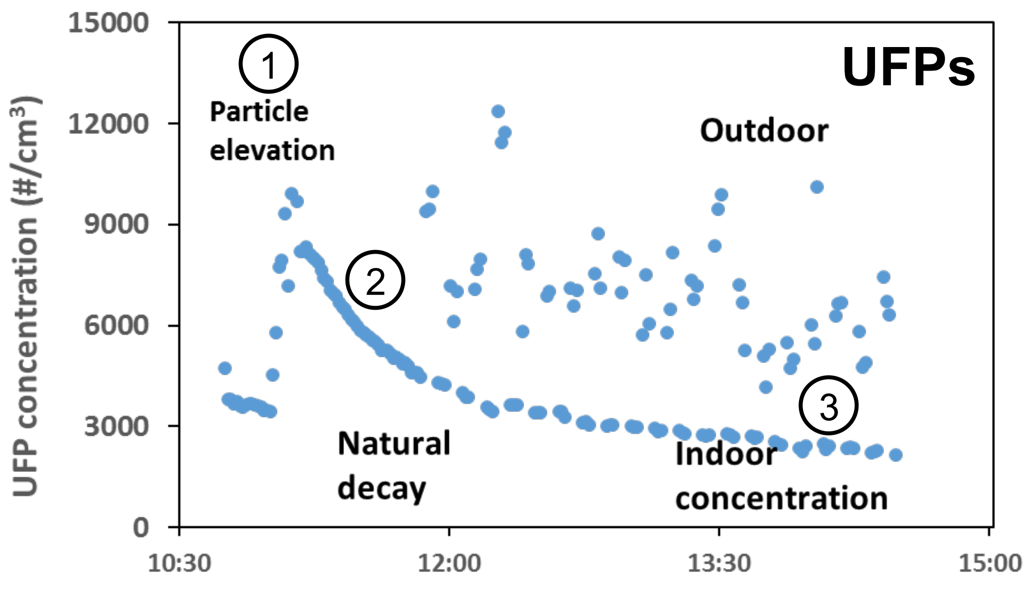


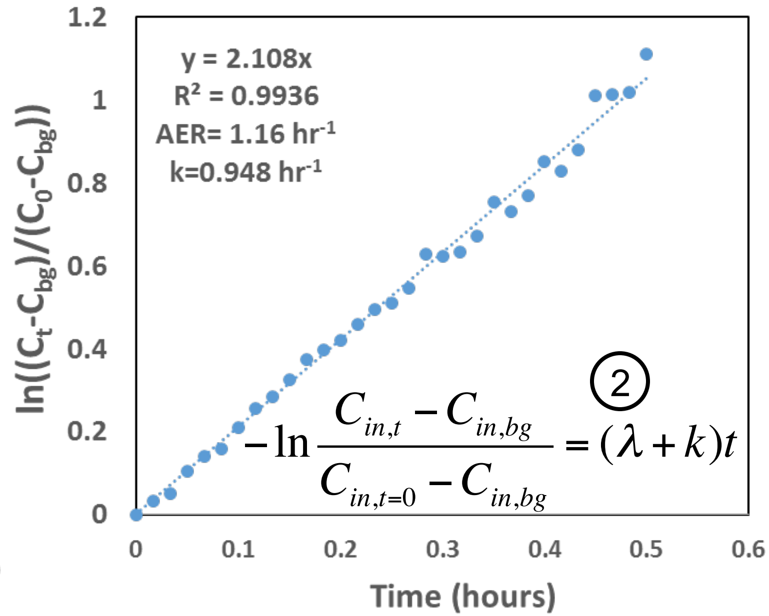
Three distinct test periods to solve for *P* and *k*:

1. Elevation w/ open windows + blower door
   - Indoor only for ~15 minutes
2. Decay to background
   - Indoor only for ~45 minutes
3. Response/rebound period → infiltration factor
   - Alternating indoor/outdoor for ~3 hours

Houses are unoccupied during testing

Solving for infiltration and penetration factors





Mass or number balance: $$\frac{dC_{in}}{dt}=P\lambda C_{out}-(\lambda+k)C_{in}\longrightarrow F_{\inf}=\frac{P\lambda}{\lambda+k} \quad ③$$

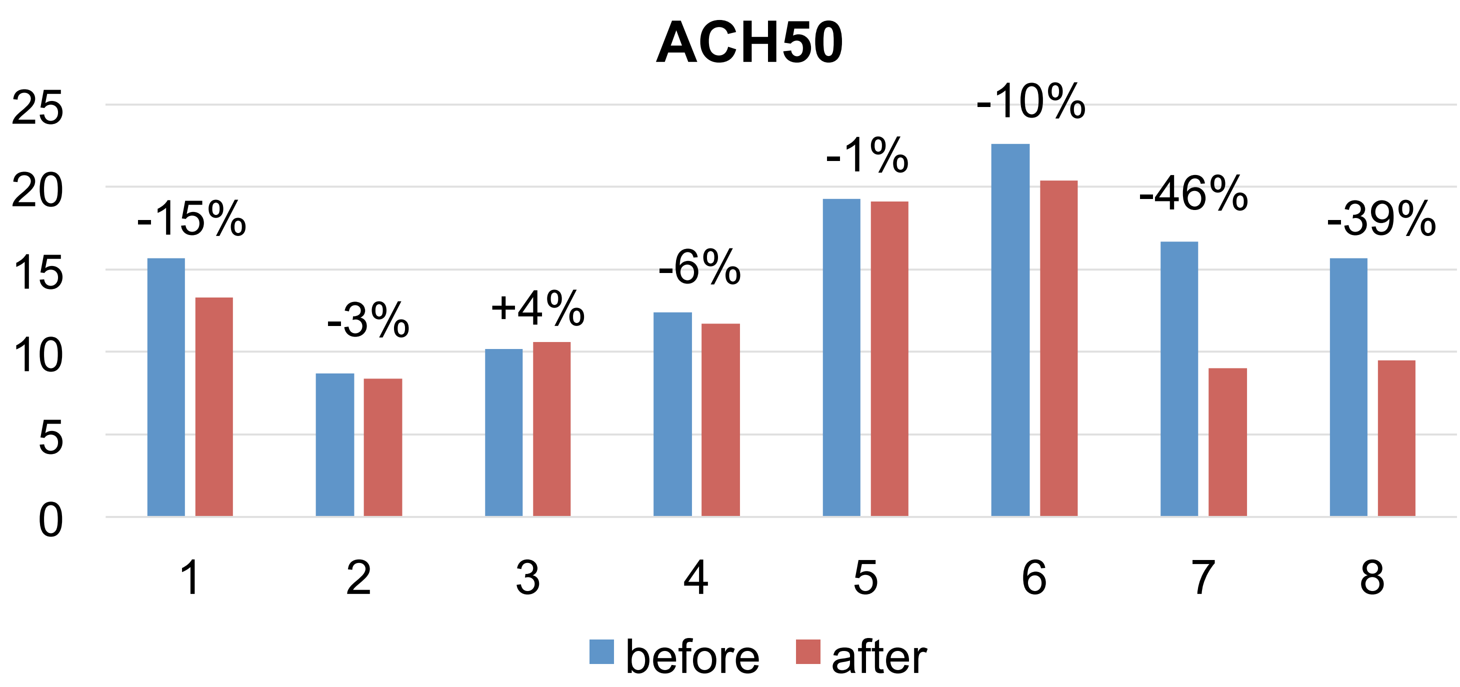
- C_{in} *and* C_{out} are indoor and outdoor concentrations (ppb or μg/m^3 or #/cm^3)
- *P* is the penetration factor (-)
- *k* is the first order deposition loss rate constant/first order reaction rate (h^{-1})
- *λ* is the air exchange rate (AER) (h^{-1}), which is simultaneously measured using injection and decay of CO_2 as a tracer gas

Solve for *P* using *k* and *λ*: $$C_{in,t}=P\lambda C_{out,t}\Delta t+(1-(\lambda+k)\Delta t)C_{in,t-1} \quad ②+③$$

Preliminary results: ACH_{50}

The retrofits reduced ACH_{50} by between -4% and 46%

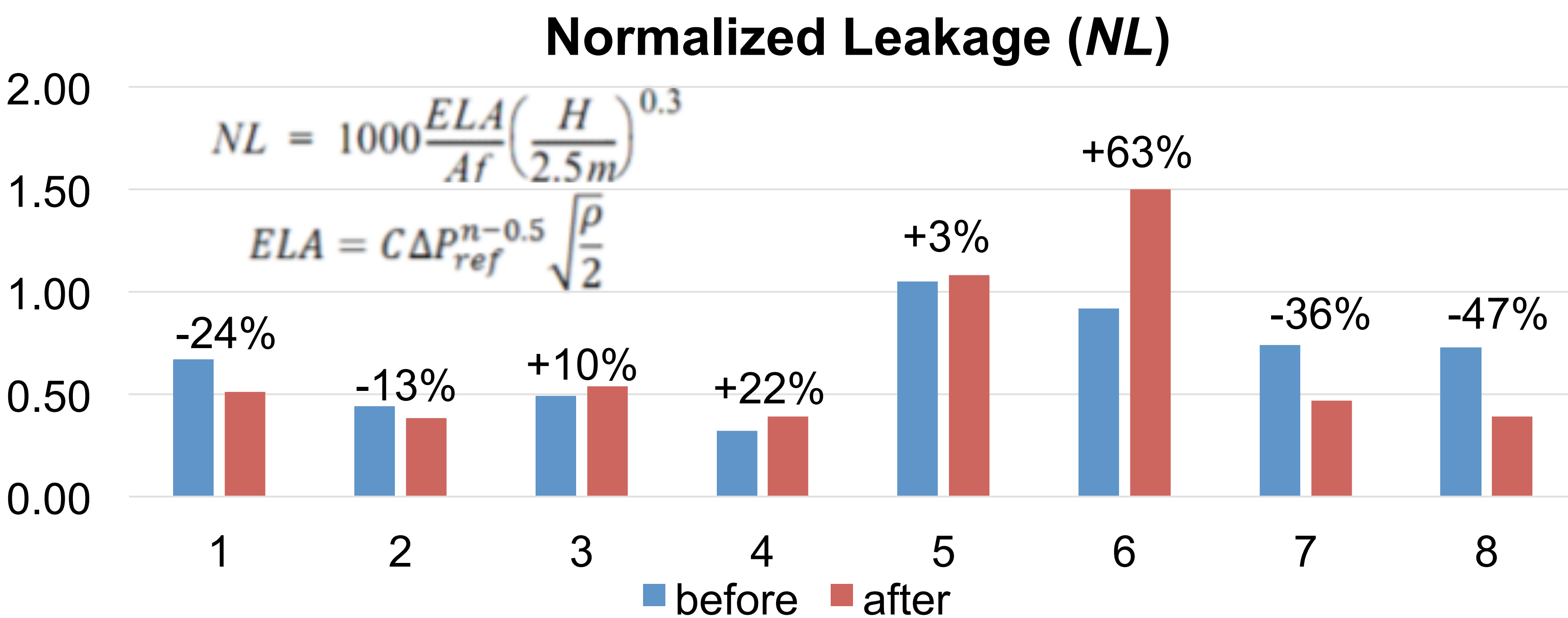
- Average change: -15%



Preliminary results: Normalized Leakage (*NL*)

The retrofits decreased *NL* by as much as -47% but *increased* as much as 63%

- Average change: -4%
- NL is calculated based on both the leakage coefficient (*C*) and the leakage exponent (*n*)
  - ✓ Influenced by the nature of building crack geometry

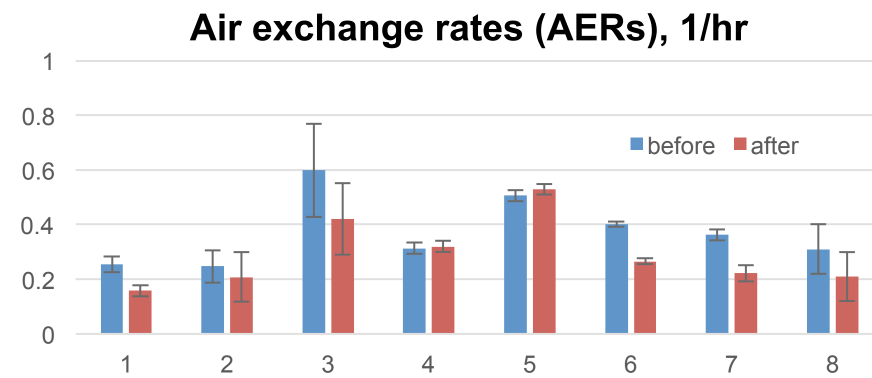


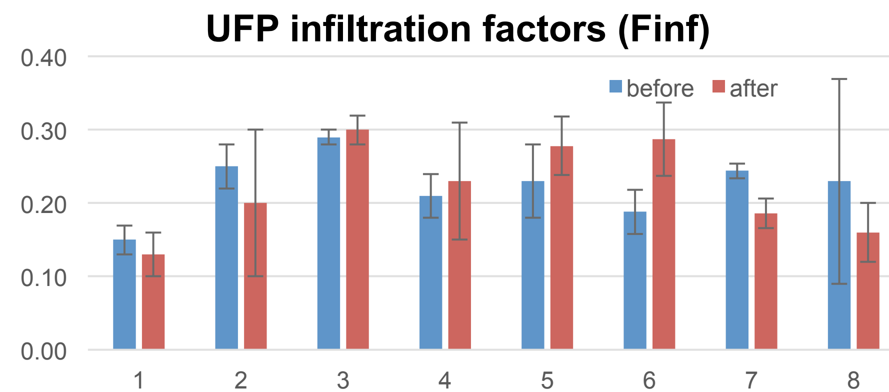
$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

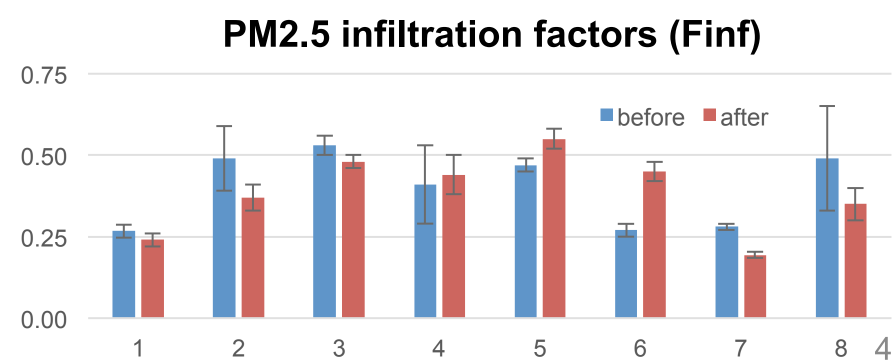
$$ELA = C\Delta P_{ref}^{n-0.5}\sqrt{\frac{\rho}{2}}$$

Preliminary results: AERs and infiltration factors

- Air exchange rates were between 39% lower and 5% higher during measurements before and after retrofits
  - Influenced by airtightness, temperature differences, and wind speed/direction
- Average UFP infiltration factors were 0.22±0.04 before retrofits and 0.22±0.06 after retrofits
  - No difference (some up, some down)
- Average $PM_{2.5}$ infiltration factors were 0.40±0.11 before retrofits and 0.39±0.12 after retrofits
  - No difference (some up, some down)
- F_{inf} influenced by multiple factors
  - Retrofits + climate conditions + PSDs

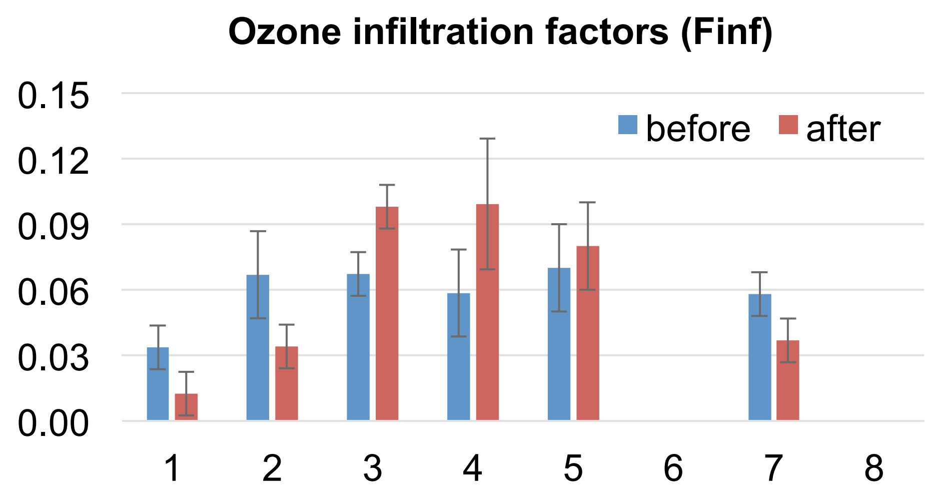




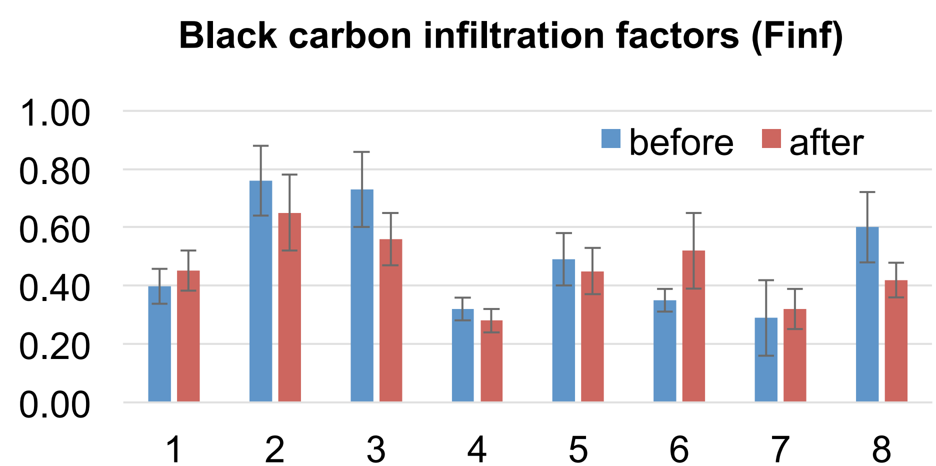


Preliminary results: AERs and infiltration factors

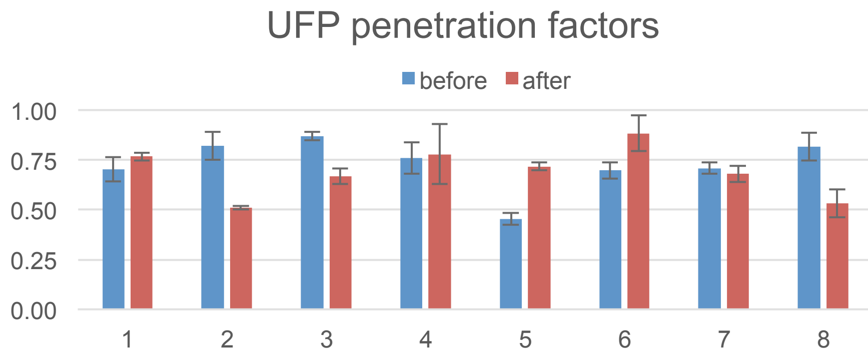
- Average ozone infiltration factors were 0.05±0.02 before retrofits and 0.06±0.03 after retrofits
  - No difference (some up, some down)



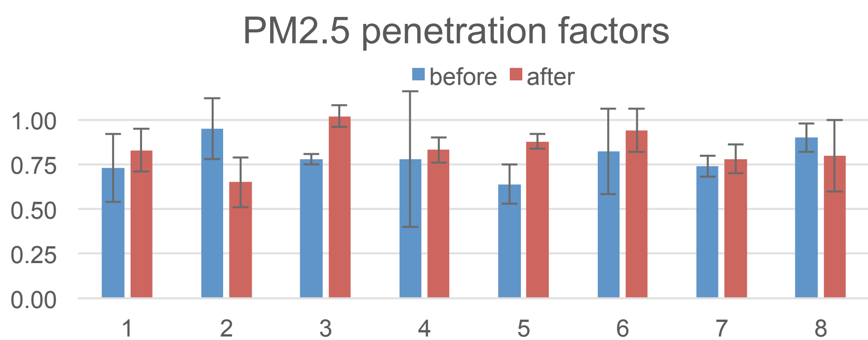
- Average black carbon infiltration factors were 0.48±0.18 before retrofits and 0.46±0.12 after retrofits
  - No difference (some up, some down)



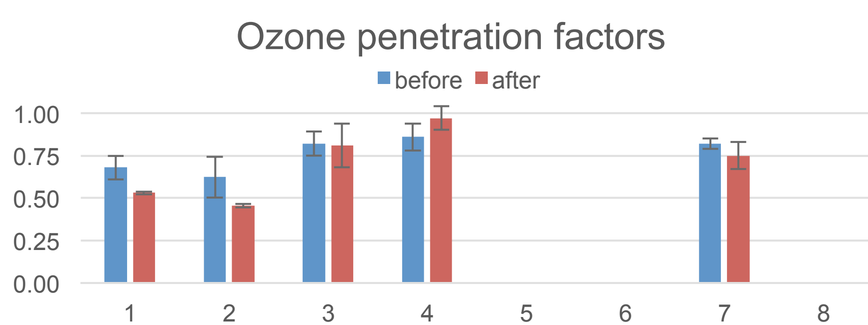
Preliminary results: UFP, $PM_{2.5}$, and O_3 penetration factors



- Estimates of UFP penetration factors (mean ± SD) were 0.72±0.12 before retrofits and 0.72±0.10 after retrofits
  - Ranging from 0.46±0.03 to 0.88±0.09

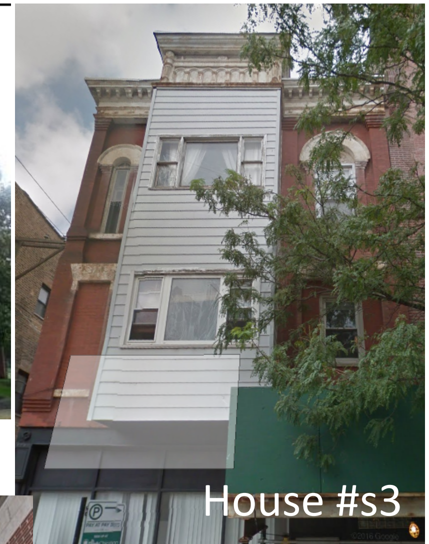


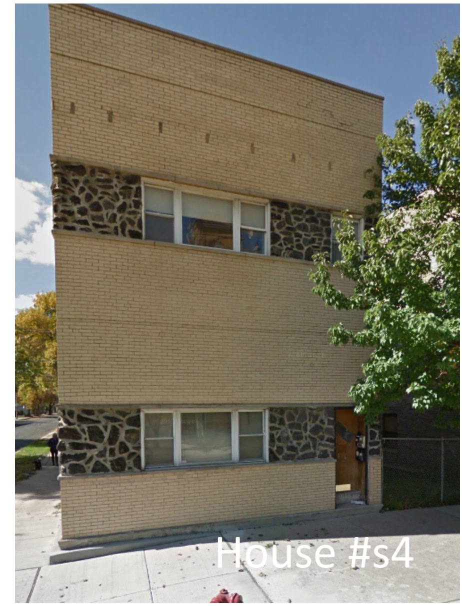
- Estimates of $PM_{2.5}$ penetration factors (mean ± SD) were 0.78±0.09 before retrofits and 0.85±0.11 after retrofits
  - Ranging from 0.64±0.11 to 1.02±0.06



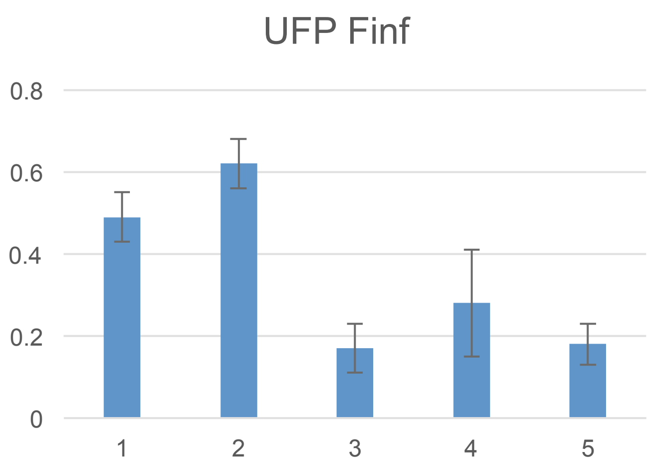
- Estimates of ozone penetration factors (mean ± SD) were 0.76±0.09 before retrofits and 0.70±0.19 after retrofits
  - Ranging from 0.68±0.07 to 0.97±0.07

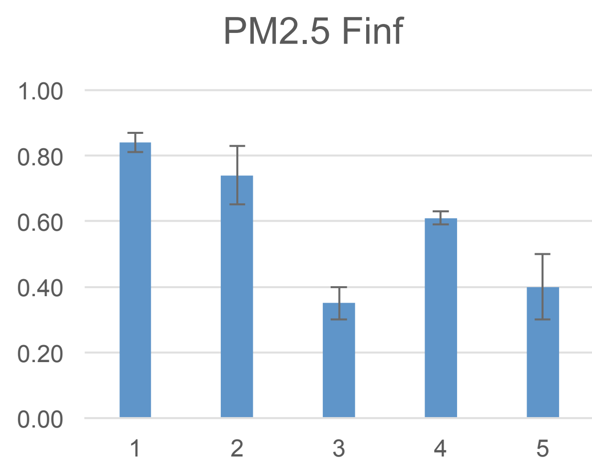
Non-retrofit homes (all multi-family)

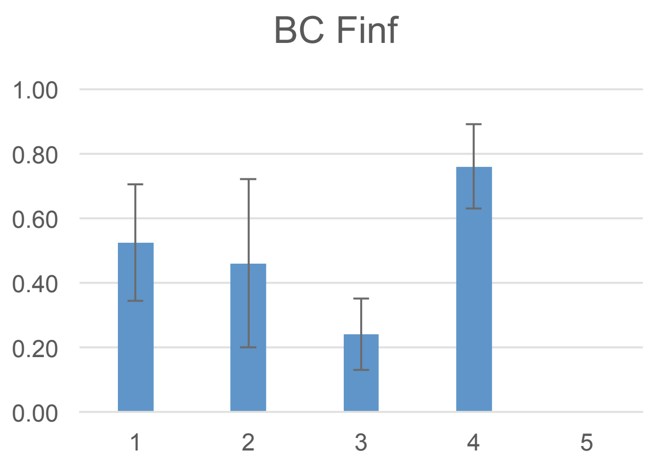


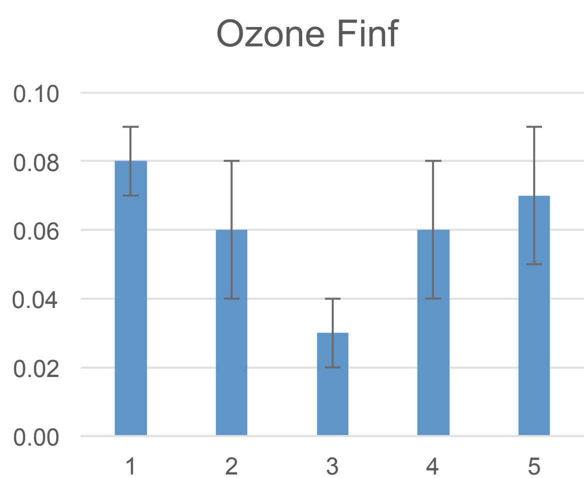


Preliminary results: Non-retrofit home infiltration factors







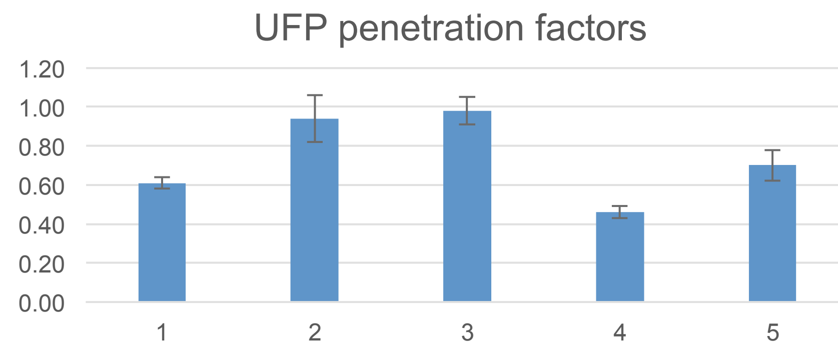


- Average (SD) UFP infiltration factors: 0.35±0.07
  - Ranging from 0.17 to 0.62
- Average (SD) $PM_{2.5}$ infiltration factors: 0.59±0.06
  - Ranging from 0.40 to 0.84
- Average (SD) BC infiltration factors: 0.49±0.17
  - Ranging from 0.24 to 0.76
- Average (SD) ozone infiltration factors: 0.06±0.02
  - Ranging from 0.03 to 0.08

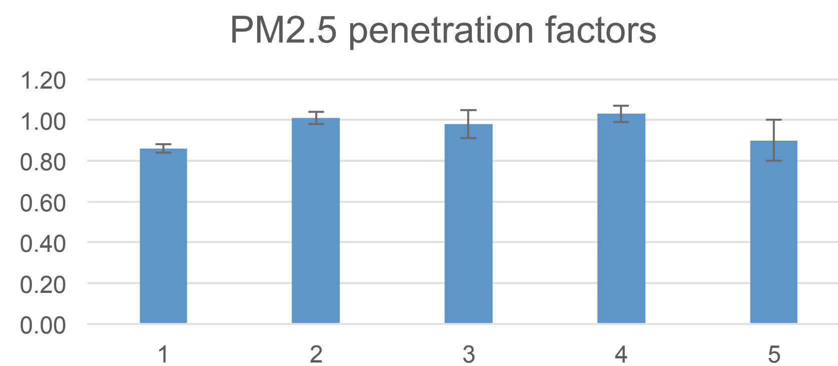
All homes were multi-family units

Preliminary results: Non-retrofit home penetration factors

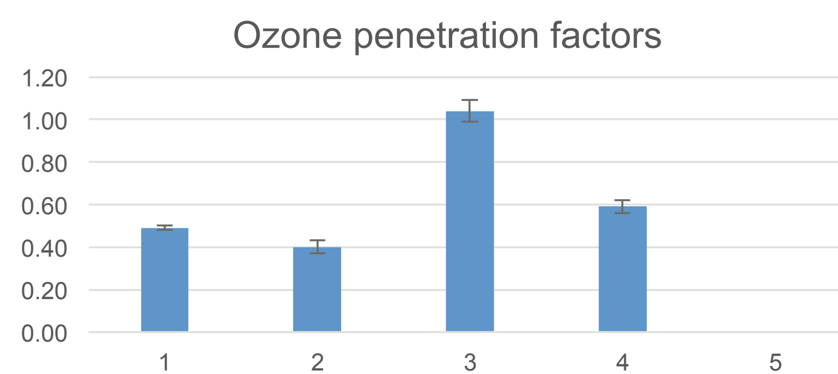
- Estimates of UFP penetration factors (mean ± SD) were 0.74±0.07
  - Ranging from 0.46±0.03 to 0.98±0.07



- Estimates of $PM_{2.5}$ penetration factors (mean ± SD) were 0.96±0.05
  - Ranging from 0.86±0.02 to 1.03±0.04



- Estimates of ozone penetration factors (mean ± SD) were 0.76±0.03
  - Ranging from 0.40±0.0 to 1.04±0.04



All homes were multi-family units

Summary of work to date

Modeling

- New residential building energy and IAQ modeling framework developed
- Still need to incorporate health outcomes analysis (e.g., DALYs, CCRs), develop future policy scenarios, and figure out how to handle future hourly outdoor pollutant data

Field measurements

- Tested 8 homes pre/post retrofit (6 SF + 2 MF) and 5 non-retrofit MF units
- No apparent strong correlations between changes in pollutant infiltration factors or penetration factors with envelope airtightness alone
  - Some suggestion of the impact of a combination of change in envelope airtightness (i.e., NL or ACH50) in addition to changes in meteorological and/or pollutant conditions during testing
- Original goal of testing 30 homes pre/post retrofit will be difficult to meet

Acknowledgments

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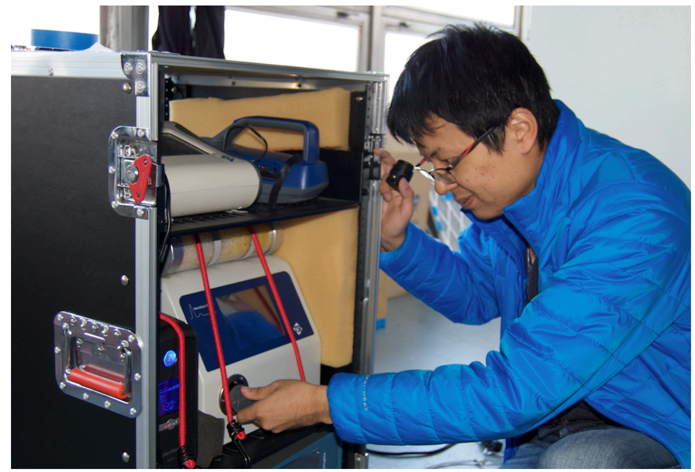

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Smarter energy use for all

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