Energy Analysis of the Built Environment: from unit to the city-scale

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The built environment: from unit to city-scale

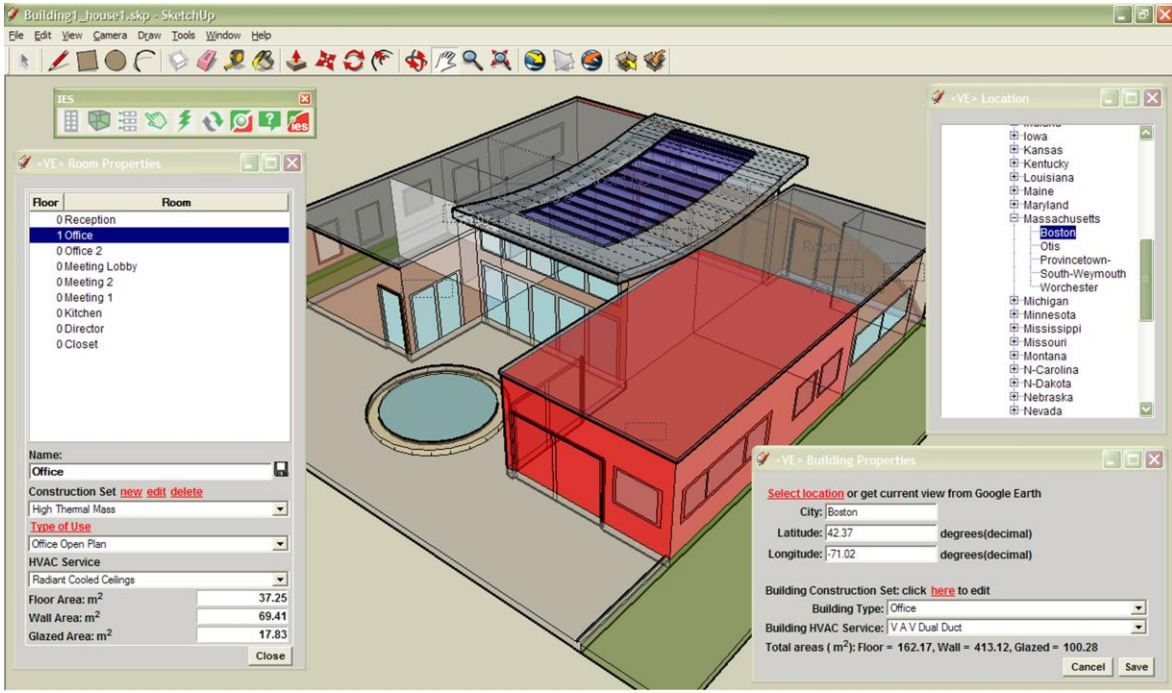
Dynamic Building Energy Simulation:

Characteristics:

- 3-dimensional representation of building form and heat transfer
- Solution of energy balance equations at small intervals (e.g., hourly) over an entire year

Caveats:

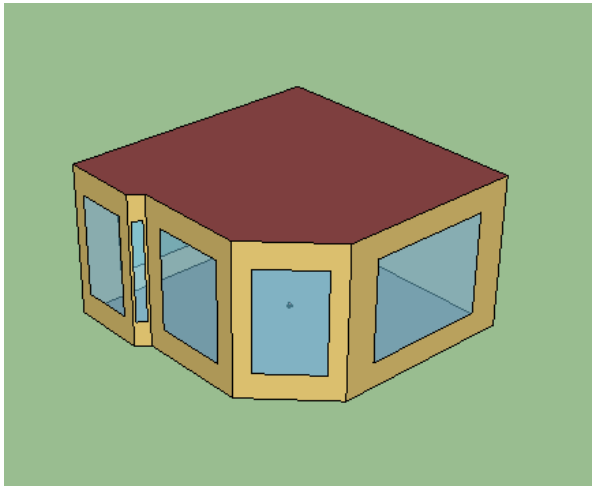
- Requires 3D building geometry data
- Requires sensible inputs for hourly energy services demand



Westminster Annual Heat Intensity

Spot Check 1: Polygon G9527333 - Office
(NE Corner of Regent St. and Great Marlborough St.)

Generated IDF (Wei's script)



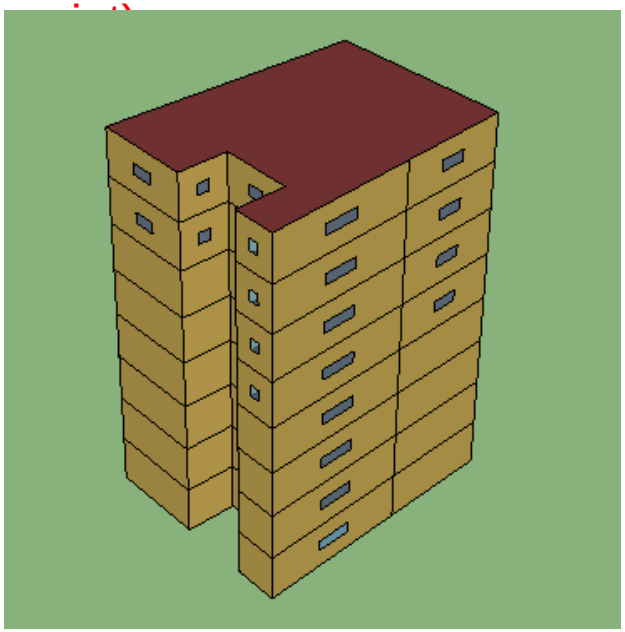
GIS Data

Google StreetView

- This polygon represents the top three floors of the corner suite (14.5 m in height). It is an office situated above a Banana Republic retail outlet

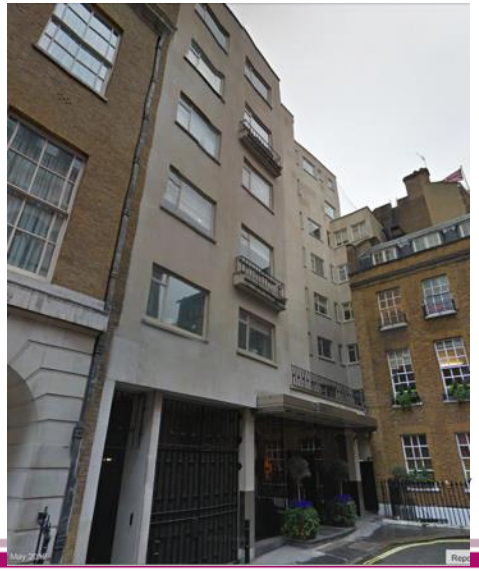
Spot Check 2: Polygon G9532901 - Office
(NW Corner of St James Place, Alongside Hyde Park)

Generated IDF (Wei's



GIS Data

- This is a complete building with partial exposure on side facades, and full exposure on front and rear facades.



Google StreetView

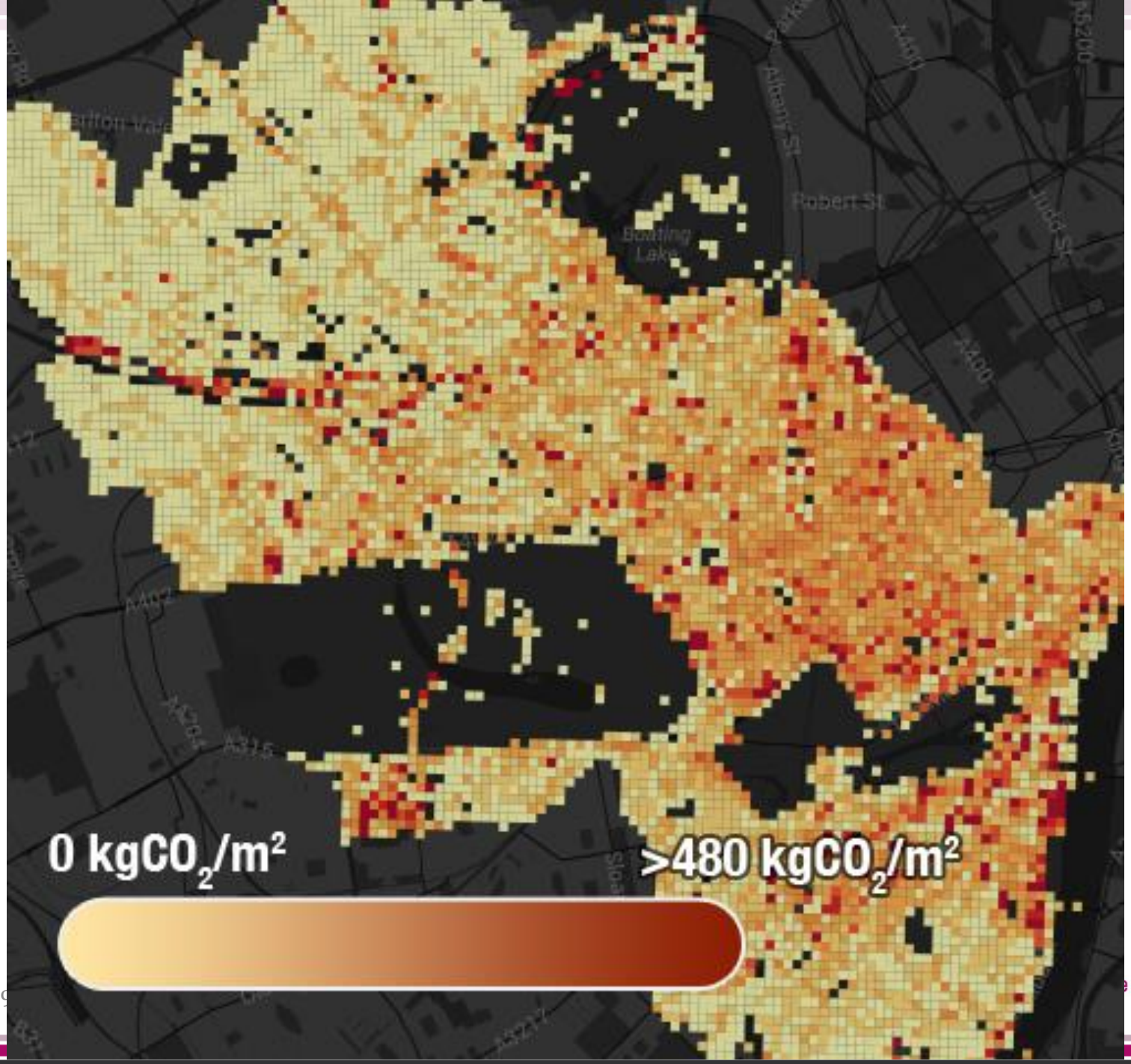
Spot Check 1: Polygon G9527333 - Office
(NE Corner of Regent St. and Great Marlborough St.)

Input Data (as sampled)

Variable	Value
Floor Area (m2)	517
Shape Area (m2)	517.5
Number Floors	1
Vertical location	top
Floor height (m)	13.5
Wall U value (W/m2K)	0.9286659
Ground floor U value (W/m2K)	2.963241
Roof U-value (W/m2K)	2.504509
Window U-value (W/m2K)	5.610624
Window SHGC	0.6
Window-Wall-Ratio	0.4420269
Infiltration rate (ACH)	0.478629

Variable	Value
Occupant Density (m2/pers)	9.009009009
Occupant Metabolic Rate (W)	123
Lighting Intensity (W/m2)	15
Equipment intensity (W/m2)	11
Gains Schedule File	GAINS_OFF.csv
Makes Use of Daylighting? (1=yes,0=no)	1
Required illuminance (400 lux)	400
AC or NV?	NV
Setpoints Schedule File	SETPTS_OFF.csv
Veniltation Rate (ACH)	0.01
Heat Recovery (1=yes, 0=no)	1
DHW requirements (L/pers/day)	0.2


Cardton Vale
Abbey Rd
A5
A503
A400
Outer Cir
Albany St
Beating
Gower St
Grays Inn Rd
Euston Rd
A401
A40
B450
B412
A402
A3204
A315
Kensington Gore
Queen's Gate
Sloane Ave
A3217
Kings Rd
A219
Shepherds Bush Rd
Stamford St
Waterloo Rd
A201
A302



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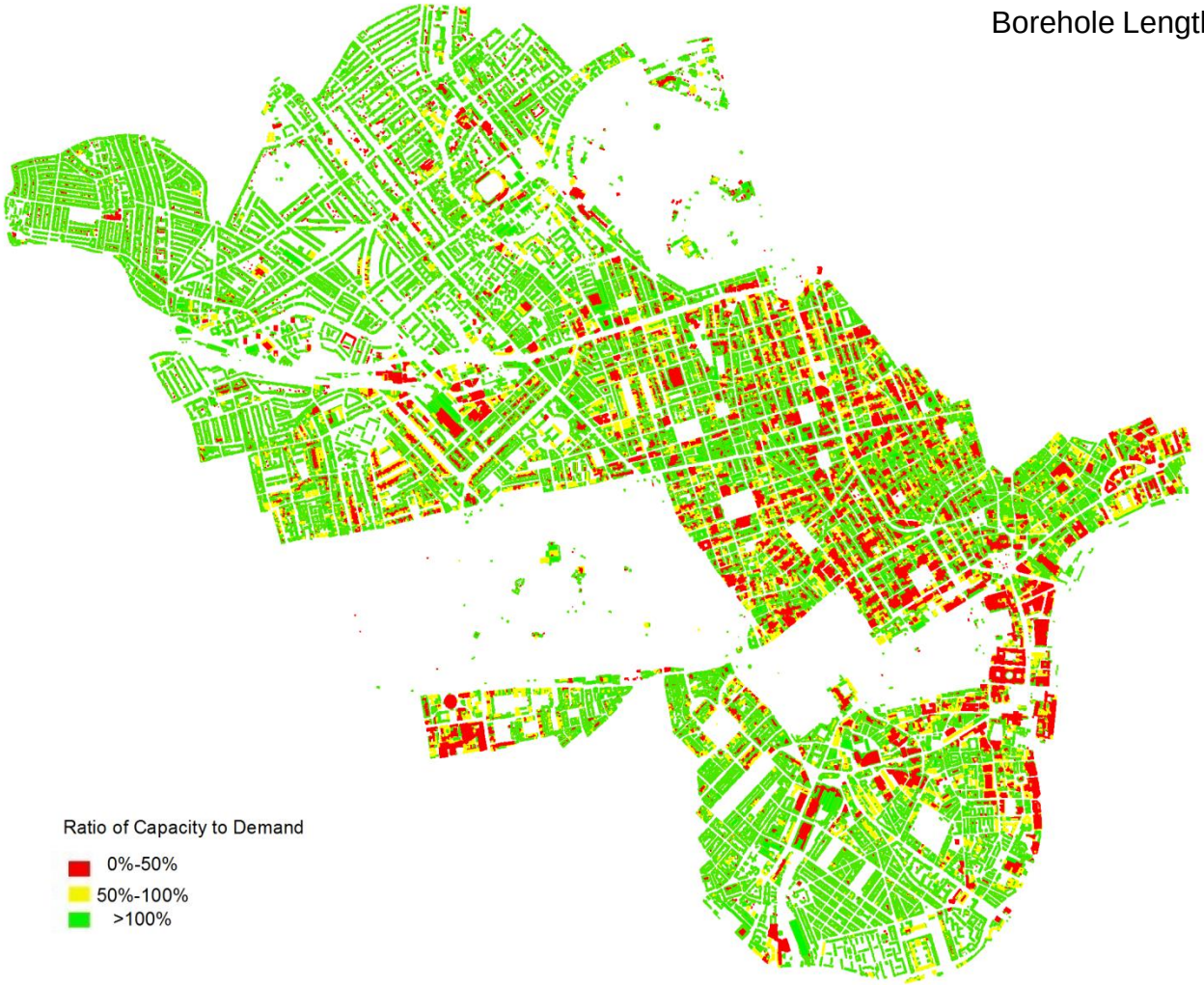
Geothermal Potential Around Buildings

Borehole Length:150m



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Necessary Features and Associated Challenges

- **Desired Features:**
  - Transportable;
  - Incremental;
  - Usable;

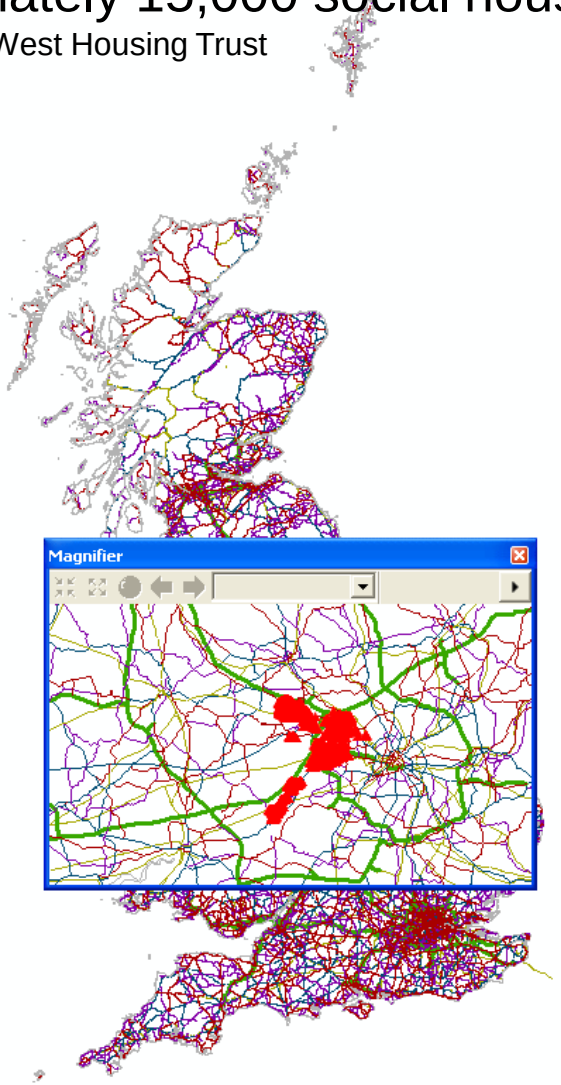
  - Physics based, w/ individual buildings and streets as unit of analysis;
  - Calibrated to better represent reality;
  - **Incorporation of first and second order uncertainties is important!**

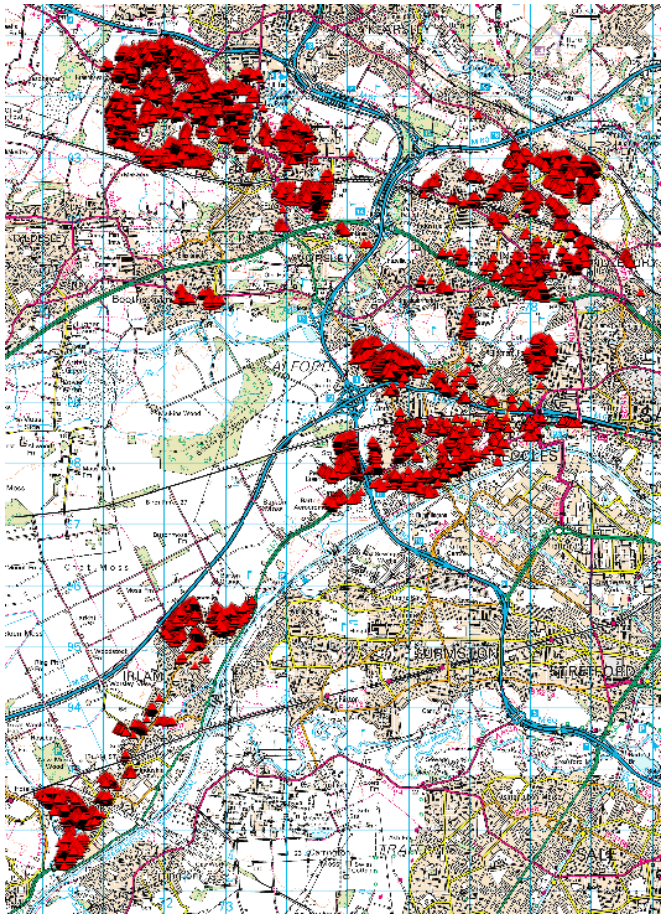
- **Challenges:**
  - Scaling up (or scaling down) is prohibitive;
  - Data/information is often incomplete or not available;
  - Model fidelity is difficult to gauge/prove;

SUSDEM: Stochastic Urban-scale Domestic Energy Model

approximately 15,000 social households in Manchester, UK

Sponsor: City West Housing Trust





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Analogy: populations

UK housing stock:

Retrofit options

Energy saved

UK population:

Medical procedures

QALYs

Building class	Structural type	Construction age	% of total floor area, $\frac{\sum_{i=1}^{N} x_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{P} x_{ij}}$
1	Flat	1870-1914	0.4
2	Terraced	1870-1914	21.1
3	Semi	1870-1914	4.2
4	Detached	1870-1914	5.0
5	Flat	1914-1945	0.3
6	Terraced	1914-1945	0.2
7	Semi	1914-1945	25.9
8	Detached	1914-1945	2.0
9	Flat	1945-1964	1.8
10	Terraced	1945-1964	1.4
11	Semi	1945-1964	10.5
12	Detached	1945-1964	0.4
13	Flat	1964-1979	3.2
14	Terraced	1964-1979	5.4
15	Semi	1964-1979	3.9
16	Detached	1964-1979	3.0
17	Flat	1979-2011	1.0
18	Terraced	1979-2011	1.4
19	Cottage flat	1979-2011	4.3
20	Semi	1979-2011	1.4
21	Detached	1979-2011	3.4

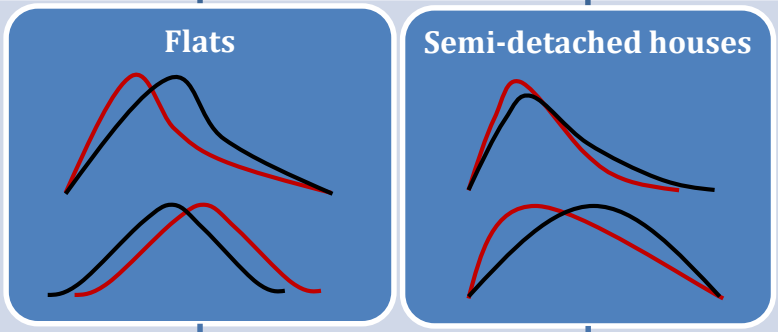
Clustering Households by Structure & Age

Hierarchical Urban Scale Analysis

1) The housing stock is split into separate sub-groups or "clusters" of homogeneous dwellings, e.g. flats and semi-detached houses

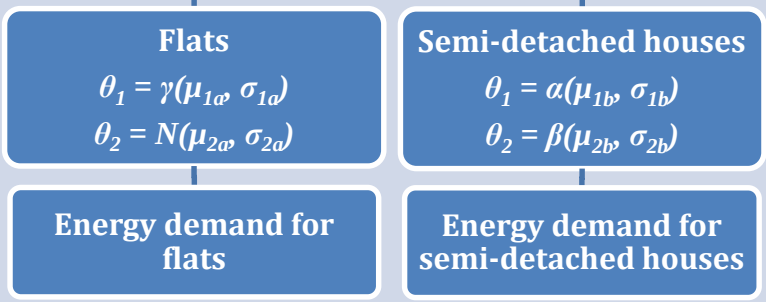
Clustering

2) For each cluster, priors of the calibration parameters are estimated to represent 2nd-order uncertainty. These distributions are then calibrated to create posteriors.



2nd-order uncertainty

3) A sample from the posteriors in (2) is used as a parameter (e.g. μ_{xy}) to define the 1st-order uncertainty for each calibration parameter for each cluster



1st-order uncertainty

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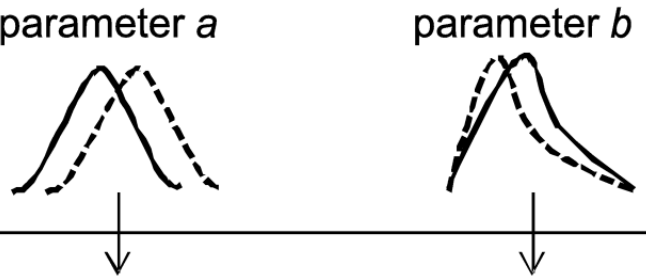
3: Bayesian calibration of uncertain parameters in energy model



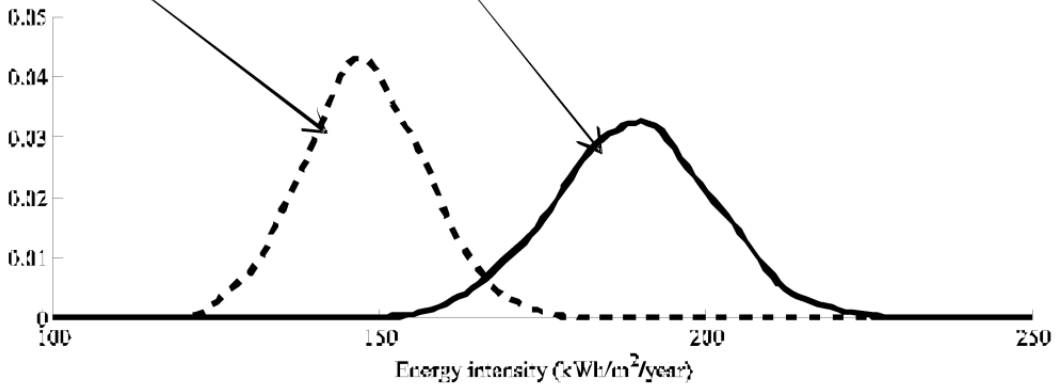
4(a): Sample from posterior distributions

$\boldsymbol{a} = [a_1, a_2, \ldots, a_{1000}]$ $\boldsymbol{b} = [b_1, b_2, \ldots, b_{1000}]$

4(b): Calculate energy demands for *n* dwellings and *R* retrofit scenarios

Baseline scenario:	Retrofit scenario 1:	⋯	Retrofit scenario *R*:
Dwelling 1	*Dwelling 1*		*Dwelling 1*
Dwelling 2	*Dwelling 2*		*Dwelling 2*
…	…		…
Dwelling n	*Dwelling n*		*Dwelling n*

5: Calculate average energy demand for each sample and energy savings for each retrofit scenario



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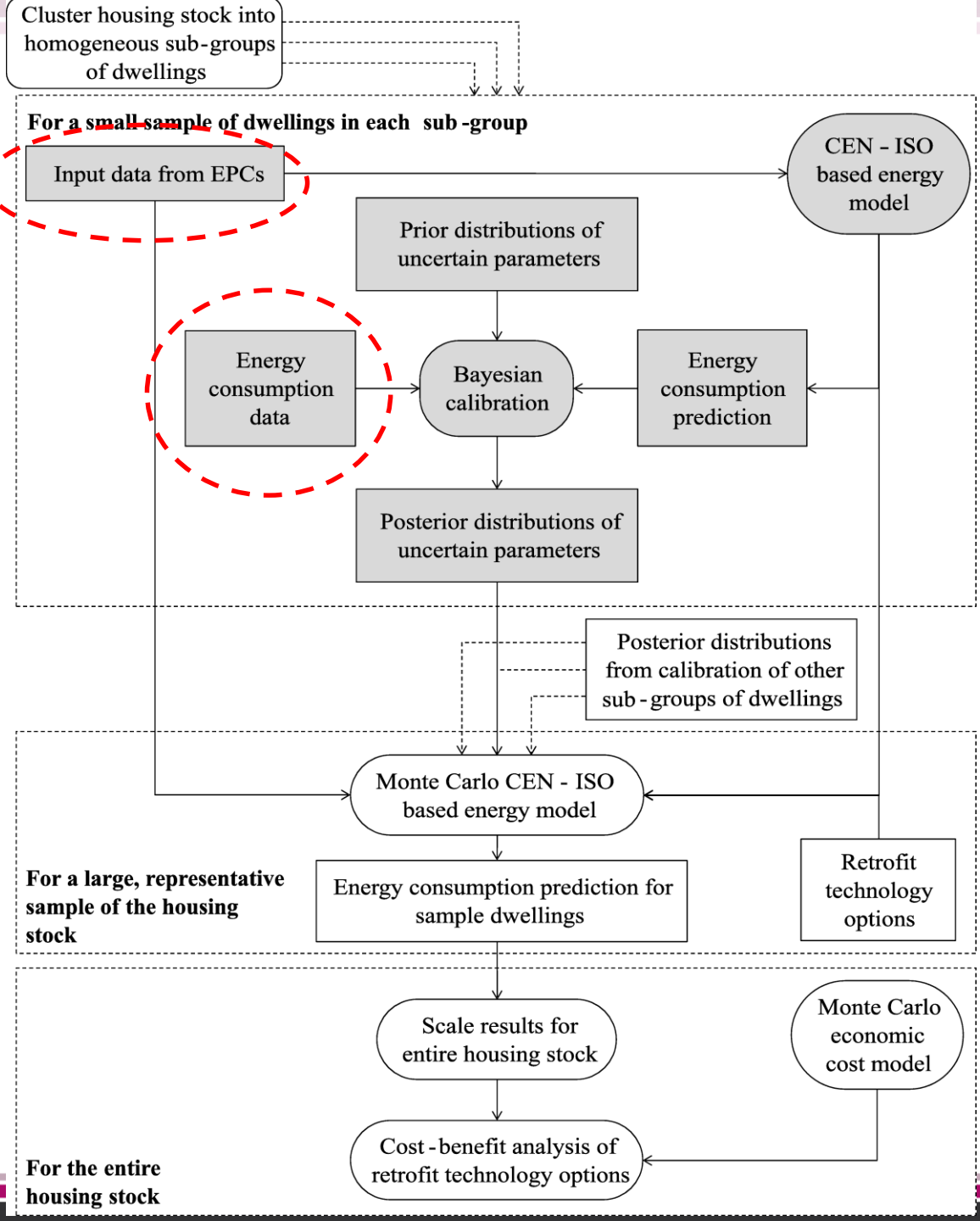
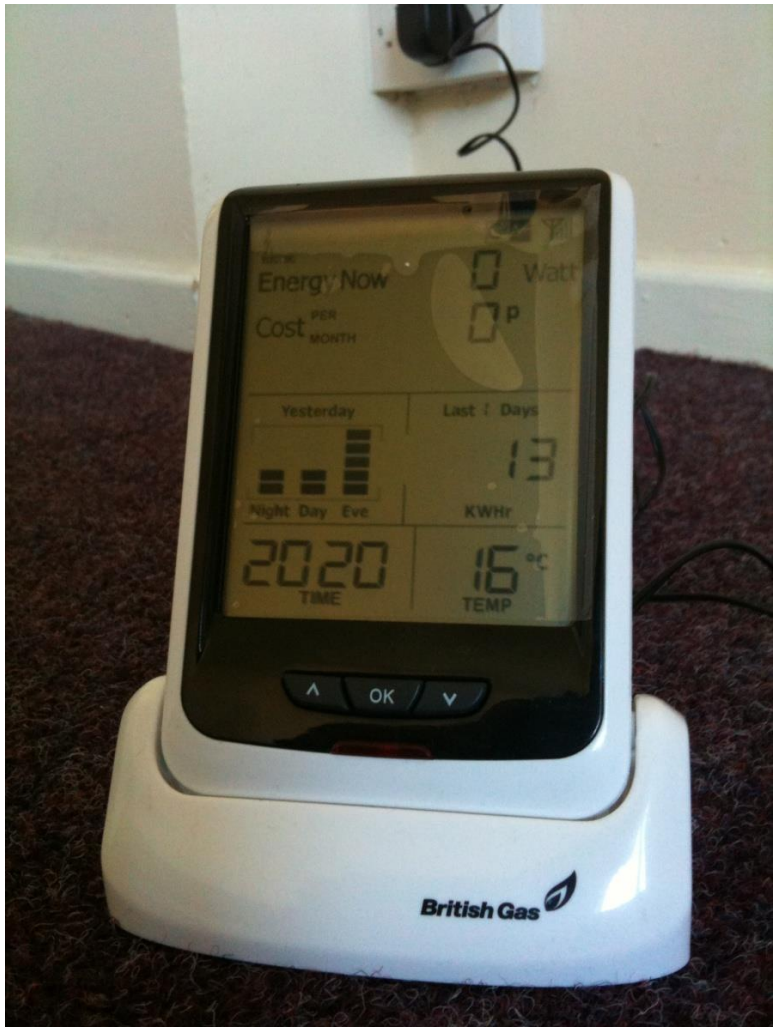
The Promise of Data....

- The owners do not have access to relevant information :/



Data Collection



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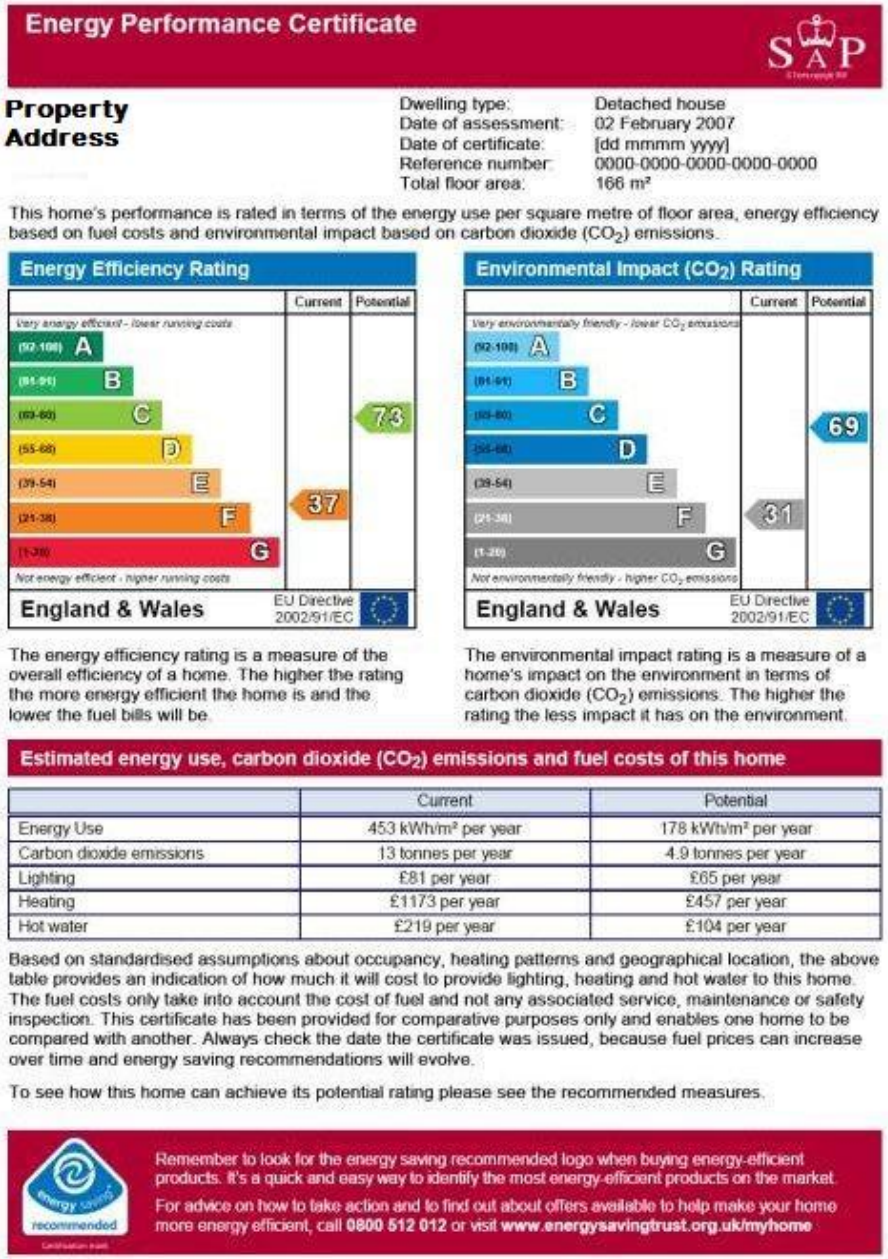
DCLG's EPC Register

Summary (Domestic sector)

- Includes building construction information (wall type, window type, etc.)
- Includes heating system type

- Needs translation of qualitative information into quantitative model input parameters

Inputs for Energy Model



Energy Performance Certificate

SAP

Property Address

Dwelling type:	Detached house
Date of assessment:	02 February 2007
Date of certificate:	[dd mmmm yyyy]
Reference number:	0000-0000-0000-0000-0000
Total floor area:	166 m²

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

Energy Efficiency Rating

	Current	Potential
Very energy efficient - lower running costs		
(92-100) A		
(81-91) B		73
(69-80) C		
(55-68) D		
(39-54) E		
(21-38) F	37	
(1-20) G		
Not energy efficient - higher running costs		
England & Wales	EU Directive 2002/91/EC	

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills will be.

Environmental Impact (CO_2) Rating

	Current	Potential
Very environmentally friendly - lower CO_2 emissions		
(92-100) A		
(81-91) B		
(69-80) C		69
(55-68) D		
(39-54) E		
(21-38) F	31	
(1-20) G		
Not environmentally friendly - higher CO_2 emissions		
England & Wales	EU Directive 2002/91/EC	

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy Use	453 kWh/m² per year	178 kWh/m² per year
Carbon dioxide emissions	13 tonnes per year	4.9 tonnes per year
Lighting	£81 per year	£65 per year
Heating	£1173 per year	£457 per year
Hot water	£219 per year	£104 per year

Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

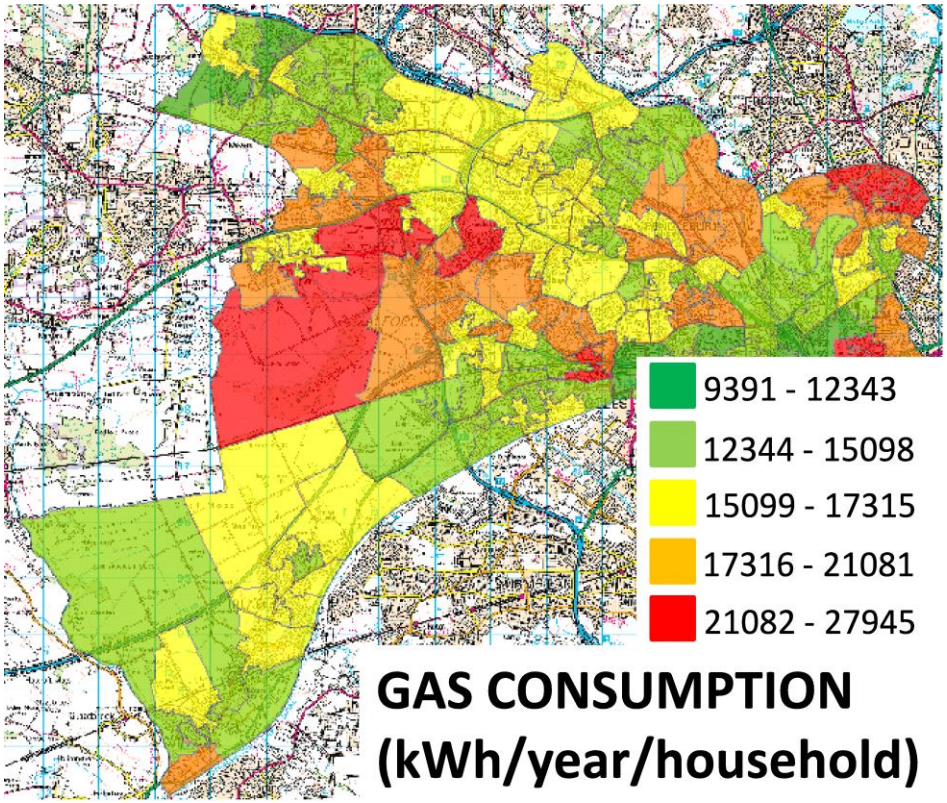
To see how this home can achieve its potential rating please see the recommended measures.

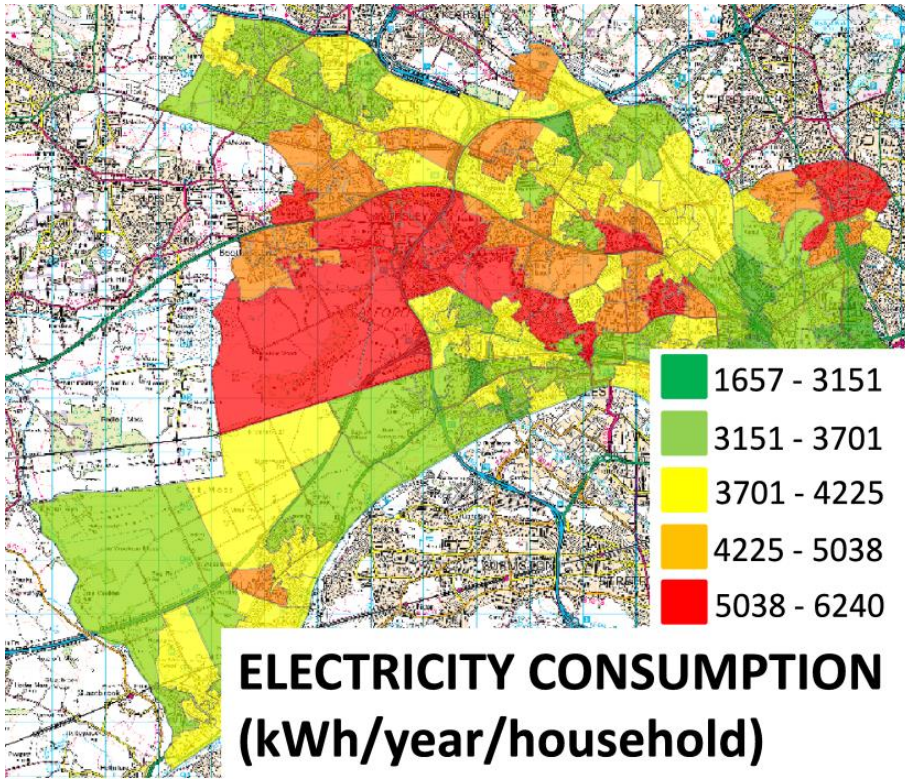
energy saving recommended

Remember to look for the energy saving recommended logo when buying energy-efficient products. It's a quick and easy way to identify the most energy-efficient products on the market.

For advice on how to take action and to find out about offers available to help make your home more energy efficient, call **0800 512 012** or visit **www.energysavingtrust.org.uk/myhome**

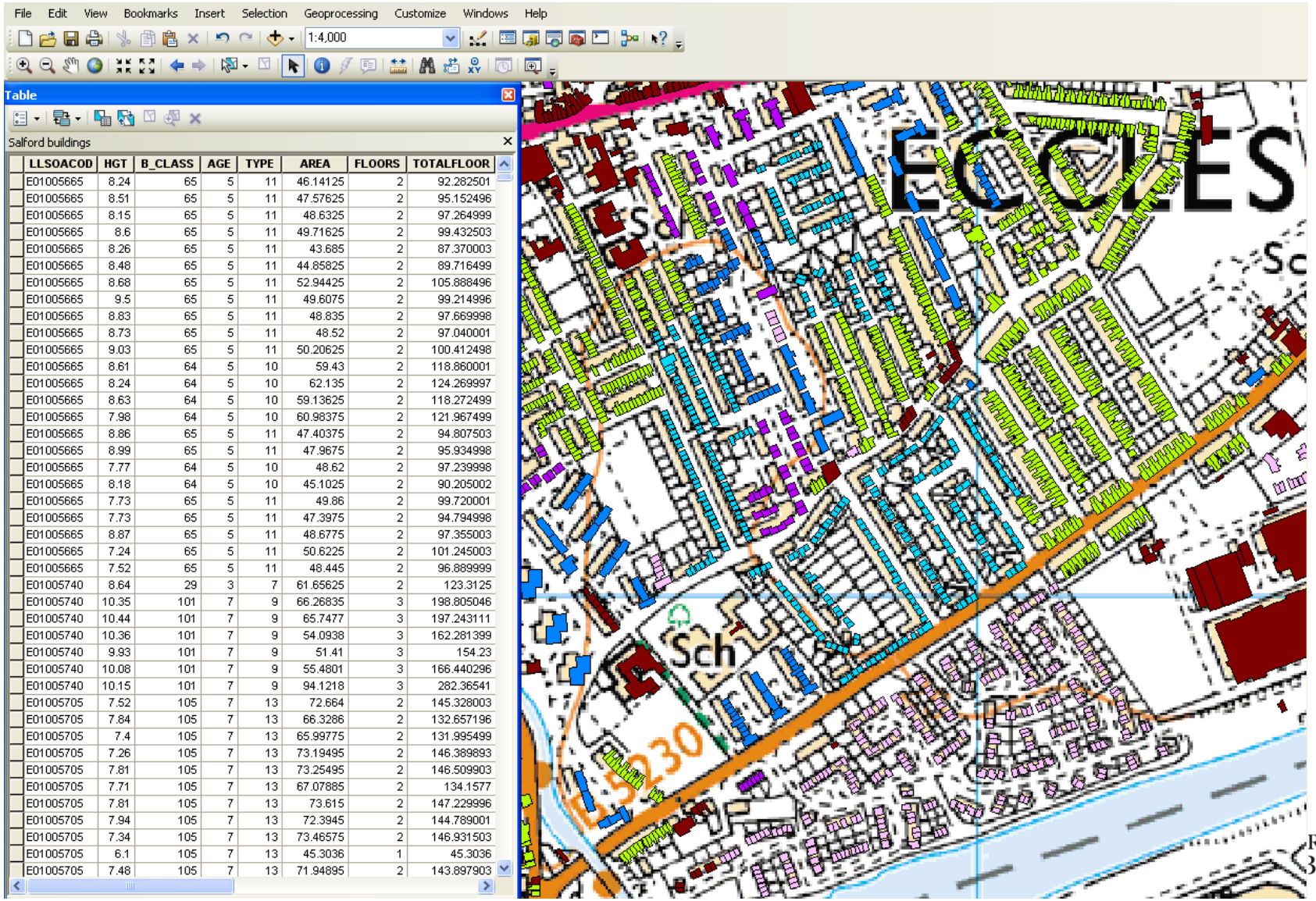
DECC's Sub-national energy statistics



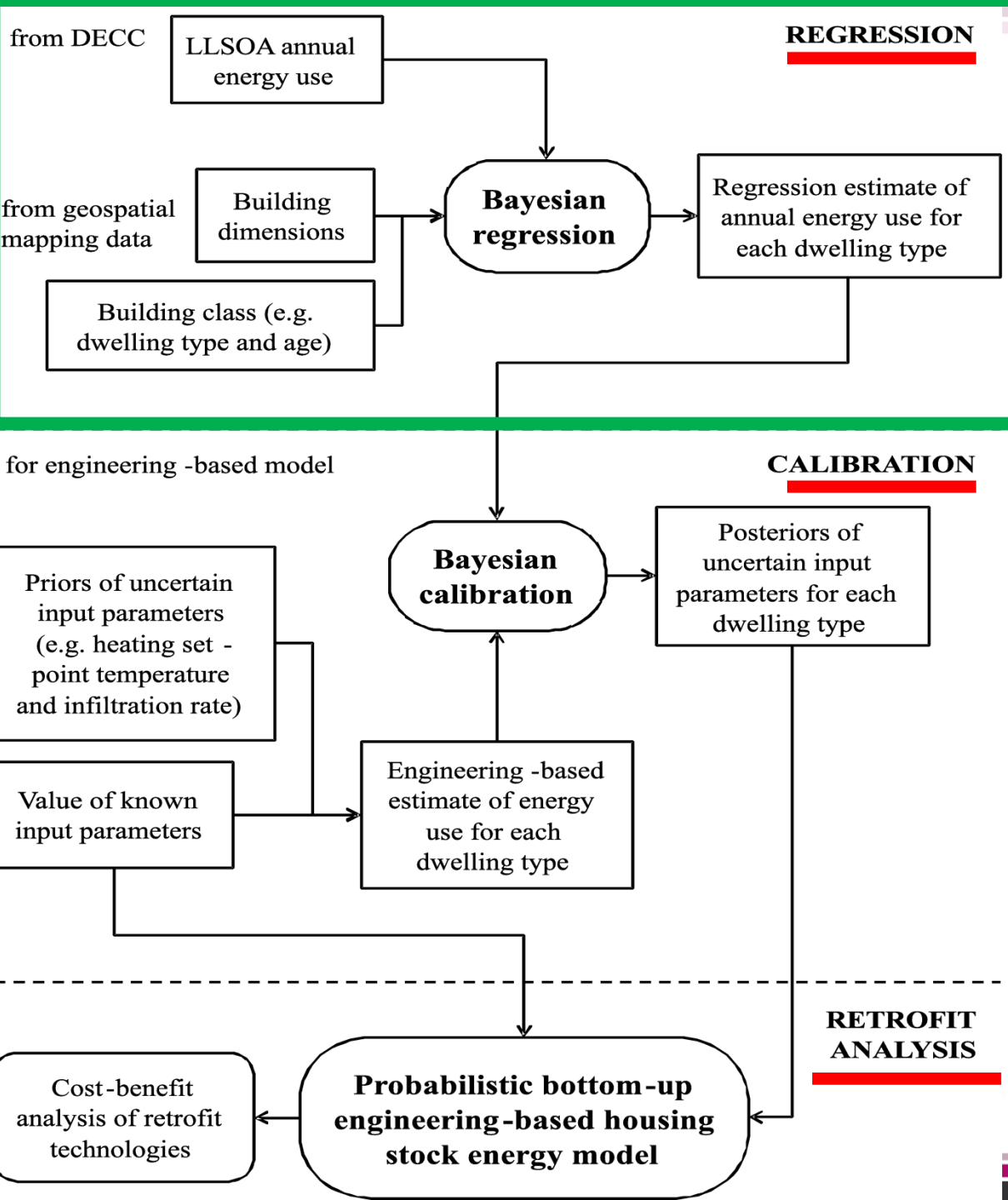


Annual Observations, but by districts (not individual houses)

GIS Mapping Databases



LLSOACOD	HGT	B_CLASS	AGE	TYPE	AREA	FLOORS	TOTALFLOOR
E01005665	8.24	65	5	11	46.14125	2	92.282501
E01005665	8.51	65	5	11	47.57625	2	95.152496
E01005665	8.15	65	5	11	48.6325	2	97.264999
E01005665	8.6	65	5	11	49.71625	2	99.432503
E01005665	8.26	65	5	11	43.685	2	87.370003
E01005665	8.48	65	5	11	44.85825	2	89.716499
E01005665	8.68	65	5	11	52.94425	2	105.888496
E01005665	9.5	65	5	11	49.6075	2	99.214996
E01005665	8.83	65	5	11	48.835	2	97.669998
E01005665	8.73	65	5	11	48.52	2	97.040001
E01005665	9.03	65	5	11	50.20625	2	100.412498
E01005665	8.61	64	5	10	59.43	2	118.860001
E01005665	8.24	64	5	10	62.135	2	124.269997
E01005665	8.63	64	5	10	59.13625	2	118.272499
E01005665	7.98	64	5	10	60.98375	2	121.967499
E01005665	8.86	65	5	11	47.40375	2	94.807503
E01005665	8.99	65	5	11	47.9675	2	95.934998
E01005665	7.77	64	5	10	48.62	2	97.239998
E01005665	8.18	64	5	10	45.1025	2	90.205002
E01005665	7.73	65	5	11	49.86	2	99.720001
E01005665	7.73	65	5	11	47.3975	2	94.794998
E01005665	8.87	65	5	11	48.6775	2	97.355003
E01005665	7.24	65	5	11	50.6225	2	101.245003
E01005665	7.52	65	5	11	48.445	2	96.889999
E01005740	8.64	29	3	7	61.65625	2	123.3125
E01005740	10.35	101	7	9	66.26835	3	198.805046
E01005740	10.44	101	7	9	65.7477	3	197.243111
E01005740	10.36	101	7	9	54.0938	3	162.281399
E01005740	9.93	101	7	9	51.41	3	154.23
E01005740	10.08	101	7	9	55.4801	3	166.440296
E01005740	10.15	101	7	9	94.1218	3	282.36541
E01005705	7.52	105	7	13	72.664	2	145.328003
E01005705	7.84	105	7	13	66.3286	2	132.657196
E01005705	7.4	105	7	13	65.99775	2	131.995499
E01005705	7.26	105	7	13	73.19495	2	146.389893
E01005705	7.81	105	7	13	73.25495	2	146.509903
E01005705	7.71	105	7	13	67.07885	2	134.1577
E01005705	7.81	105	7	13	73.615	2	147.229996
E01005705	7.94	105	7	13	72.3945	2	144.789001
E01005705	7.34	105	7	13	73.46575	2	146.931503
E01005705	6.1	105	7	13	45.3036	1	45.3036
E01005705	7.48	105	7	13	71.94895	2	143.897903



Data Generation

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Generating Virtual Data for Calibration

Full Model

$$E_k = \sum_{i=1}^{N} \mathrm{EUI}(i).\mathrm{PA}(i,k) + \varepsilon$$

$$\mathrm{EUI}(i) = \sum_{l=1}^{nsubt_i} \mathrm{EUI}_i(l).\mathrm{PA}_{i,k}(l)$$

Macro-level Data

Bayesian Regression

$$Y_k \sim \mathcal{N}(E_k, \sigma^2), \quad k = 1, \cdots, D$$

$$E_k = \mathrm{EUI}(1).\mathrm{PA}(1,k) + \cdots + \mathrm{EUI}(N).\mathrm{PA}(N,k)$$

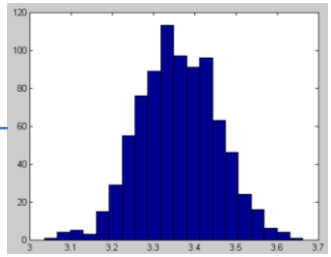
Quantity of Interest

Prior Estimates

$$\mathrm{EUI}(i) = \mathrm{B}_i(\alpha, \beta), \quad i = 1, \cdots, N$$

$$\sigma^{-2} \sim \mathrm{Gamma}(x, y)$$

Prior Beliefs



Energy Use Intensity per Dwelling Type

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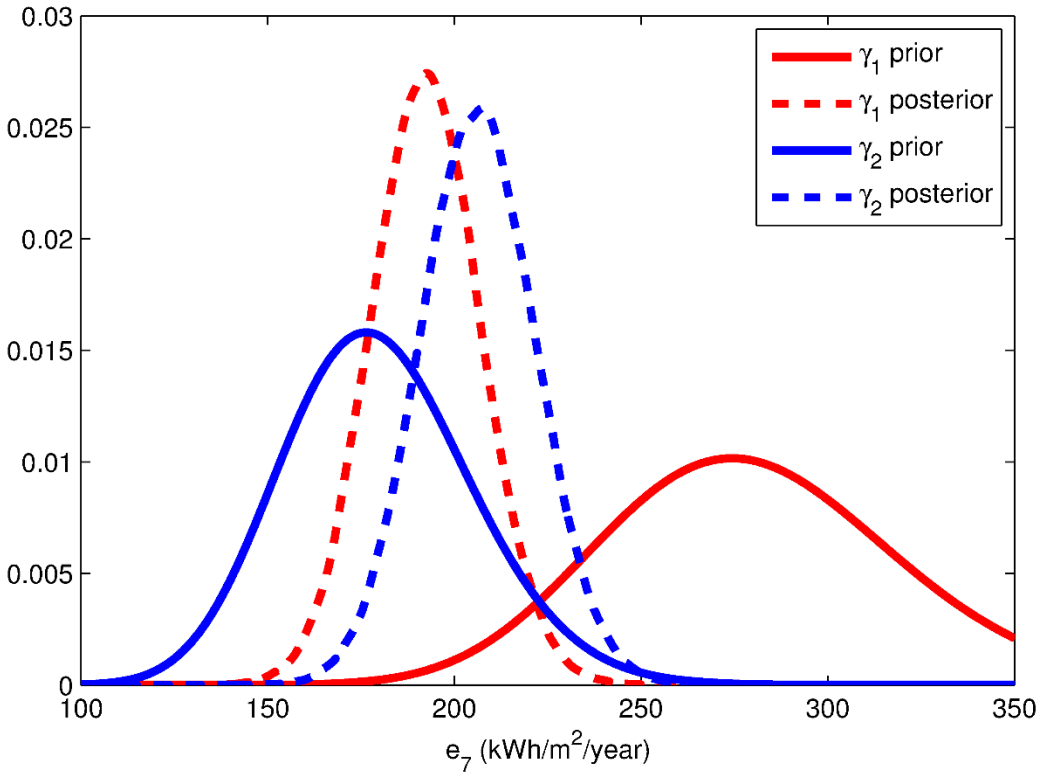
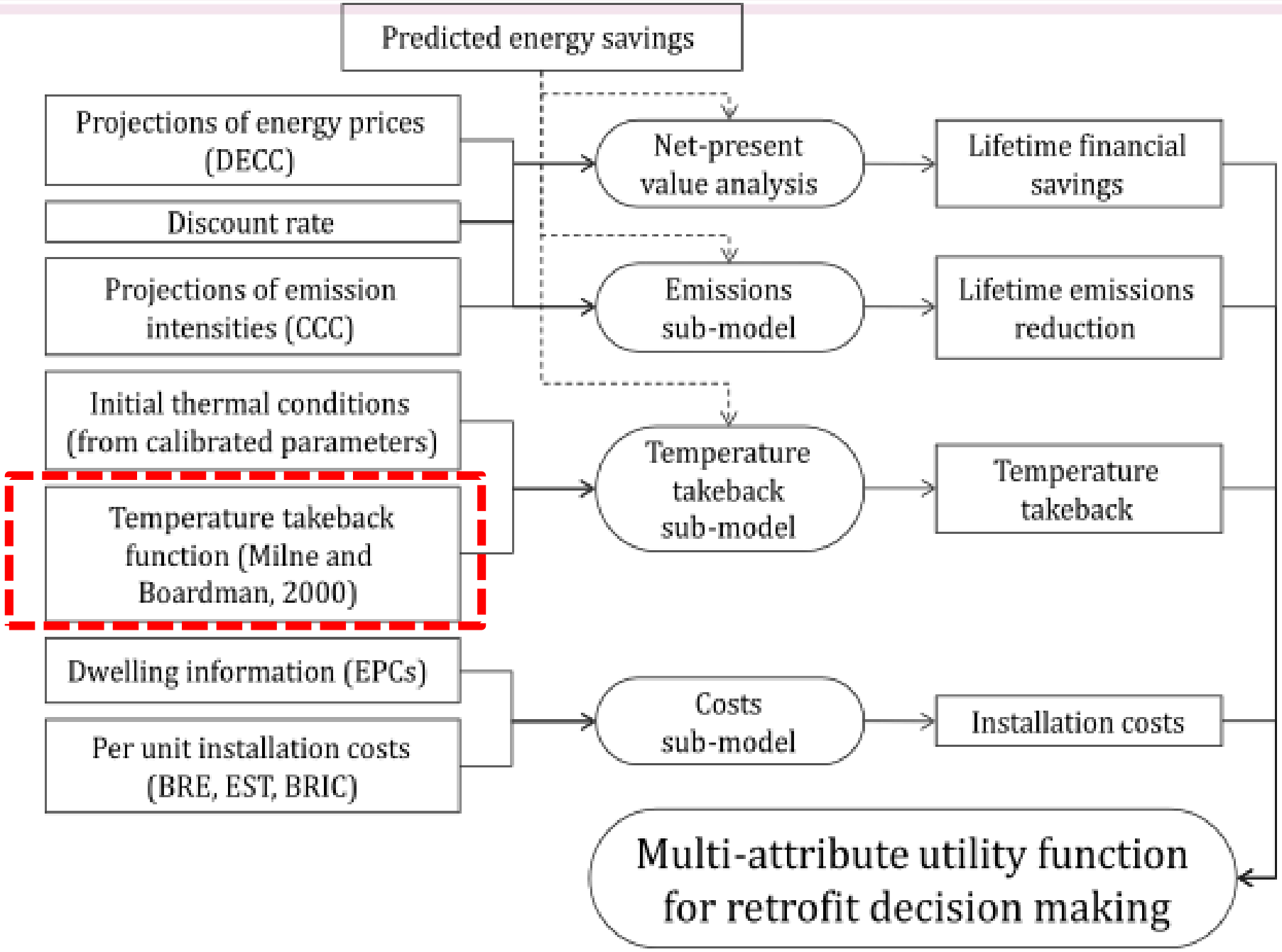
Priors from recent studies



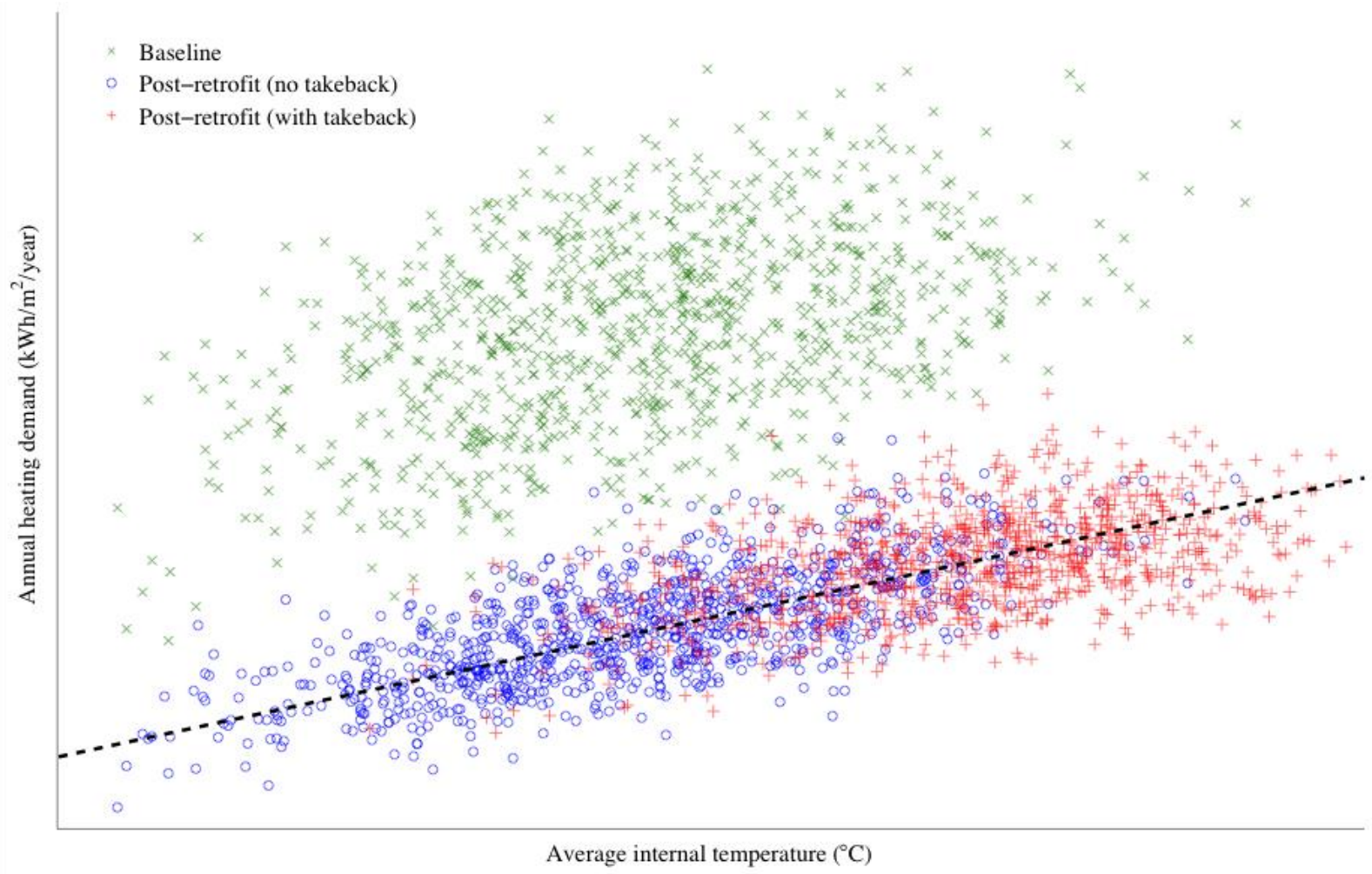
with two separate sets of priors

EUI of 1914–1964 semi-detached houses

Two Conflicting Sets of Priors


Predicted energy savings
Projections of energy prices (DECC)
Discount rate
Projections of emission intensities (CCC)
Initial thermal conditions (from calibrated parameters)
Temperature takeback function (Milne and Boardman, 2000)
Dwelling information (EPCs)
Per unit installation costs (BRE, EST, BRIC)
Net-present value analysis
Emissions sub-model
Temperature takeback sub-model
Costs sub-model
Lifetime financial savings
Lifetime emissions reduction
Temperature takeback
Installation costs
Multi-attribute utility function for retrofit decision making

Incorporating rebound effect



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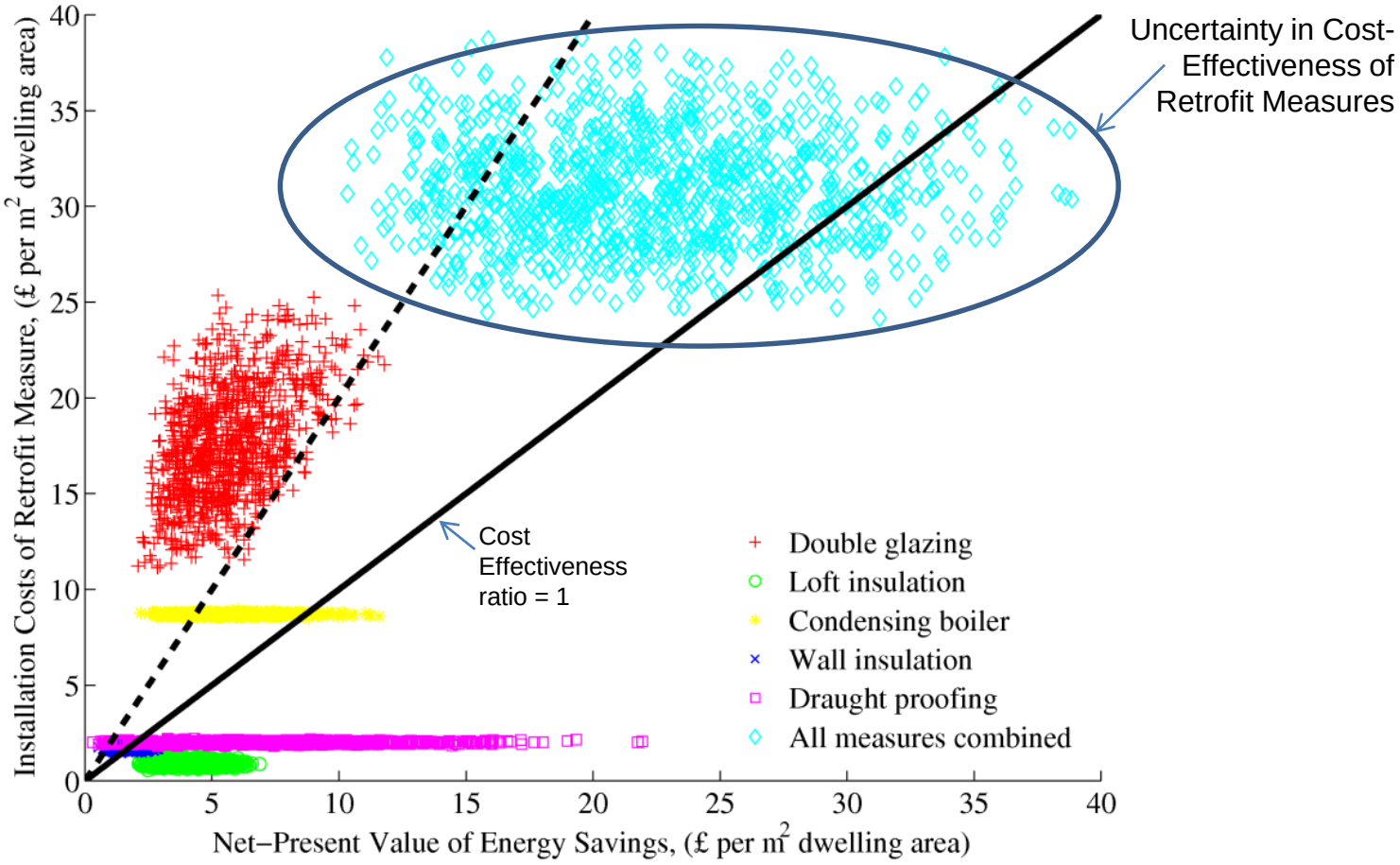
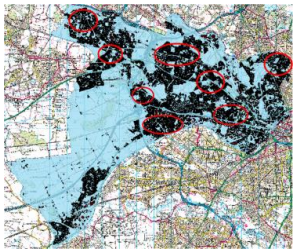
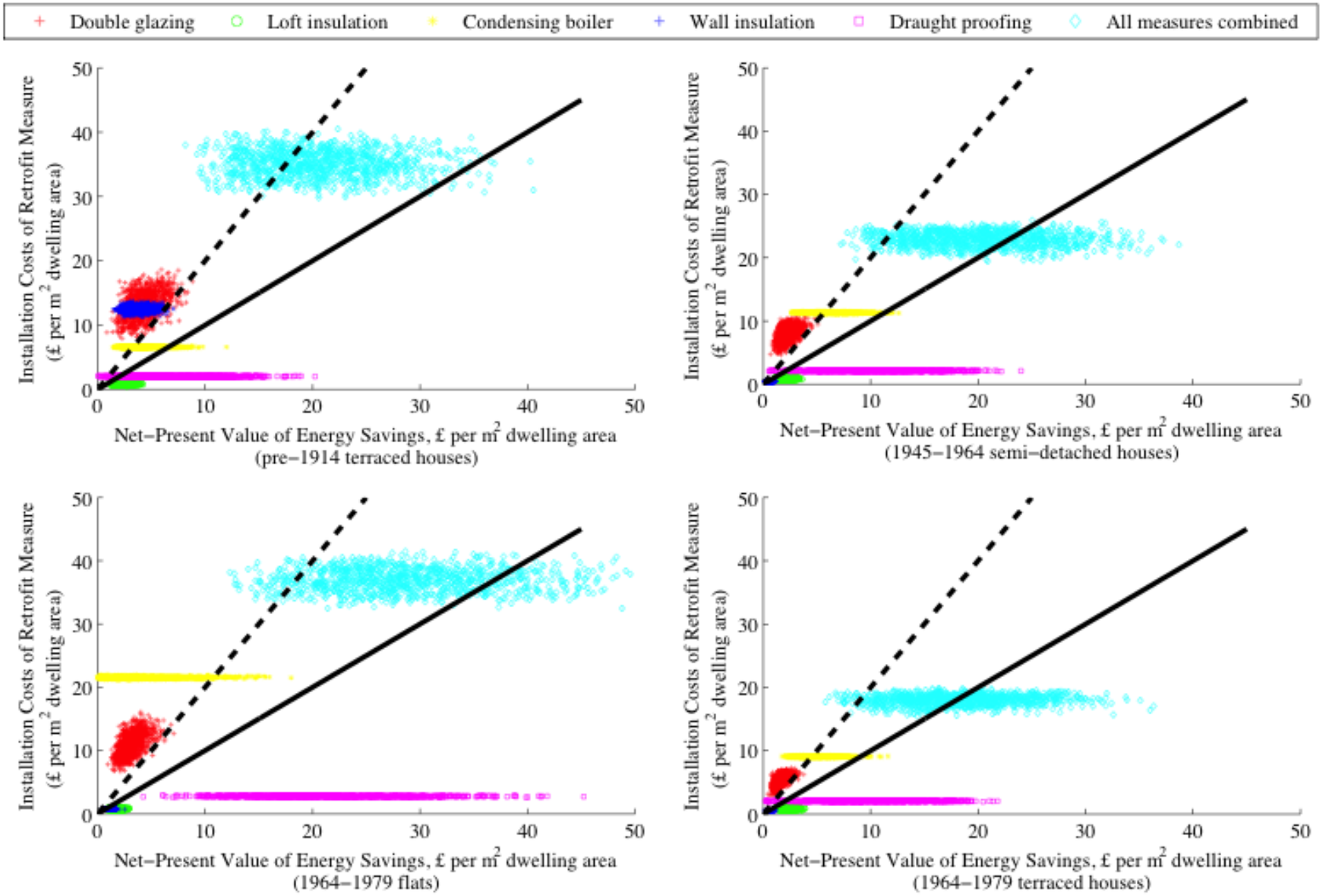
Implications for the Green Deal

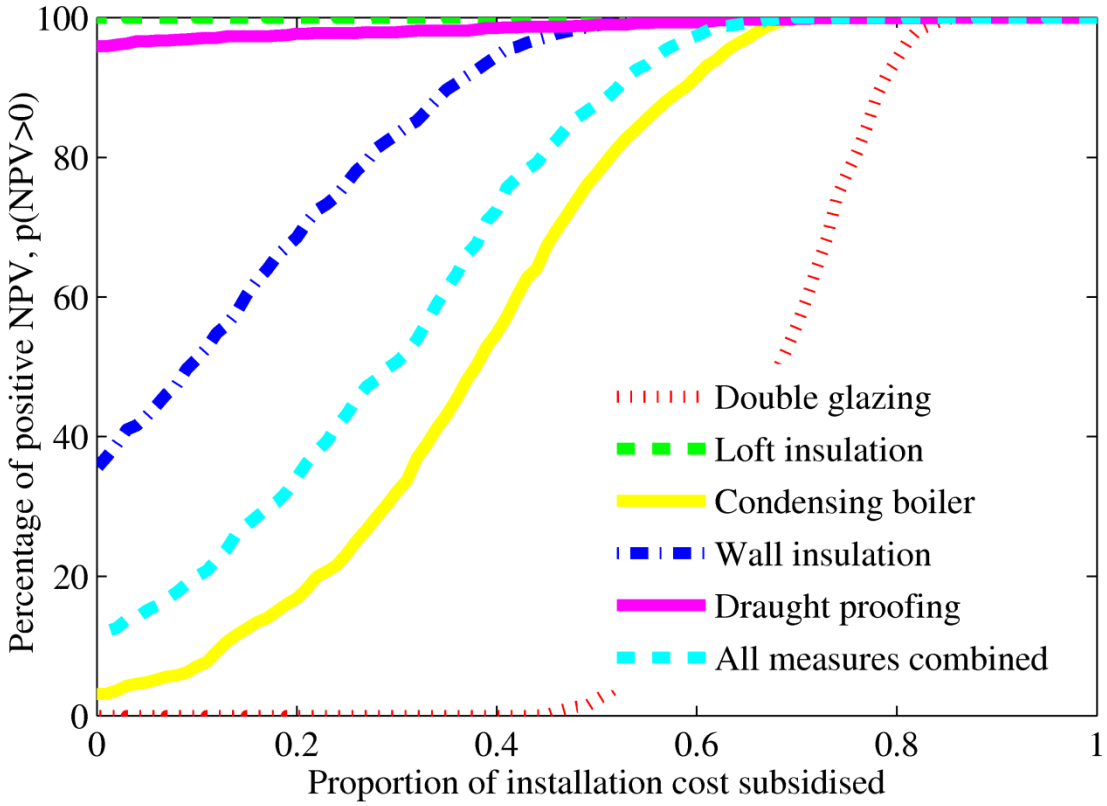




Cost-effectiveness plane of 5 retrofit measures
for 2,300 semi-detached houses built in 1914-45


Double glazing
Loft insulation
Condensing boiler
Wall insulation
Draught proofing
All measures combined
Installation Costs of Retrofit Measure (£ per m2 dwelling area)
Net−Present Value of Energy Savings, £ per m2 dwelling area (pre−1914 terraced houses)
Net−Present Value of Energy Savings, £ per m2 dwelling area (1945−1964 semi−detached houses)
Net−Present Value of Energy Savings, £ per m2 dwelling area (1964−1979 flats)
Net−Present Value of Energy Savings, £ per m2 dwelling area (1964−1979 terraced houses)
0
10
20
30
40
50

Influence of subsidies on investments



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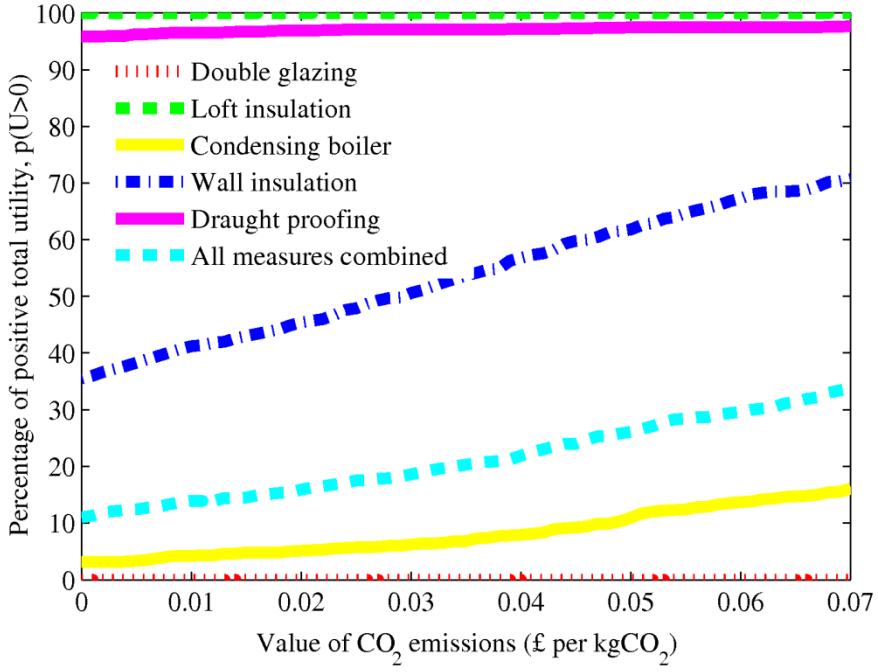
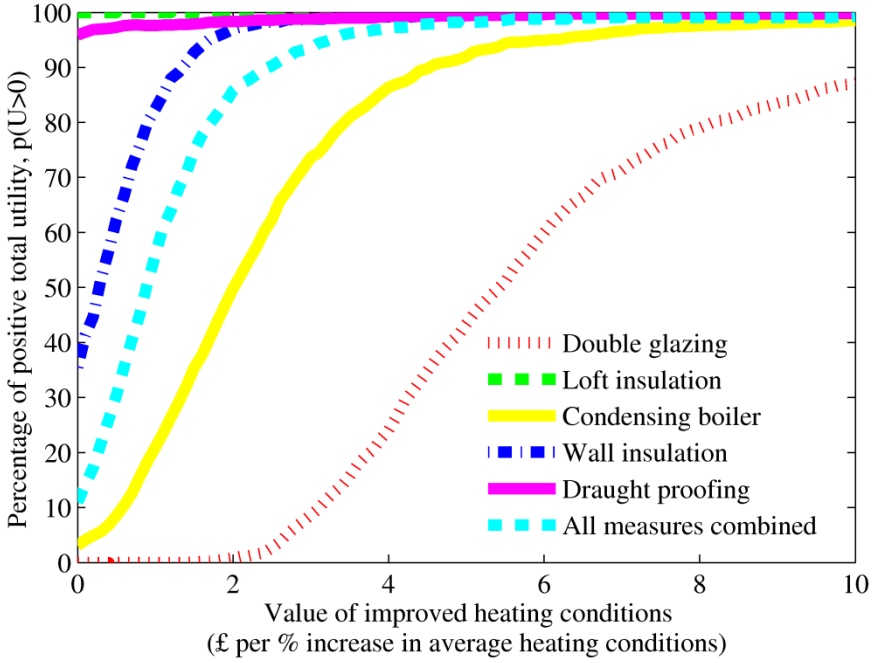
Valuation of improvements

$$U = NPV_{TOT} + \beta . CO_2 + \lambda . T$$





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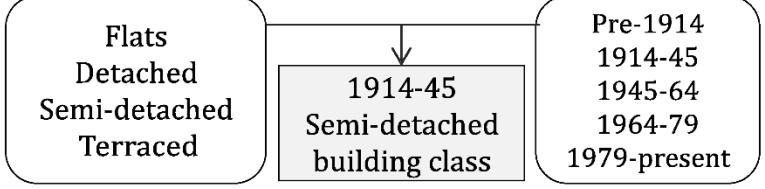
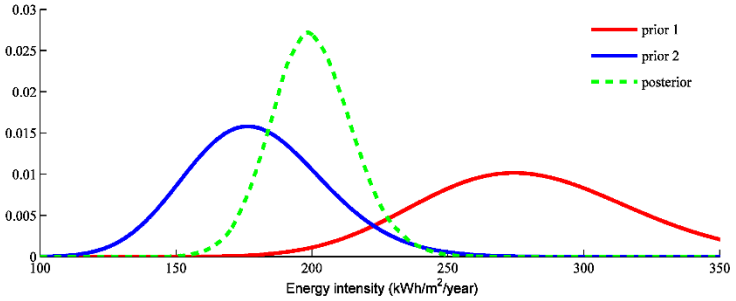
(1) Cluster housing stock into building classes by structural type and construction age

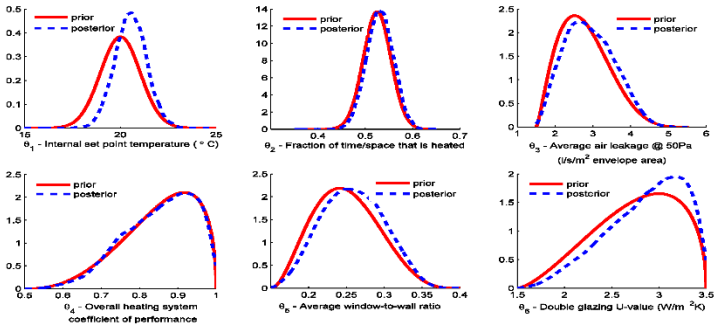


(2) Bayesian regression using district level data to synthesise building level "observations" for each building class



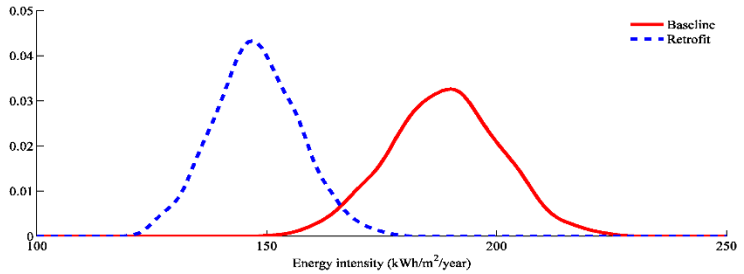
Booth, A. T., R. Choudhary, and D. J. Spiegelhalter. "A hierarchical Bayesian framework for calibrating micro-level models with macro-level data." *Journal of Building Performance Simulation* 6.4 (2013): 293-318.

(3) Bayesian calibration of uncertain parameters in engineering-based building level model using synthetic data



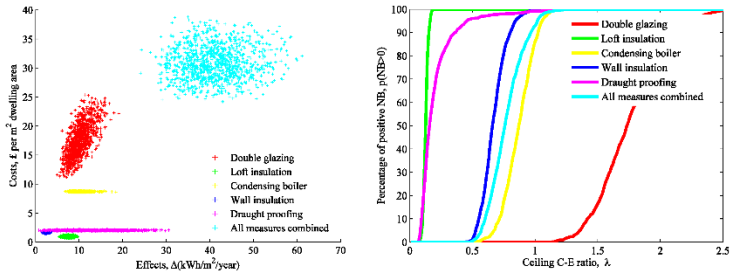
Booth, A. T., R. Choudhary, and D. J. Spiegelhalter. "Handling uncertainty in housing stock models." *Building and Environment* 48 (2012): 35-47.

(4) Probabilistic sensitivity analysis using Monte Carlo simulation to propagate uncertainty through the model and quantify uncertainty in the outputs



Booth, A. T., and R. Choudhary. "Decision making under uncertainty in the retrofit analysis of the UK housing stock: Implications for the Green Deal." *Energy and Buildings* 64 (2013): 292-308.

(5) Calculate energy savings by subtracting retrofit demands from baseline demand and compare retrofit measures using Bayesian multi-attribute utility theory



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