How can I make some money while lowering a building's GHG emissions?

Optimized marginal abatement cost curves of individual buildings

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University of Cambridge

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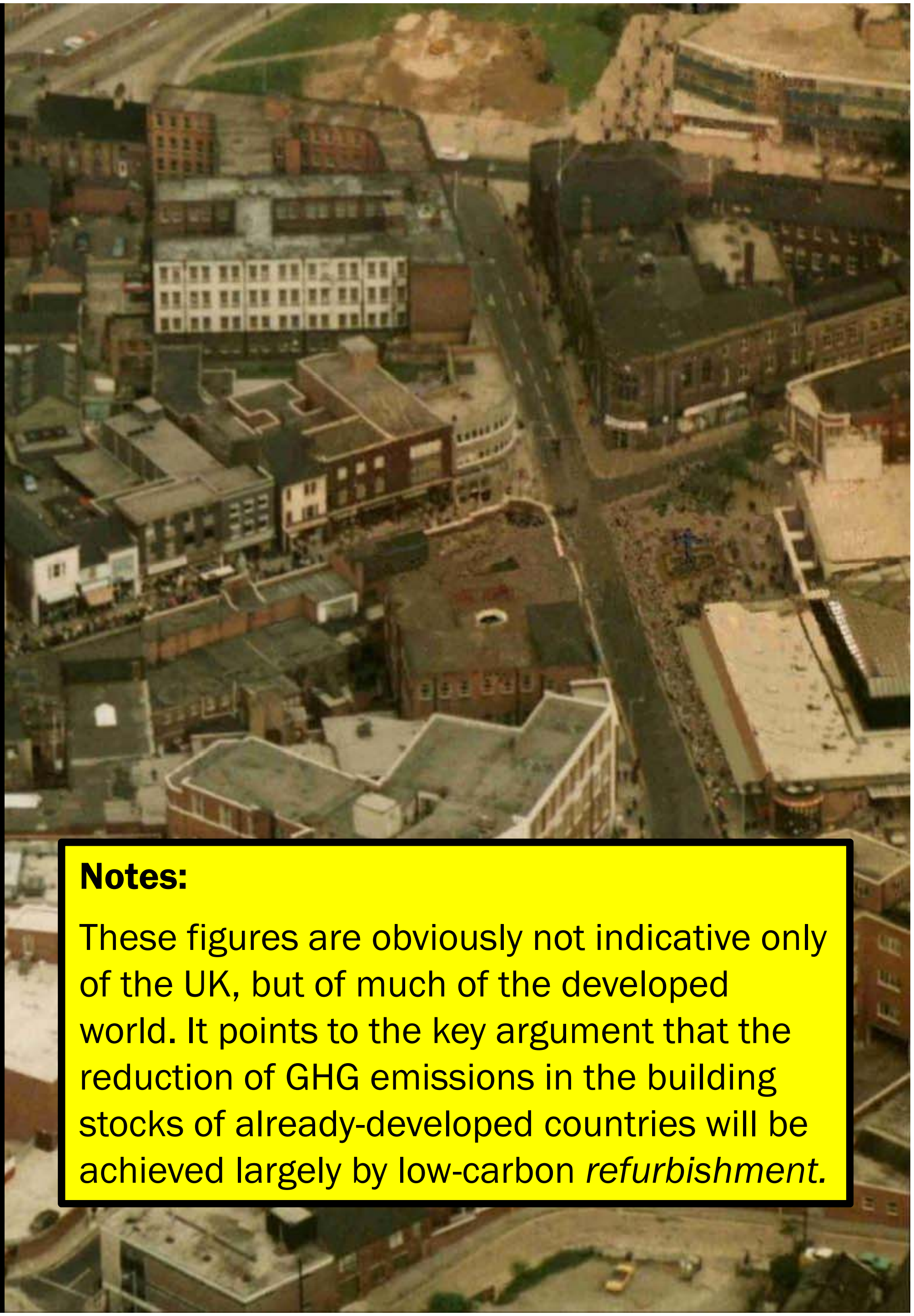
Electricity Policy Research Group

Facts about the energy consumption and GHG emissions from buildings, globally:

- China's building footprint is increasing annually by about 2 billion m^2, almost double England's entire non-domestic building stock. (Li and Yao 2009)
- Global GHG emissions from buildings continues to rise at an annual rate of 1.5% (2.5% in the BRICs) (Perez-Lombard et al. 2009)
- Targets, targets, targets......

Facts about the energy consumption and GHG emissions from buildings, in the UK:

- It's expected that over 90% of the UK's building stock beyond 2030 will consist of buildings already existing today. (Hinnells et al. 2008)
- Energy demand from commercial buildings in the UK accounts currently for roughly 14% of total UK GHG Emissions (CCC 2008)
- By 2030, the CCC predicts that 74% of building-related emissions in the UK could be saved at a cost of ~£1.4 billion (CCC 2010)

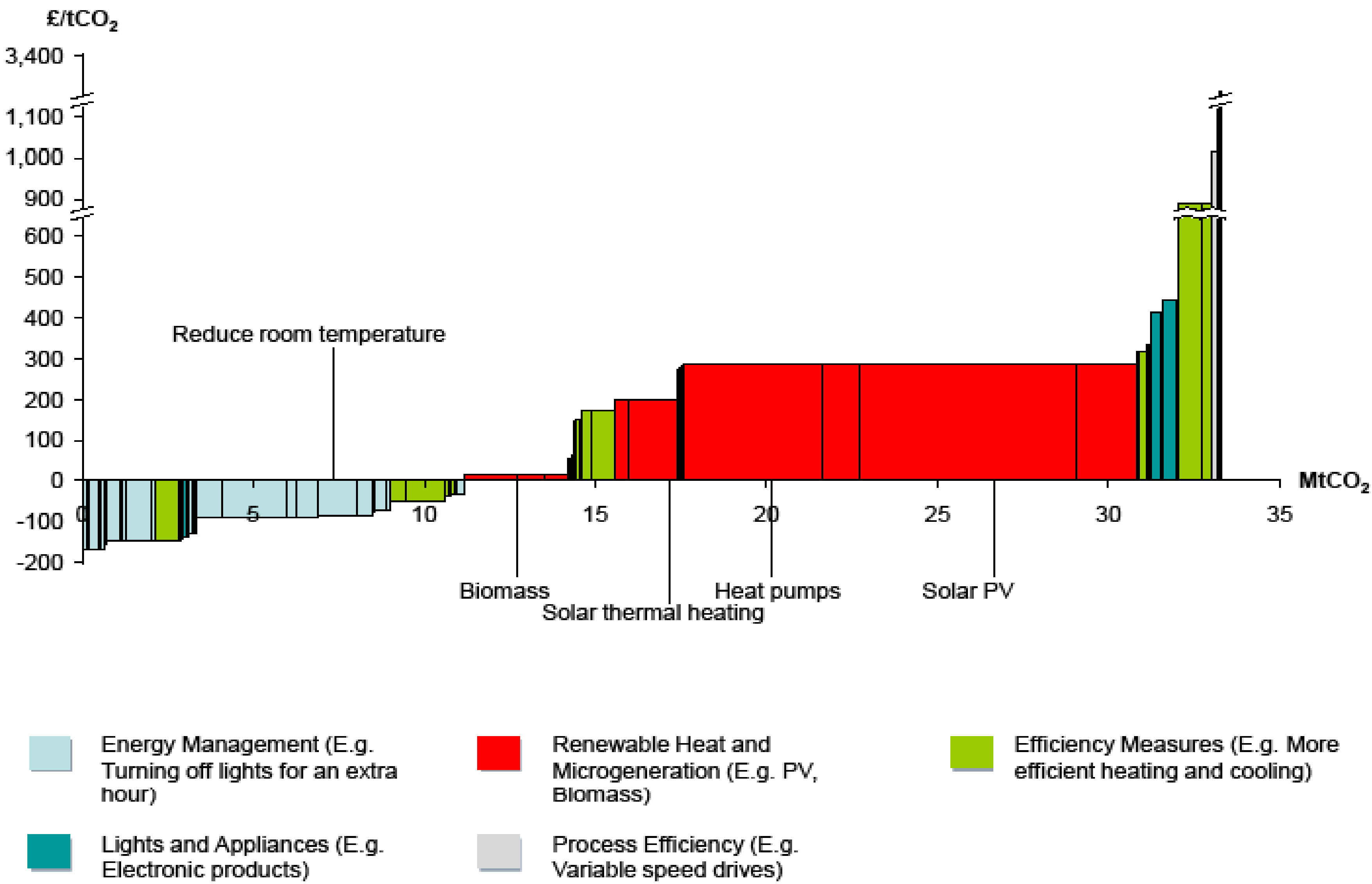


Notes:

These figures are obviously not indicative only of the UK, but of much of the developed world. It points to the key argument that the reduction of GHG emissions in the building stocks of already-developed countries will be achieved largely by low-carbon *refurbishment.*

The Marginal Abatement Cost Curve (MACC) of the UK Non-Domestic Buildings Sector

(Source: CCC/BRE/AEA 2008,2009)



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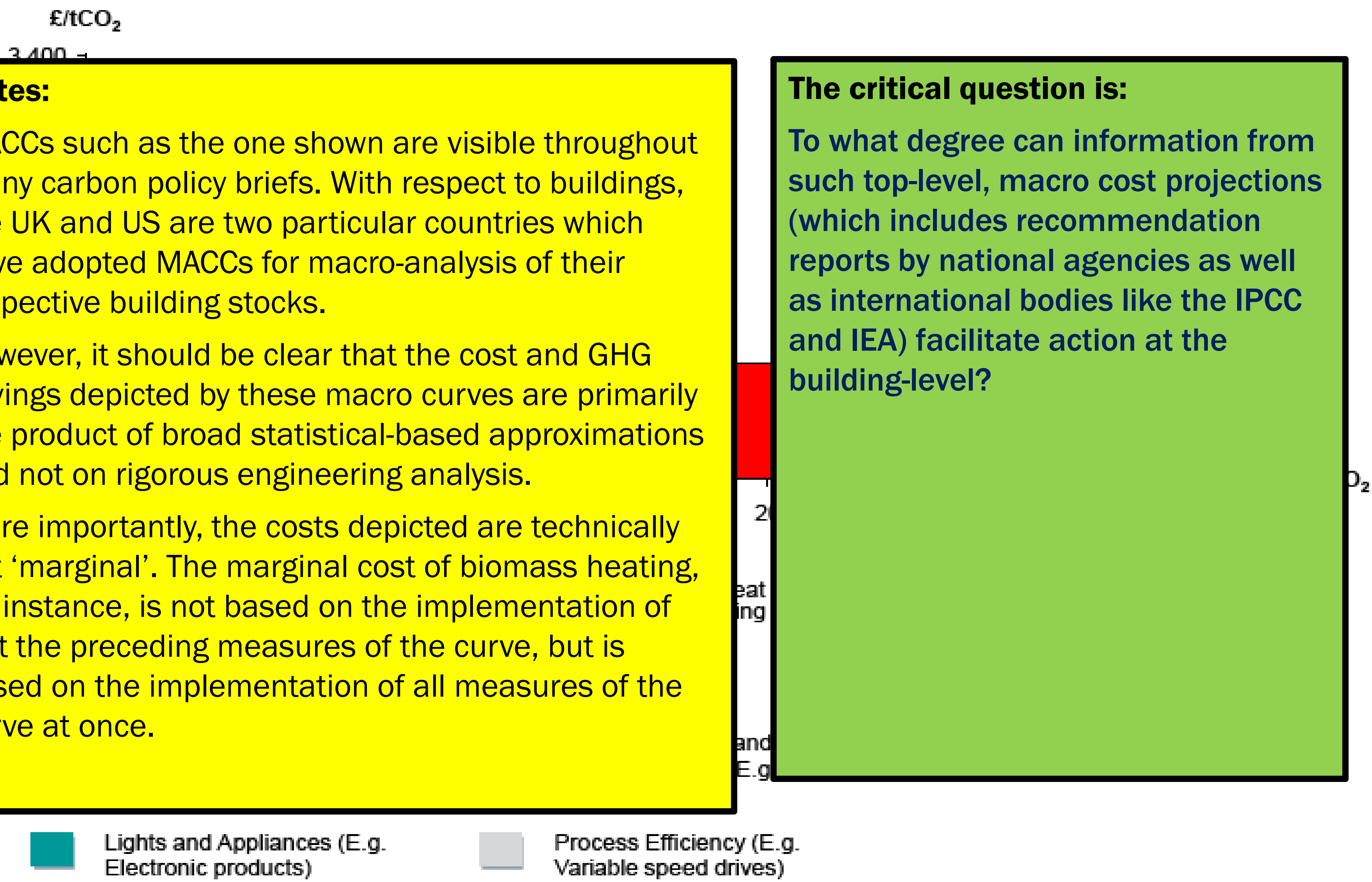


Notes:

MACCs such as the one shown are visible throughout many carbon policy briefs. With respect to buildings, the UK and US are two particular countries which have adopted MACCs for macro-analysis of their respective building stocks.

However, it should be clear that the cost and GHG savings depicted by these macro curves are primarily the product of broad statistical-based approximations and not on rigorous engineering analysis.

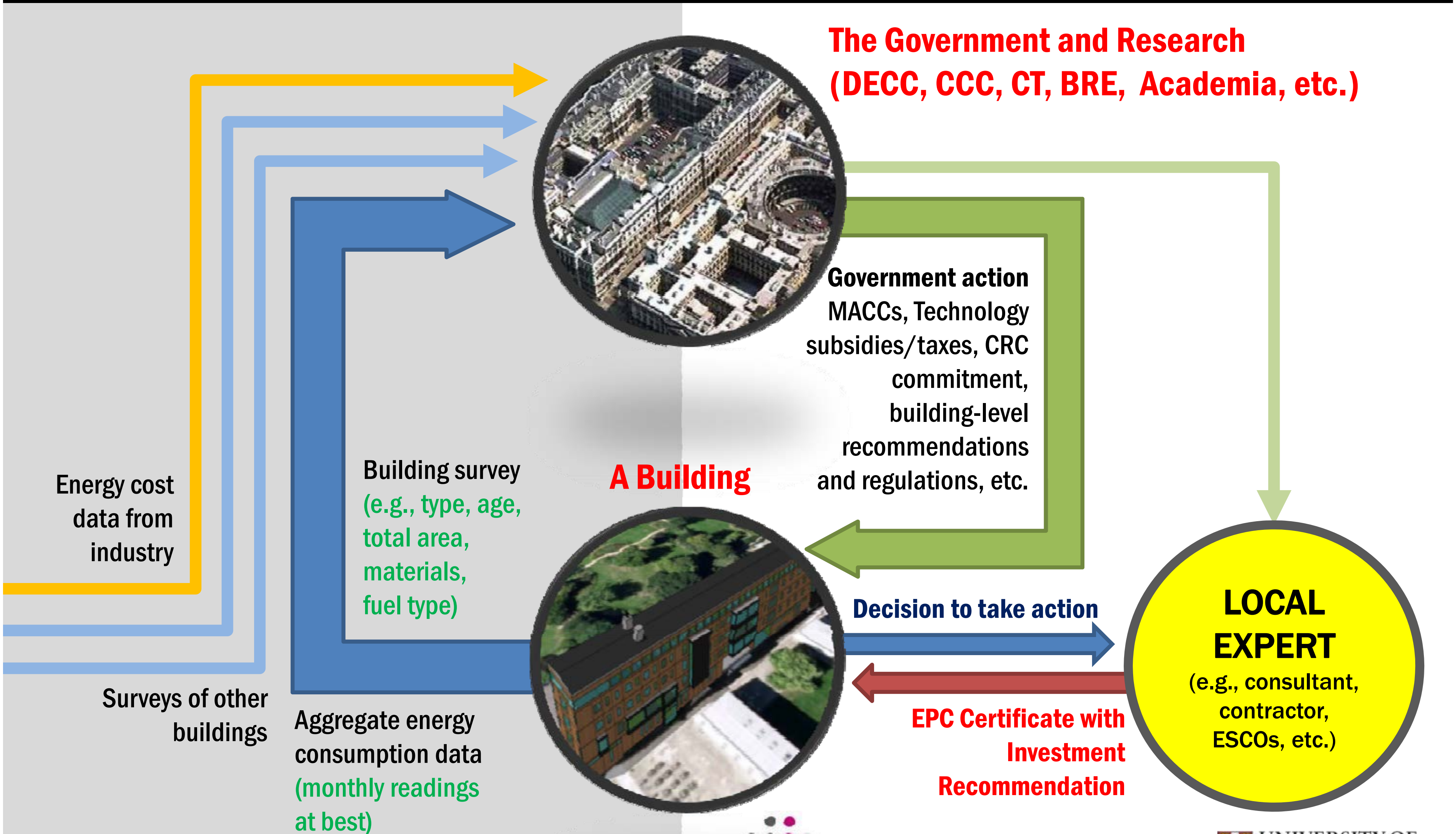
More importantly, the costs depicted are technically not 'marginal'. The marginal cost of biomass heating, for instance, is not based on the implementation of just the preceding measures of the curve, but is based on the implementation of all measures of the curve at once.

The critical question is:

To what degree can information from such top-level, macro cost projections (which includes recommendation reports by national agencies as well as international bodies like the IPCC and IEA) facilitate action at the building-level?

Information and Decision Pathways between Buildings and National Authorities

Government/Research vs. Industry



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Information and Decision Pathways between Buildings and National Authorities

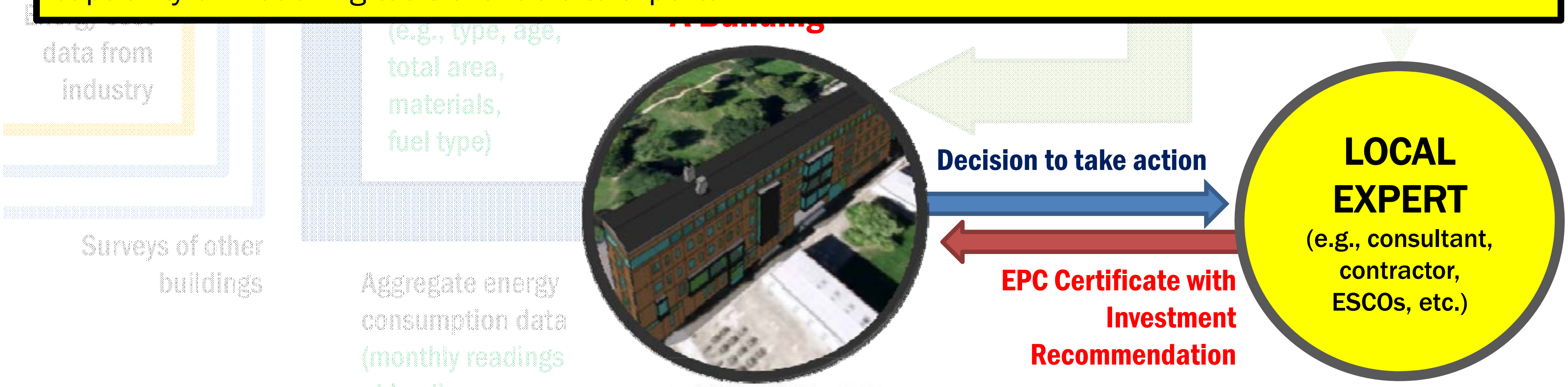
Government/Research vs. Industry

Notes:

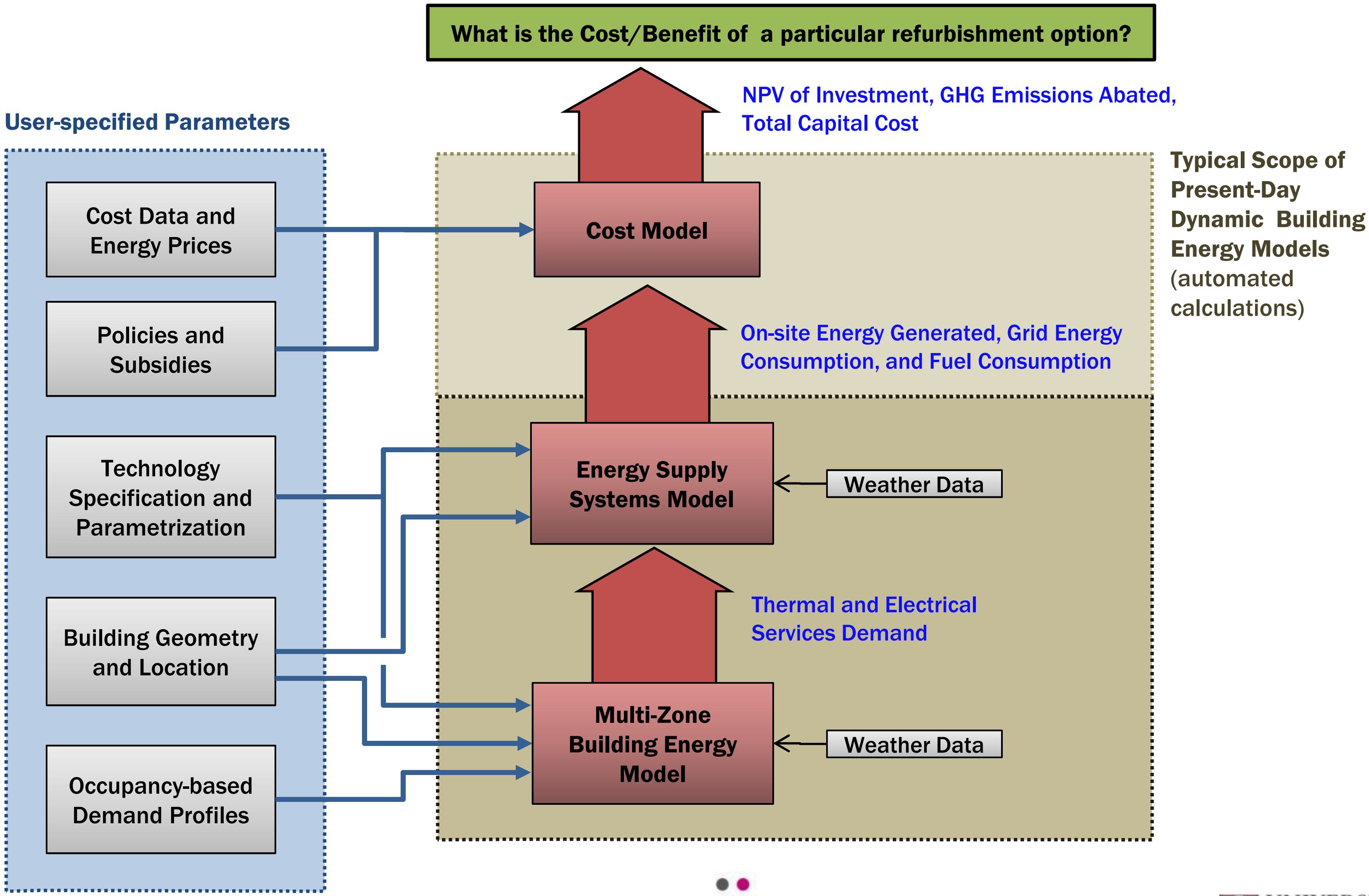
One reason for the lack of speedy uptake of cost-effective refurbishment investments at the building-level (such as distributed energy supply systems or 'smart' controls) is that, so- far, macro-level data cannot facilitate questions which remain building specific.

For every non-domestic building, we can envisage the following questions being asked by each client to a respective expert: "For my particular building, what measures are applicable to me to reduce emissions now and in the future? What are the cost of these measures? What is cheapest today, and what will be cheapest in the long-term, and what should my strategy be?"

This is an engineering question as much as it is an economic one. As such, answering it effectively depends not only on the level of expertise available in the buildings services sector, but also on the capability of modelling tools available to experts.



Computational Modelling of Building Technologies
Present-Day



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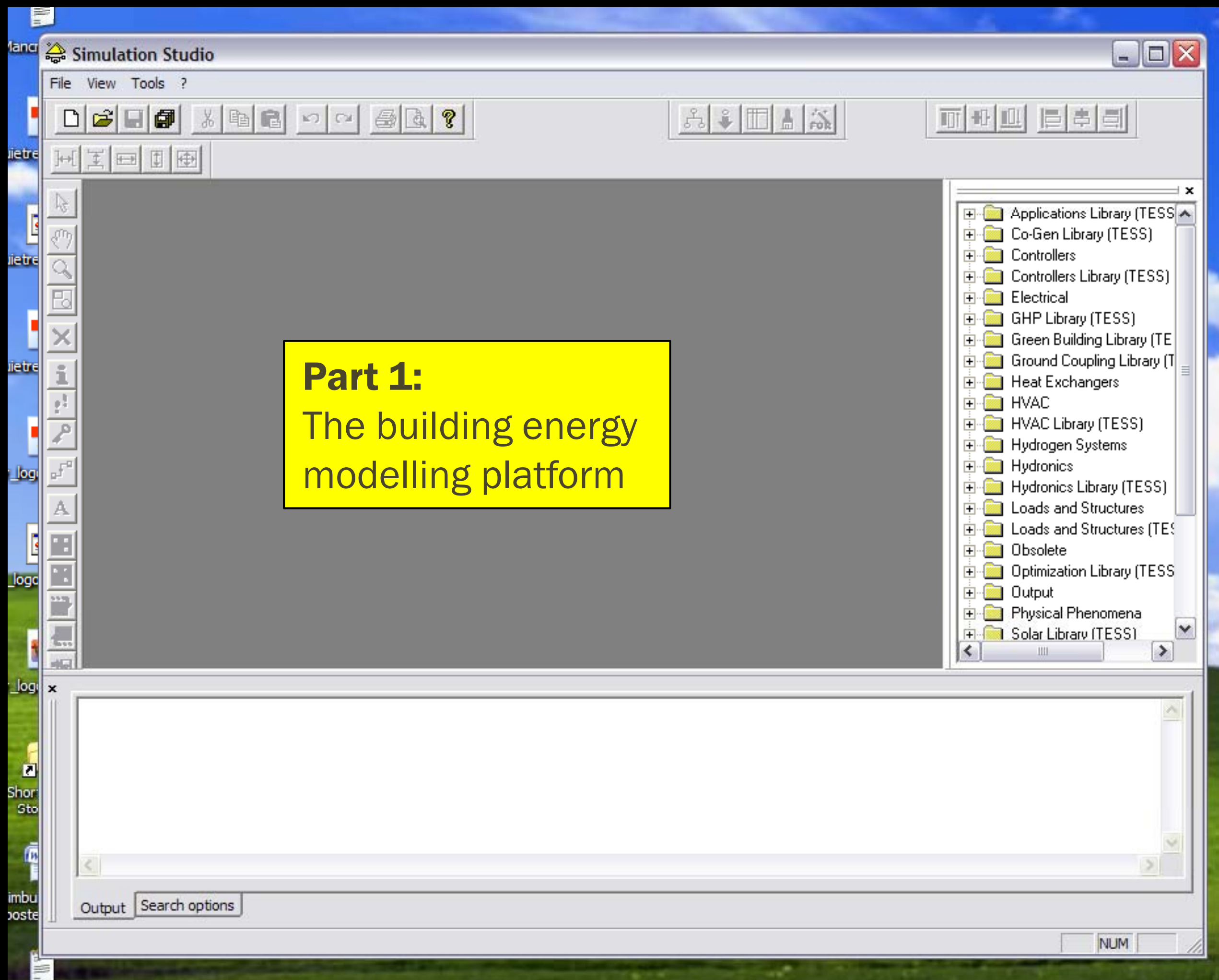
Analogy: An engineer's day in the buildings consultancy sector.....



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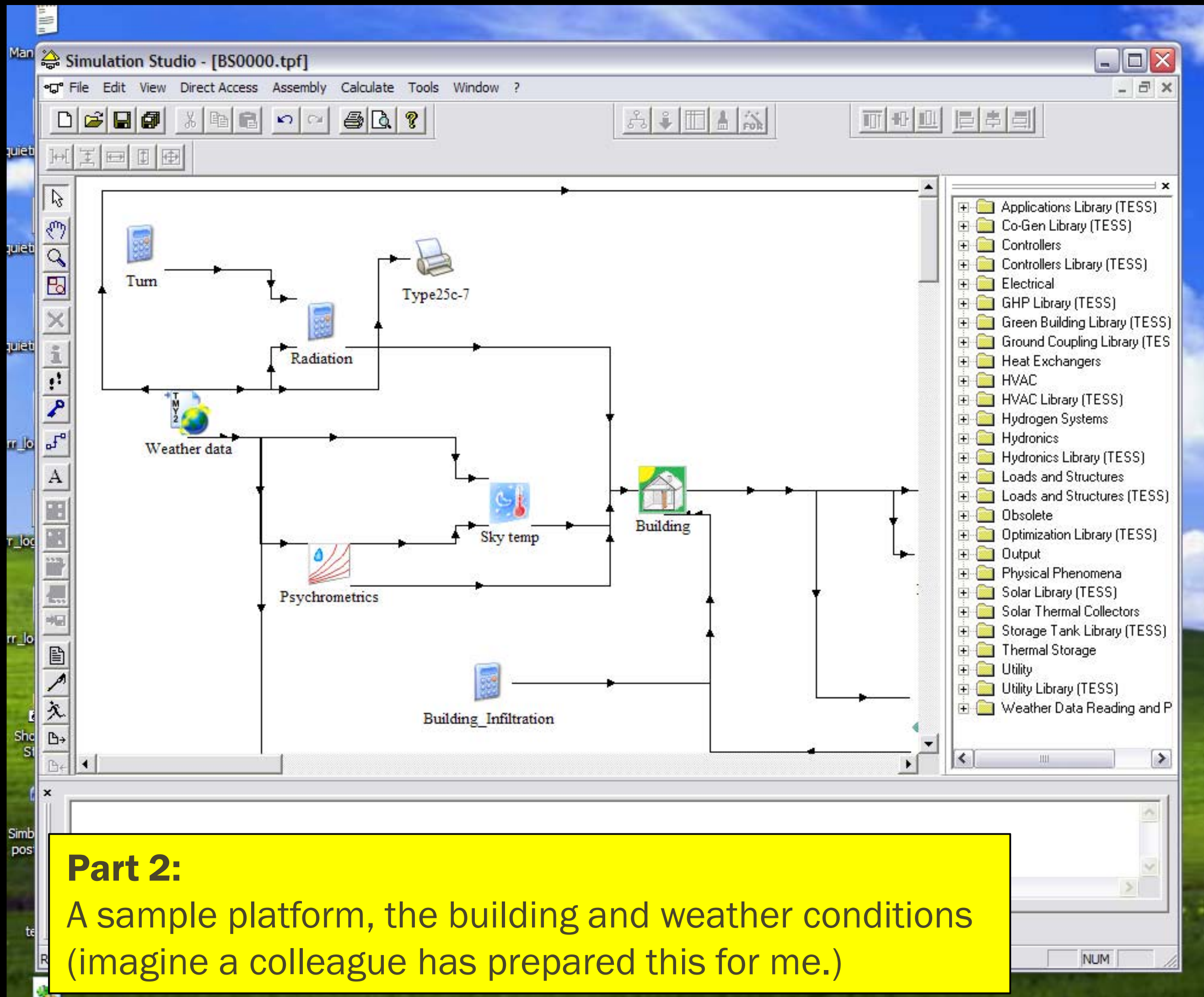
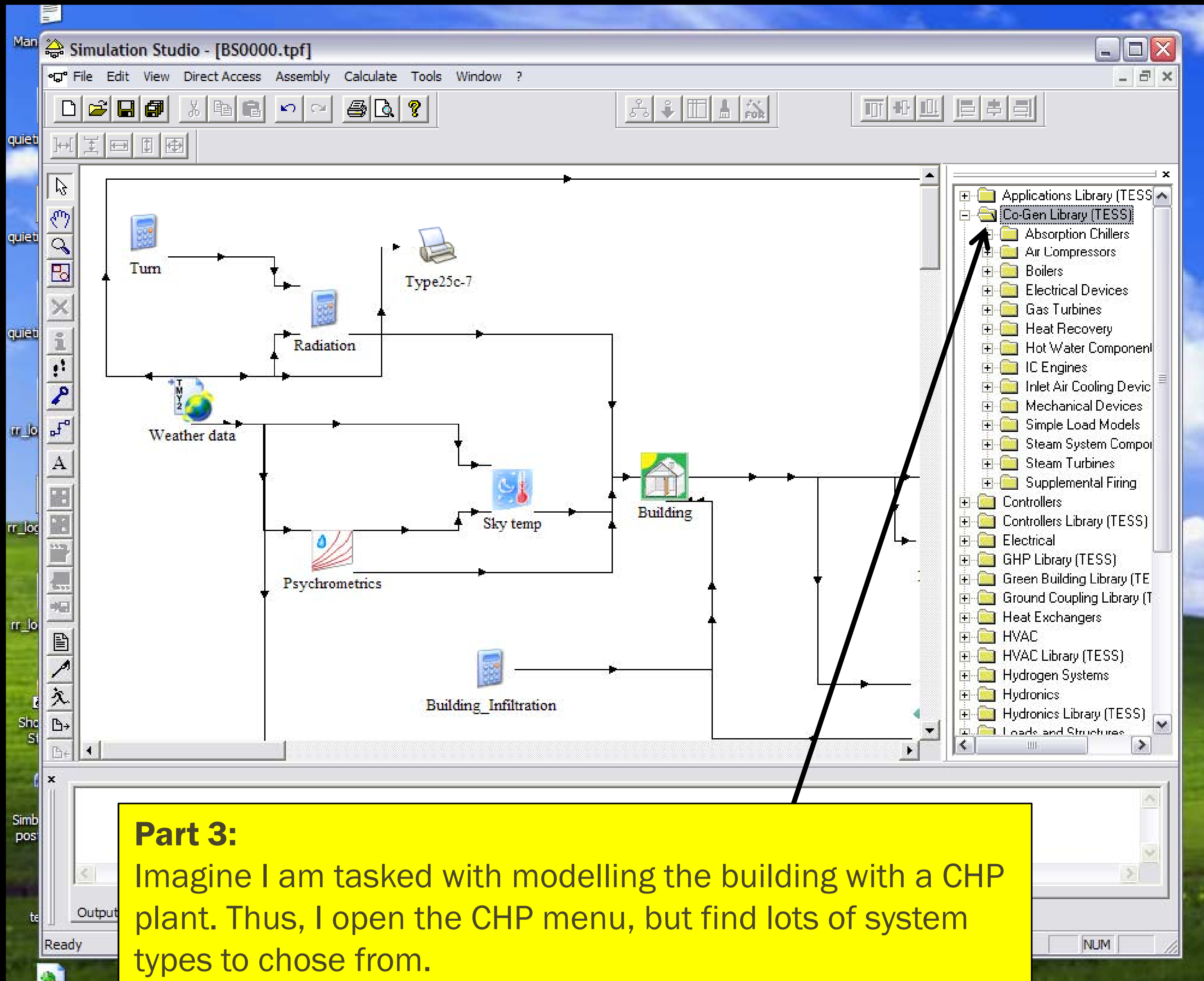


Part 2:
A sample platform, the building and weather conditions (imagine a colleague has prepared this for me.)

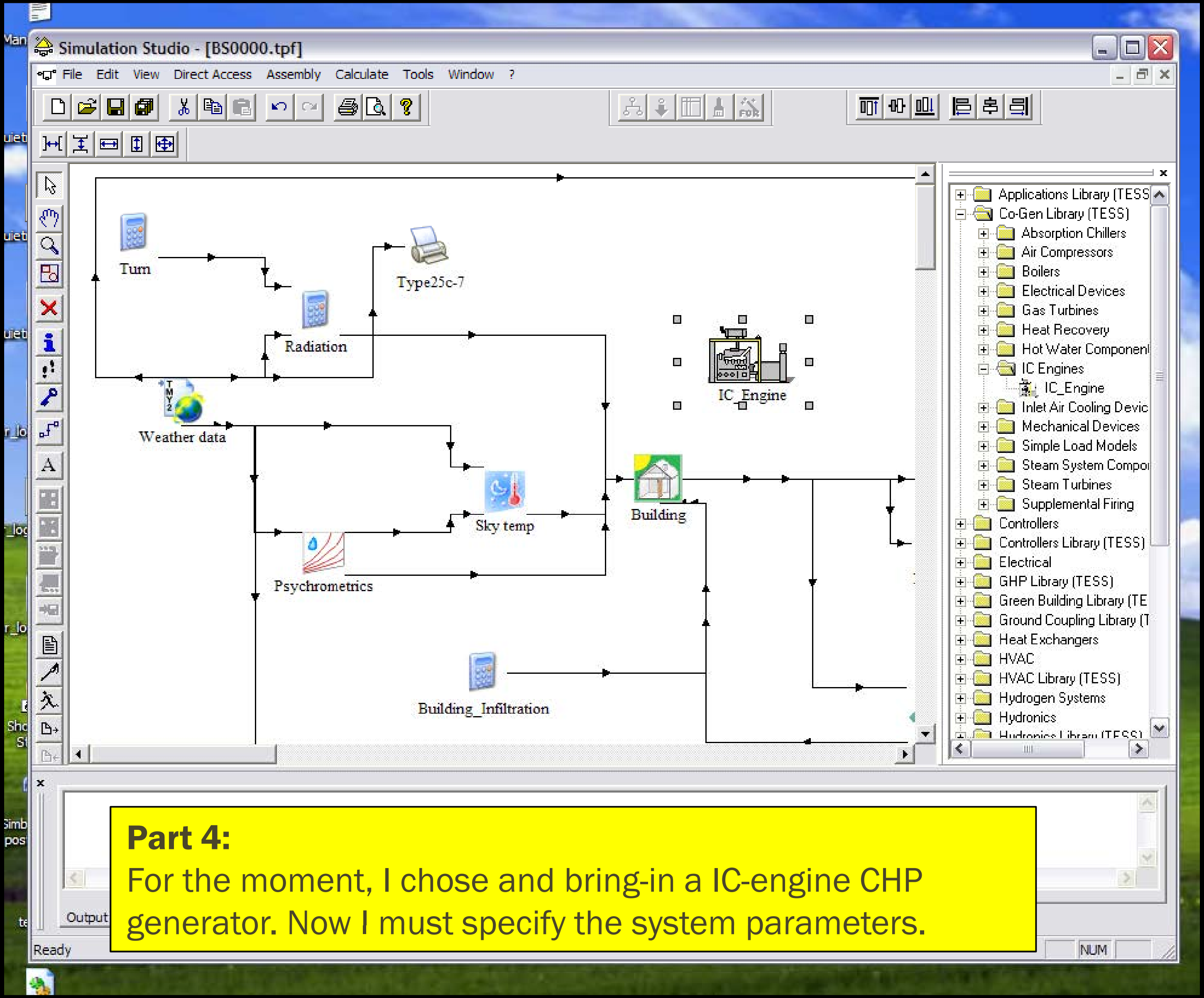
Analogy: An engineer's day in the buildings consultancy sector.....



Part 3:

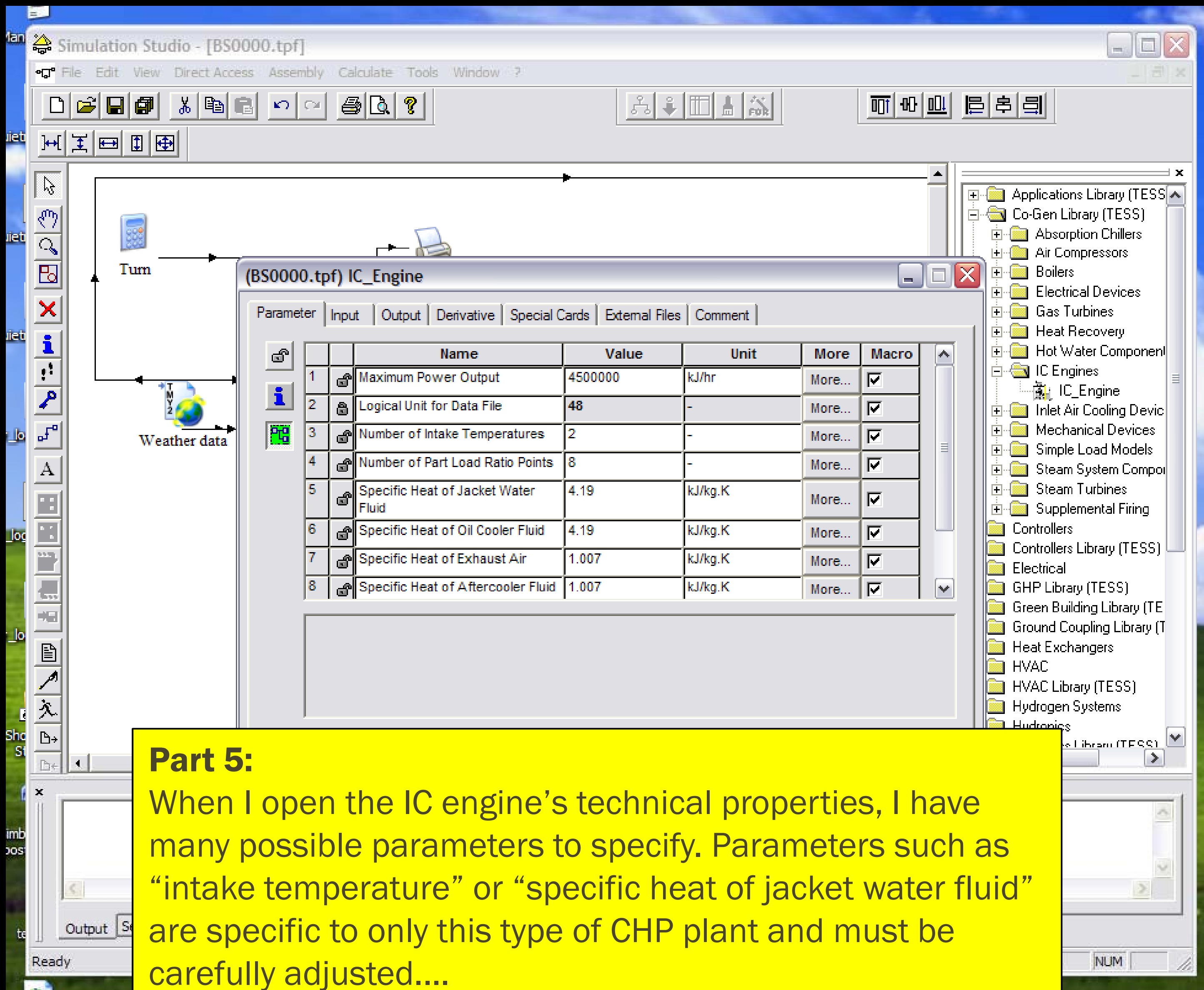
Imagine I am tasked with modelling the building with a CHP plant. Thus, I open the CHP menu, but find lots of system types to chose from.

Analogy: An engineer's day in the buildings consultancy sector…..



Part 4:
For the moment, I chose and bring-in a IC-engine CHP generator. Now I must specify the system parameters.

Analogy: An engineer's day in the buildings consultancy sector.....



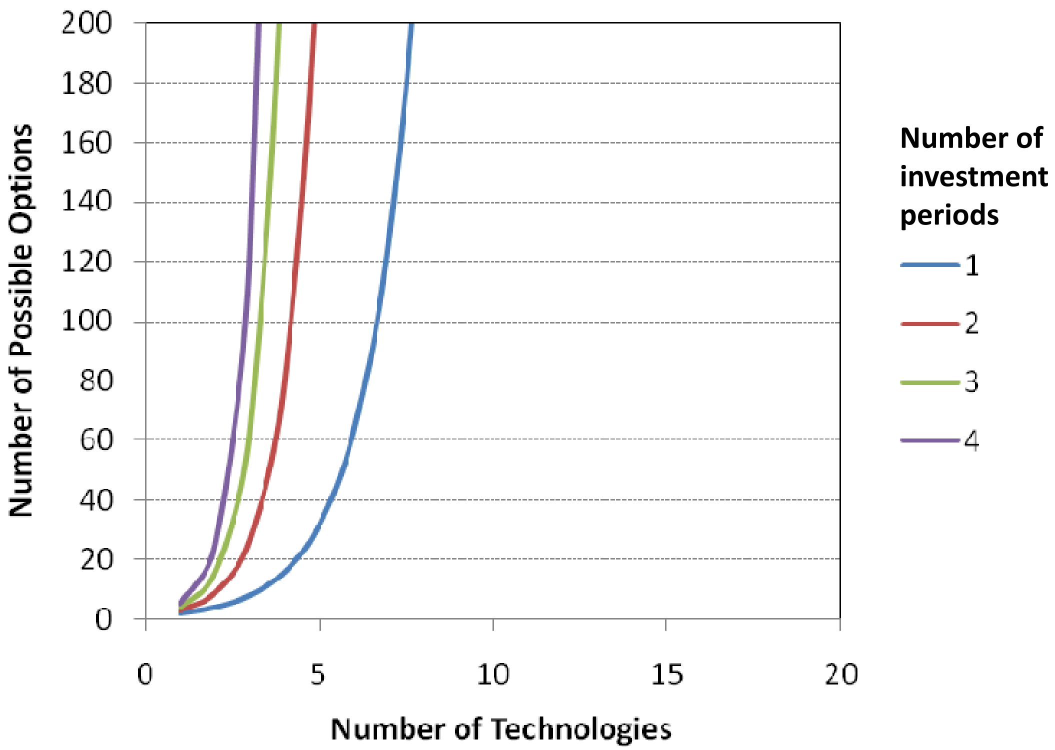
Part 5:

When I open the IC engine's technical properties, I have many possible parameters to specify. Parameters such as "intake temperature" or "specific heat of jacket water fluid" are specific to only this type of CHP plant and must be carefully adjusted....

Analogy: An engineer's day in the buildings consultancy sector.....

Part 6:
The entire process is arduous and is highly subject to computational error as the engineering system becomes more complex. The outcome may be a frustrated engineer who has spent an entire day to parameterize the thermodynamic model of only one type of technology option.

The Scale of the Problem:
Evaluating individual GHG reduction measures using present-day engineering models.



The number of possible investment options, *N*, over a certain number of investment periods, ***i***, is:

$$N = (1 + i)^n$$

Where ***n*** is the number of individual measures

Examples:

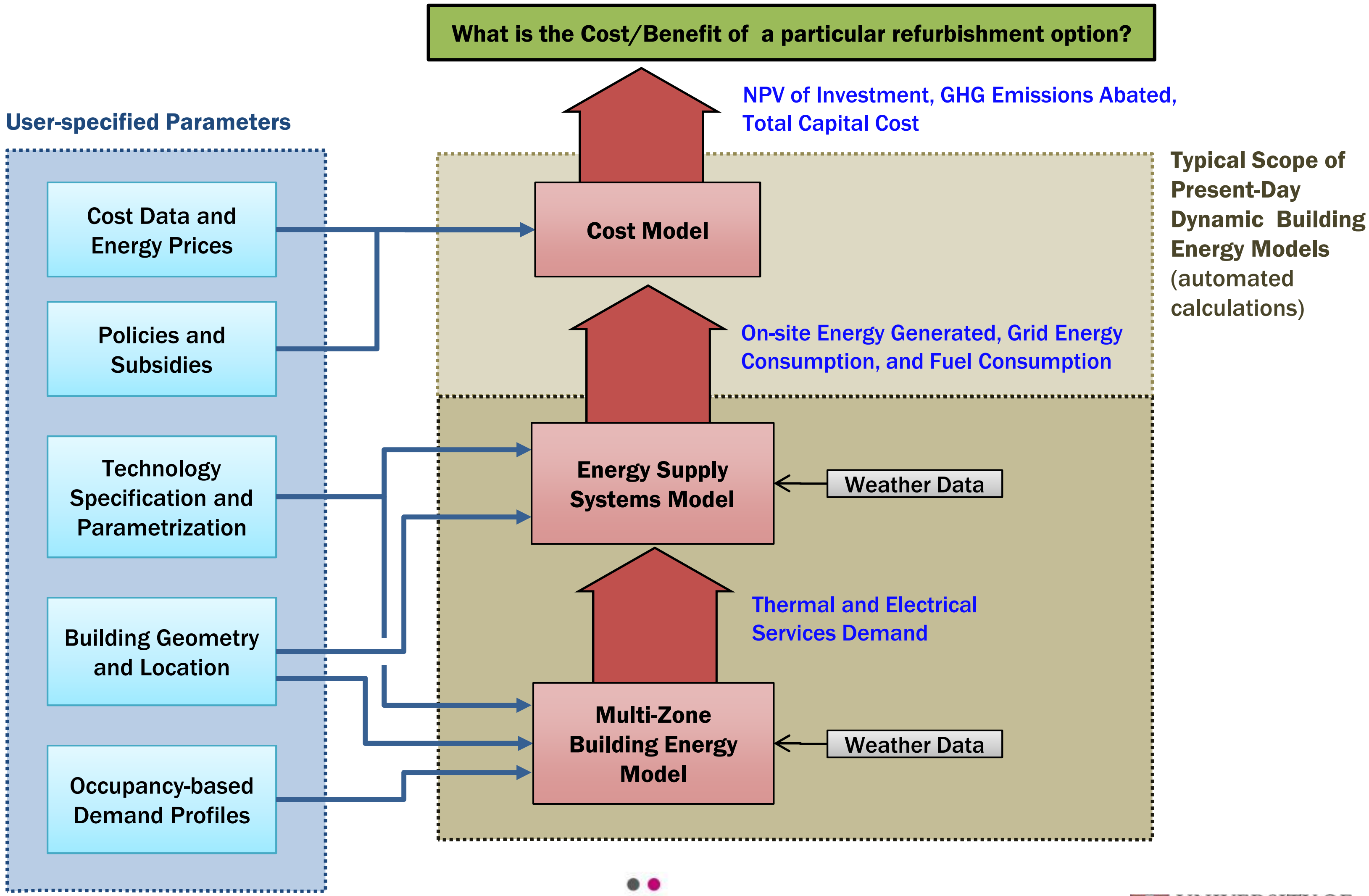
For 2 periods, and 10 measures:
N = 59,049

For 2 periods, and 20 measures:
N ≈ 3.5 billion

Notes:

Evaluating such a large number of investment options exhaustively is not feasible using present-day, state-of-the-art building energy modelling software. As described, though, this is a software issue with respect to model set-up time, rather than a lack of engineering knowledge to facilitate faster simulation.

Computational Modelling of Building Technologies
Present-Day



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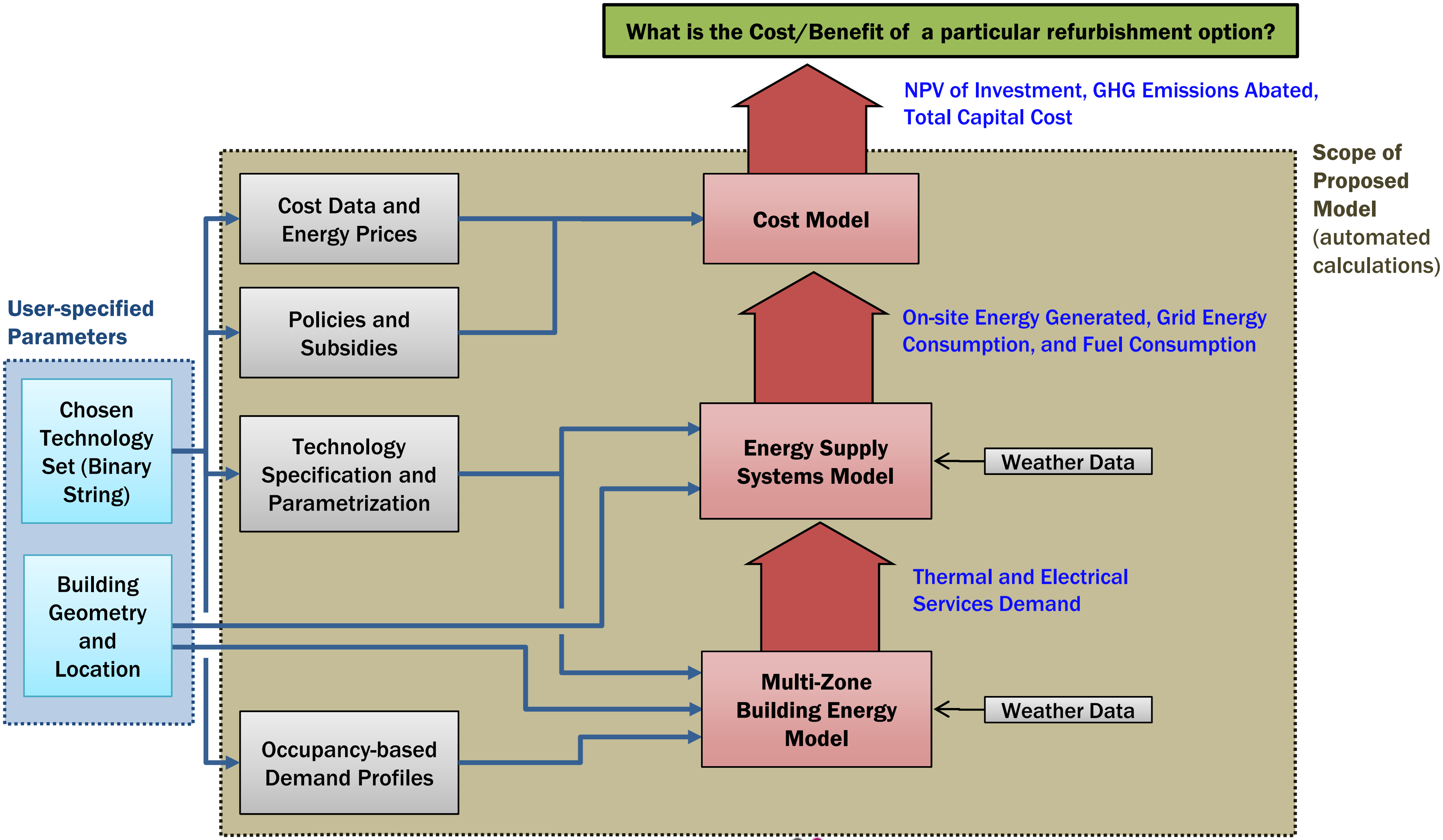
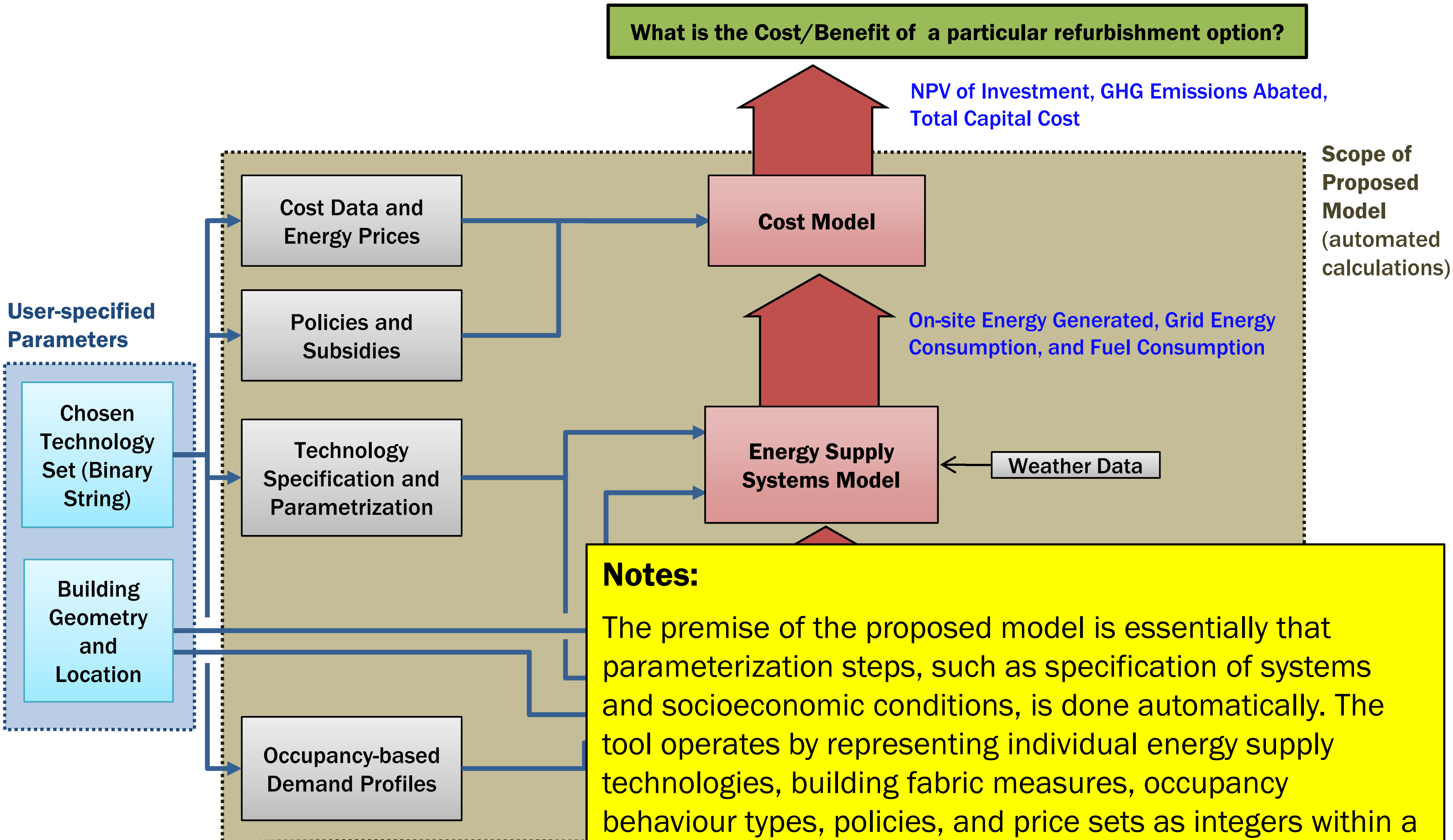
Computational Modelling of Building Technologies
Proposed



Computational Modelling of Building Technologies
Proposed

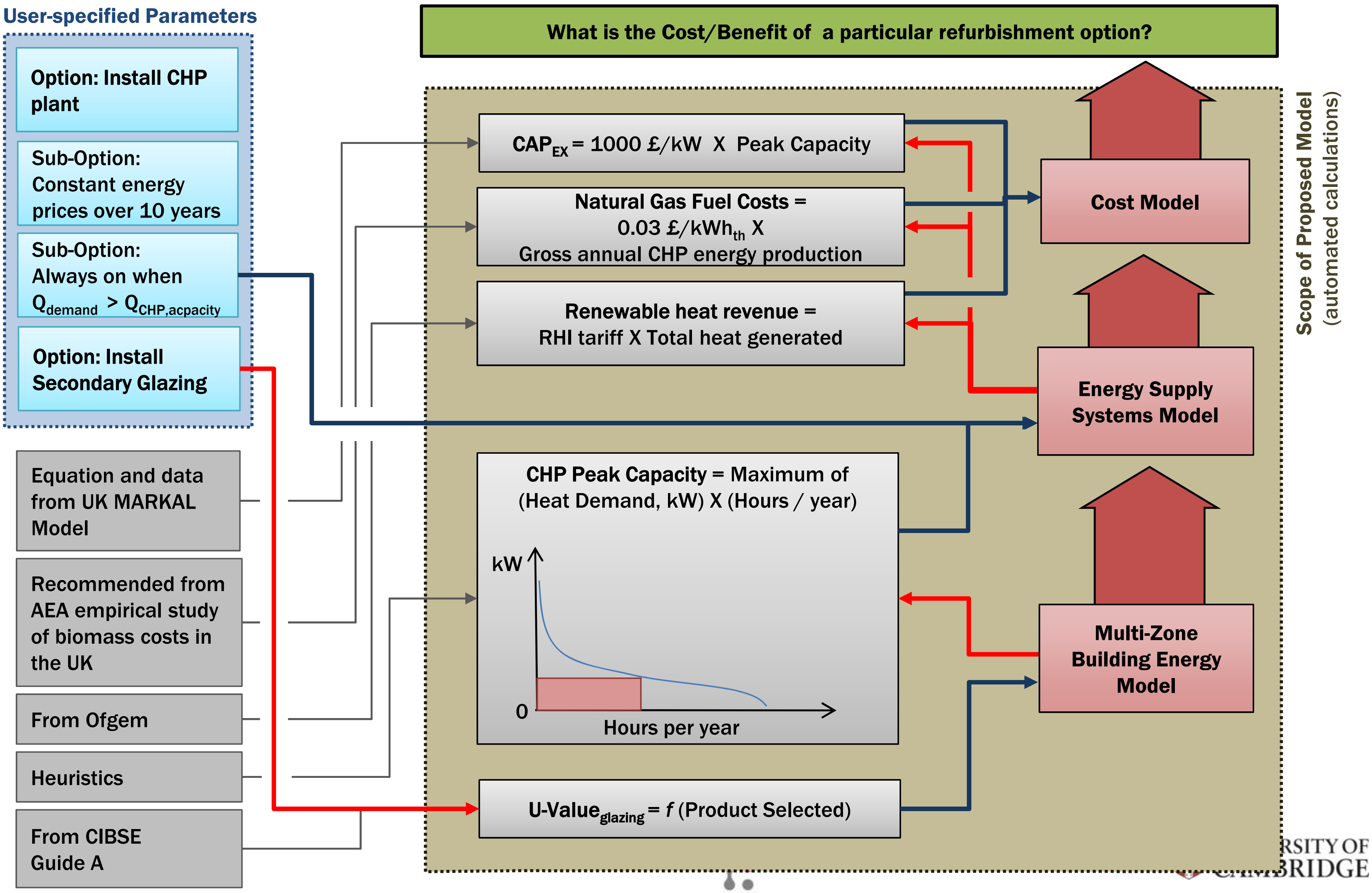


Notes:

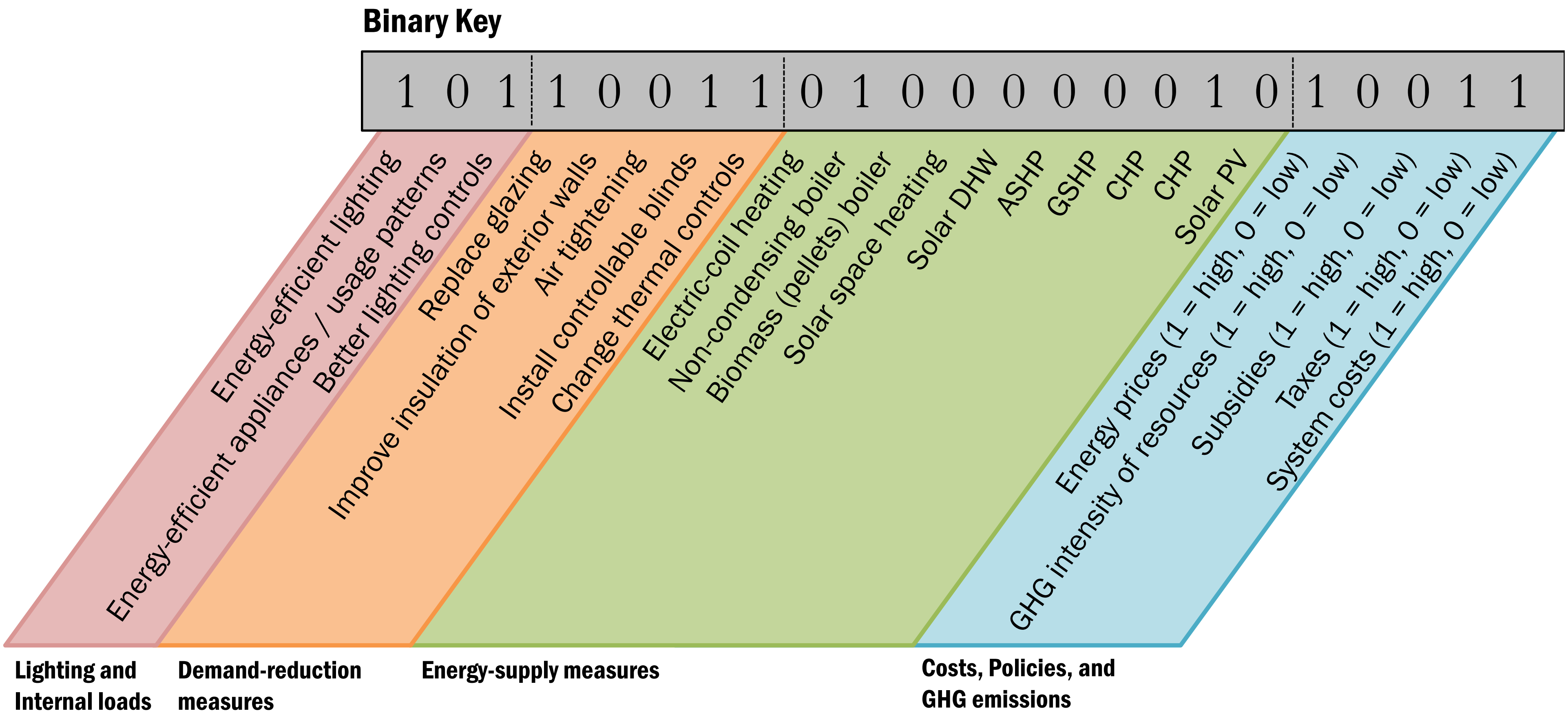
The premise of the proposed model is essentially that parameterization steps, such as specification of systems and socioeconomic conditions, is done automatically. The tool operates by representing individual energy supply technologies, building fabric measures, occupancy behaviour types, policies, and price sets as integers within a binary string.

Model Overview:

Example of data flows between sub-model outputs and system parameters



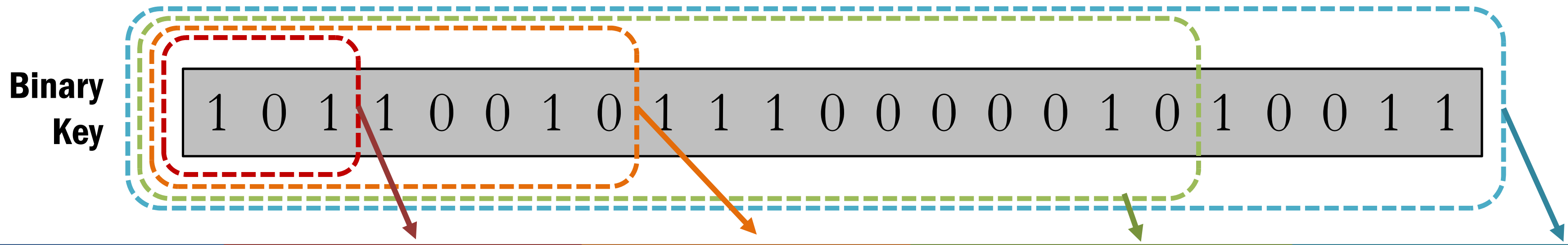
Model Overview:
Representation of technologies, measures, and policies as a binary string



Notes:

Individual measures, technologies, policies, and cost categories for a single investment scenario are organized into a single binary string. An example is shown above.

Model Overview:
Flow of simulation in actual model and purpose of individual submodels



3D Building Model

Purpose:

- Generate 3D layout of building

Outputs:

- TRNBUILD .B17 input file

Pre-processing and internal loads/demands

Purpose:

- Decompile .B17 file and assign HVAC systems to zones
- Assign demand objects to zones using DELOGE

Outputs:

- Non-HVAC transient electricity demand
- Transient internal heat gains
- Pre-processed TRNSYS . BUI file

Multi-zone building energy model

Purpose:

- Assess demand-side energy reduction measures
- Comprised of TRNSYS Types 56a and 155

Outputs:

- End-use heating, cooling, and electricity demand profiles

Energy supply systems model

Purpose:

- Assess energy supply systems and controls

Outputs:

- Primary energy consumption profiles per fuel type (gas, electricity, etc.)
- Renewable energy generation profiles, per type
- Energy supply system sizes (i.e., peak capacity)

Cost and GHG emissions model

Purpose:

- Assess costs based on reference data on energy prices, subsidies, and taxes
- Assess GHG emissions based on reference emissions intensity data

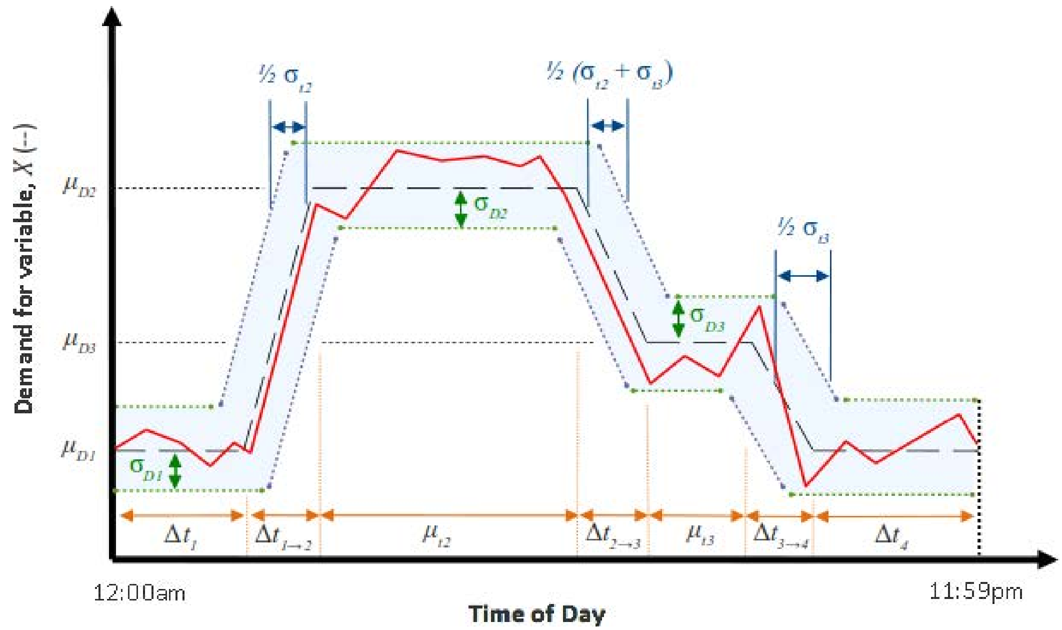
Outputs:

- Economic details (e.g., CAPex, O&M costs, etc.)
- NPV of tech. set and GHG emissions saved

Model Overview:
The Stochastic DEmand LOad GEnerator (DELOGE)

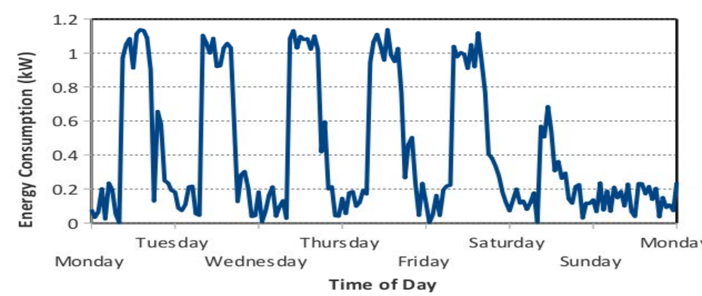
Daily probability of usage: Workday

Variable	Period		
	1	2	3
$t_{midpoint}$	11.5 h		
μ_{Di}	1	8.5	1.5
σ_{Di}	1	1	1.5
μ_{ti}	–	8.5 h	1.5 h
σ_{ti}	–	1 h	1.5 h
$\Delta t_{i \to i+1}$	1 h	2 h	2 h



Daily probability of usage: Workday, Saturday, Sunday

Variable	Weekday			Saturday			Sunday		
Period	1	2	3	1	2	3	1	2	3
$t_{midpoint}$	11.5 h			11.5 h			11.5 h		
μ_{Di}	1	8.5	3	1	4	1	1	1	1
σ_{Di}	1	1	2	1	2	0.5	1	1	1
μ_{ti}	–	8.5 h	1.5 h	–	8.5 h	1.5 h	–	4 h	2 h
σ_{ti}	–	1 h	1.5 h	–	4 h	1.5 h	–	4 h	2 h
$\Delta t_{i \to i+1}$	1 h	2 h	2 h	1 h	2 h	2 h	1 h	2 h	2 h



And so on....

Microsoft Visual Basic for Applications

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Model Overview:
The Stochastic DEmand LOad GEnerator (DELOGE)

Daily probability of usage: Workday

Variable	Period		
	1	2	3
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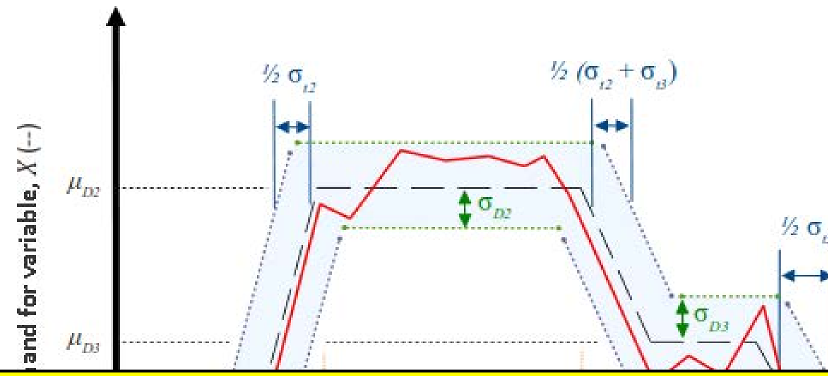
$\Delta t_{i\rightarrow i+1}$	1 h	2 h	2 h

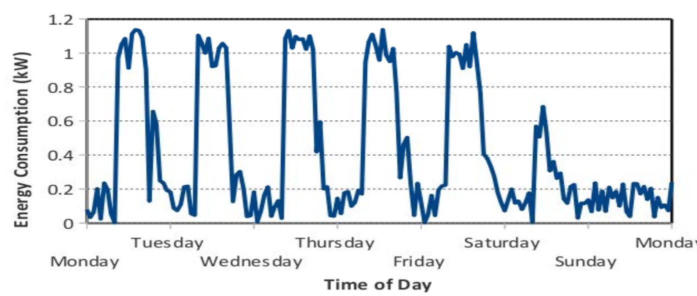


Notes:

Using DELOGE, heat-generating appliances and occupants, and their usage/behavioural patterns, are represented probabilistically. Each object is assigned a probability-of-usage at a certain period of day, week, month, and year. Doing so allows occupants and appliances to be specified as objects, whereby the generation of demand profiles is calculated algorithmically.

Daily probability of usage: Workday, Saturday, Sunday

Variable	Weekday			Saturday			Sunday		
Period	1	2	3	1	2	3	1	2	3
$t_{midpoint}$	11.5 h			11.5 h			11.5 h		
μ_{Di}	1	8.5	3	1	4	1	1	1	1
σ_{Di}	1	1	2	1	2	0.5	1	1	1
μ_{ti}	–	8.5 h	1.5 h	–	8.5 h	1.5 h	–	4 h	2 h
σ_{ti}	–	1 h	1.5 h	–	4 h	1.5 h	–	4 h	2 h
$\Delta t_{i\rightarrow i+1}$	1 h	2 h	2 h	1 h	2 h	2 h	1 h	2 h	2 h



And so on....

Microsoft Visual Basic for Applications

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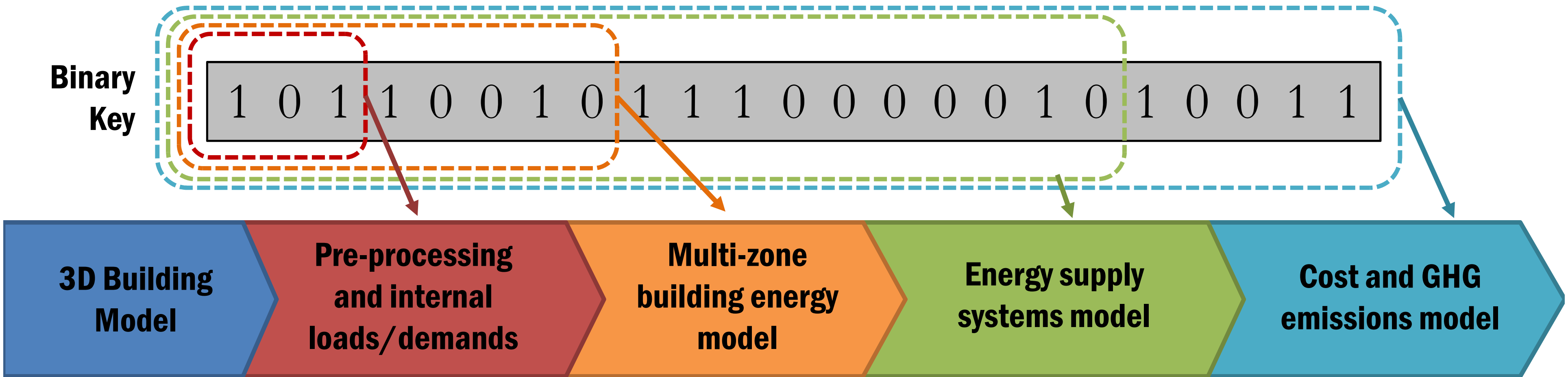
Model Overview:

Flow of simulation in actual model and purpose of individual submodels



Purpose:

- Generate 3D

Purpose:

- Decompile .B17 file and

Purpose:

- Assess demand-side

Purpose:

- Assess energy supply

Purpose:

- Assess costs based on

Notes:

Arranging the binary string in the right order allows for sequential simulation of components in the order of highest-computational expense to lowest. This is examined further on the following slide.

- Non-HVAC transient electricity demand
- Transient internal heat gains
- Pre-processed TRNSYS . BUI file

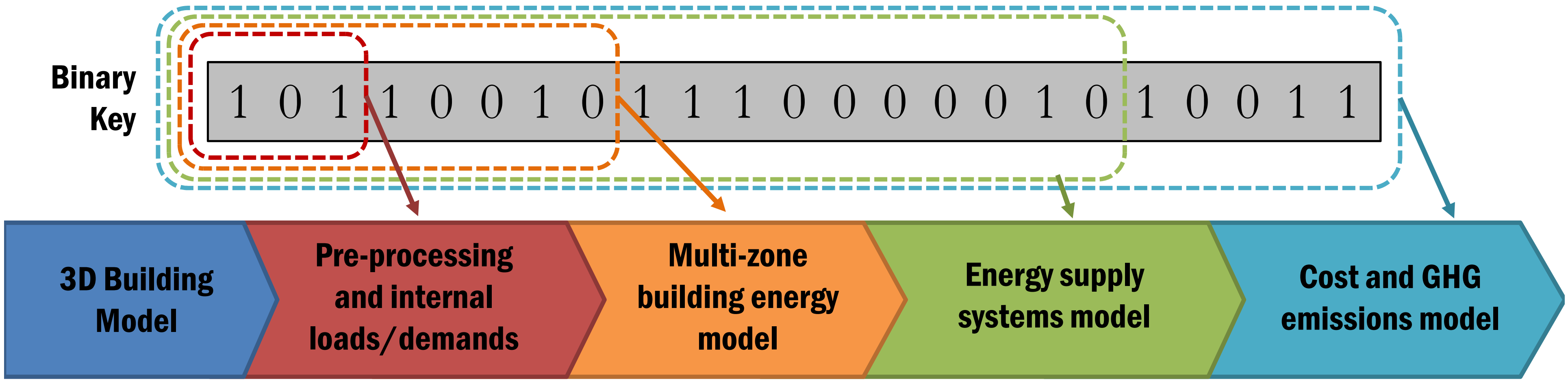
- End-use heating, cooling, and electricity demand profiles

- Renewable energy generation profiles, per type
- Energy supply system sizes (i.e., peak capacity)

- Economic details (e.g., CAPex, O&M costs, etc.)
- NPV of tech. set and GHG emissions saved

Model Overview:

Estimated computational expense of exhaustive search simulations



Pre-processing and internal loads/demands (Microsoft Excel / Visual Basic for Applications)

Number of options:

- With 3 candidates, there are a total of 8 possible combinations ($2^3 = 8$)

Duration per option:

- After initial set-up, it takes approximately 5-7 minutes to make demand changes and generate new profiles

Computational expense:

- **Approximately 40-56 minutes**

Multi-zone building energy model (TRNSYS 17 / MATLAB)

Number of options:

- With 8 candidates, there are a total of 256 possible combinations ($2^8 = 256$)

Duration per option:

- Approx. 1 minute per annual simulation at one hour iterations

Computational expense:

- **Approximately 4.5 hours**

Energy supply systems model (MATLAB)

Number of options:

- With 18 candidates, there are a total of 262,144 possible combinations ($2^9 = 262,144$)

Duration per option:

- Approx. 20-30 evaluations per second

Computational expense:

- **Approximately 2.5-3.5 hours**

Cost and GHG emissions model (MATLAB)

Number of options:

- With 23 candidates, there are a total of 8,388,608 possible combinations ($2^9 = 8.4$ M)

Duration per option:

- Approx. 150-300 evaluations per second

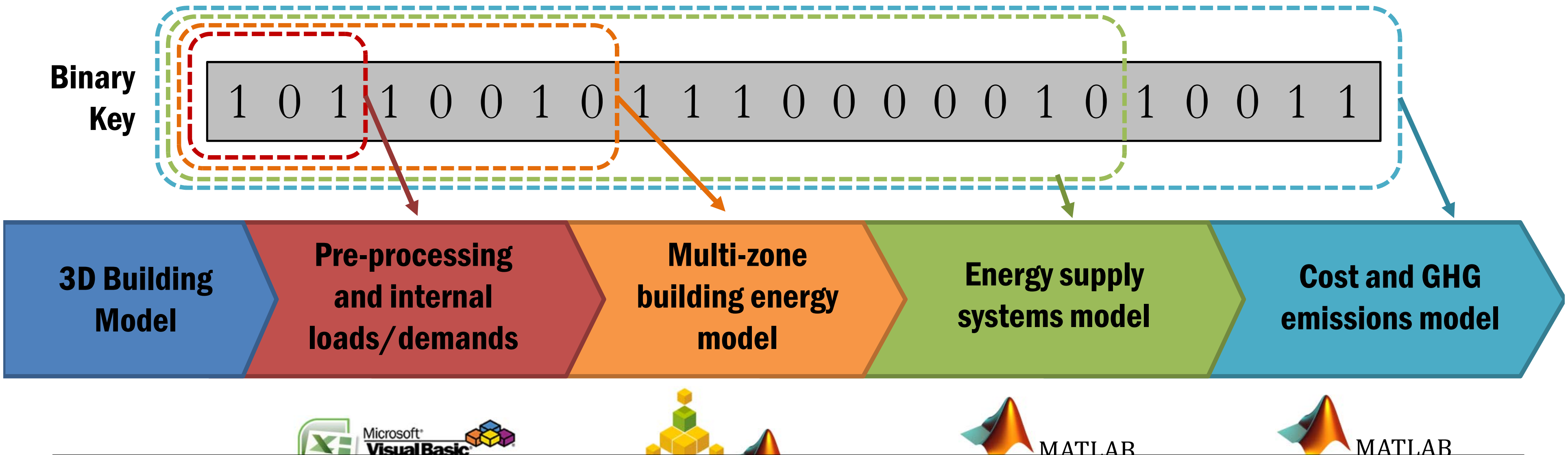
Computational expense:

- **Approximately 7.5-15.5 hours**

Total simulation time for exhaustive search: 15.5 to 24.5 hours.

Model Overview:

Estimated computational expense of exhaustive search simulations



Notes:

The estimated computational time is susceptible to the characteristics of the binary key above. However, the computational savings are not trivial. Similar works on large-scale discrete optimization of building technologies have not separated-out simulations from the building energy model. Thus, large super computing networks had been required to produce the same level of output, but with a longer running time. Parsing out the key into separate models allows only the necessary options to be modelled by the more rigorous building energy model.

Computational expense:

- Approximately 40-56 minutes

- Approximately 4.5 hours

- Approximately 2.5-3.5 hours

- Approximately 7.5-15.5 hours

Total simulation time for exhaustive search: **15.5 to 24.5 hours.**

Summary of the New Building-Energy Model for Large-Scale Automated Engineering and Economic Analysis

(NEBEMFELASCAENECAN)!

- At the core is the TRNSYS multi-zone building physics engine
- Matlab provides the engine for energy supply systems and economic analysis
- Technologies, measures, and technoeconomic scenarios are identified by a binary string
- Occupancy-based demand profiles are generated stochastically from probabilities-of-usage
- So far, the entire model is able to assess:

Demand-side
- Fabric measures
- Changing demand for services (illumination, thermal comfort, and ICT)
- Implementation of DSM for lighting and HVAC

Supply-side
- N.G.- and bio-boilers
- N.G. CHP
- ASHP
- GSHP
- Solar space heating with seasonal storage
- Solar PV

Economics
- Transient prices
- Transient taxes/subsid.
- Fixed and capacity-dependent costs

- And more in the pipeline......

Case Study:
The Austin Robinson Building
Faculty of Economics, University of Cambridge

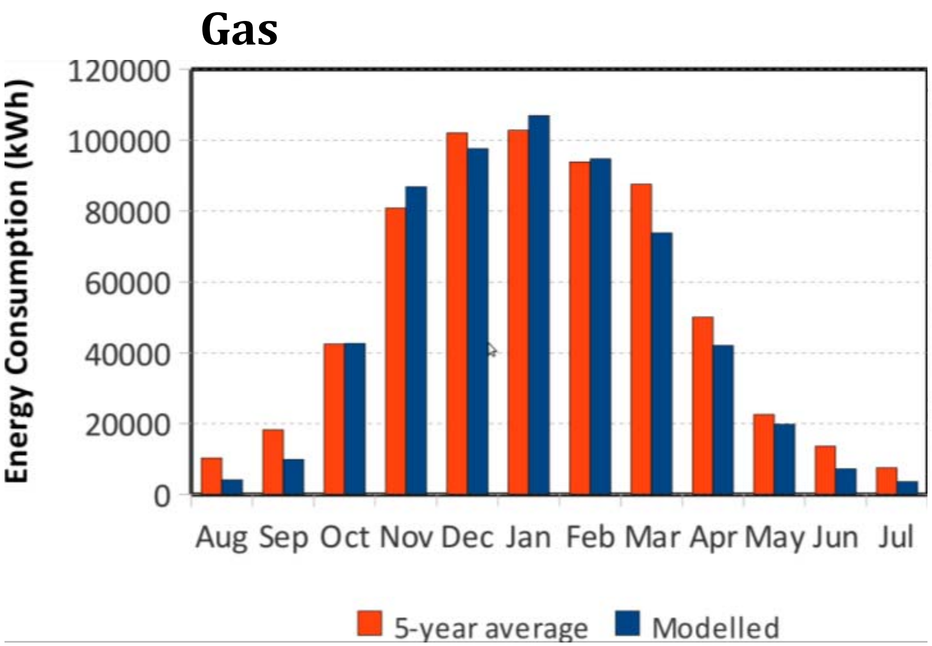
Building Data:

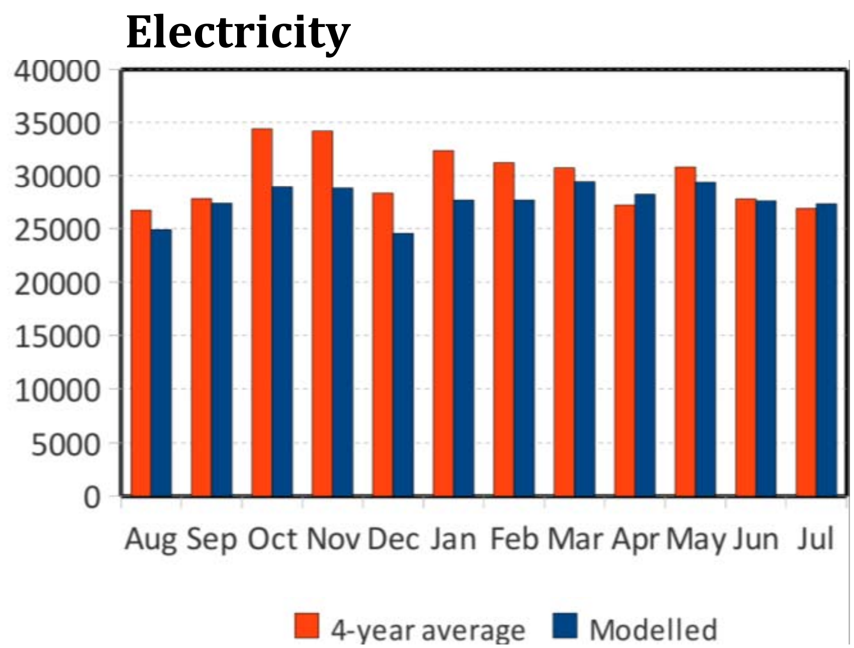
- Built in 1960-1961
- Occupied area 3,265 m^2
- Approx. 85 private offices, 3 lecture rooms, two open-concept office areas, a buttery, an IT lab, etc.

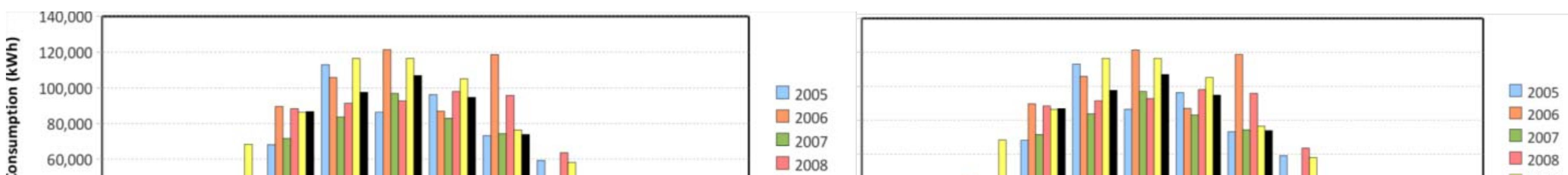
Pre-Refurbishment Systems:

- Recent installation of non-condensing boiler (85% eff.)
- Single-pane, uninsulated, and uncoated windows
- Standard fluorescent lighting, but poor control
- Centrally-controlled LPHW heating network

Case Study:
The Austin







Notes:

Initial modelling is done to validate calculated gas and electricity consumption of the existing building against metered data

- Centrally-controlled LPHW heating network

Scenarios:
Investment Overview

Description: In 2010, the building's existing non-condensing boiler is to be replaced due to life-cycle conditions. This provides an opportunity to look at cost and emissions savings by undertaking additional building refurbishments. Large-scale optimization is performed on all possible technology options against divergent economic conditions.

Business-as-usual investment: We assume the boiler is simply replaced with a new model. A replacement is sized and priced at £36,000. These funds are allocated by the university's building management budget.

Options: All 'realistic' options are assessed. For each option the £36,000 capital grant is provided.

Outlook: 15 years

Discount rate: 8% (as recommended in AEA 2008)

Scenarios:
Technologies and Capital Costs

Measure / Technology	Cost (Low)	Cost (High)	Source*
Air tightening	£14,000	£14,000	Online estimate
Roof replacement	£70,454	£105,681	Buildings Magazine (2008)
Reglazing	£118,926	£151,361	RICS BCIS (2010)
Setback temperature	£0	£0	UniCam. EMBS
Replace T8 with T5 lighting	£12,000	£20,000	Online estimate
Lighting setback	£19,951	£19,951	RICS BCIS (2010)
Non-condensing N.G. Boiler	£65/kW	£65/kW	AEA (2009)
Biomass pellets boiler	£317/kW	£423/kW	AEA (2009)
N.G. CHP (I.C. Engine)	£500/kW	£670/kW	UK MARKAL (2007)
Solar PV	£5,000/kW	£6,000/kW	EST (2005)
ASHP**	£545/kW	£610/kW	AEA (2009)

Demand Reduction Measures

Energy Supply Measures

* Values given are always approximate, and modifications are based on heuristics

** Cost estimates for ASHPs do not seem to include installation costs due to possible changes to HVAC distribution network. It is assumed that the reference product represents LTHW-producing ASHP unit which taps into the existing LPHW distribution network.

Scenarios:
Techno-economic Scenarios

Category	Unit	Property	Value*				Source
			"Best-case" Scenario**		"Worst-case" Scenario***		
			2010	2020	2010	2020	
Resource prices	p / kWh	Natural gas	1.7	2.5	3.1	4.7	DECC 2010
		Electricity	7.0	10.1	10.2	14.2	
		Biomass pell.	4.3	4.0	4.3	5.6	
Emissions Intensities	gCO_2 / kWh	Natural gas	185	185	185	185	DEFRA 2010
		Electricity	460	305	460	435	CCC 2008
		Biomass pell.	25	25	130	130	EA 2009
Subsidies (UK Renewable Heat Incentive and REFiT)	p / kWh	Biomass heat.	6.5	6.5	5.2	5.2	Ownenergy 2010 (with heuristic approx.)
		ASHP heating	2	2	1.6	1.6	
		Solar PV	33.1	33.1	31.4	31.4	
Taxes / Levies	£ / ton CO_2	CRC Commitment	12†	20†	N/A†	N/A†	CCC 2008

* Thought finite values shown here, most reference data provides annual estimates for all years between 2010 and 2020. Trendline functions were generated to provide an analytical representation.

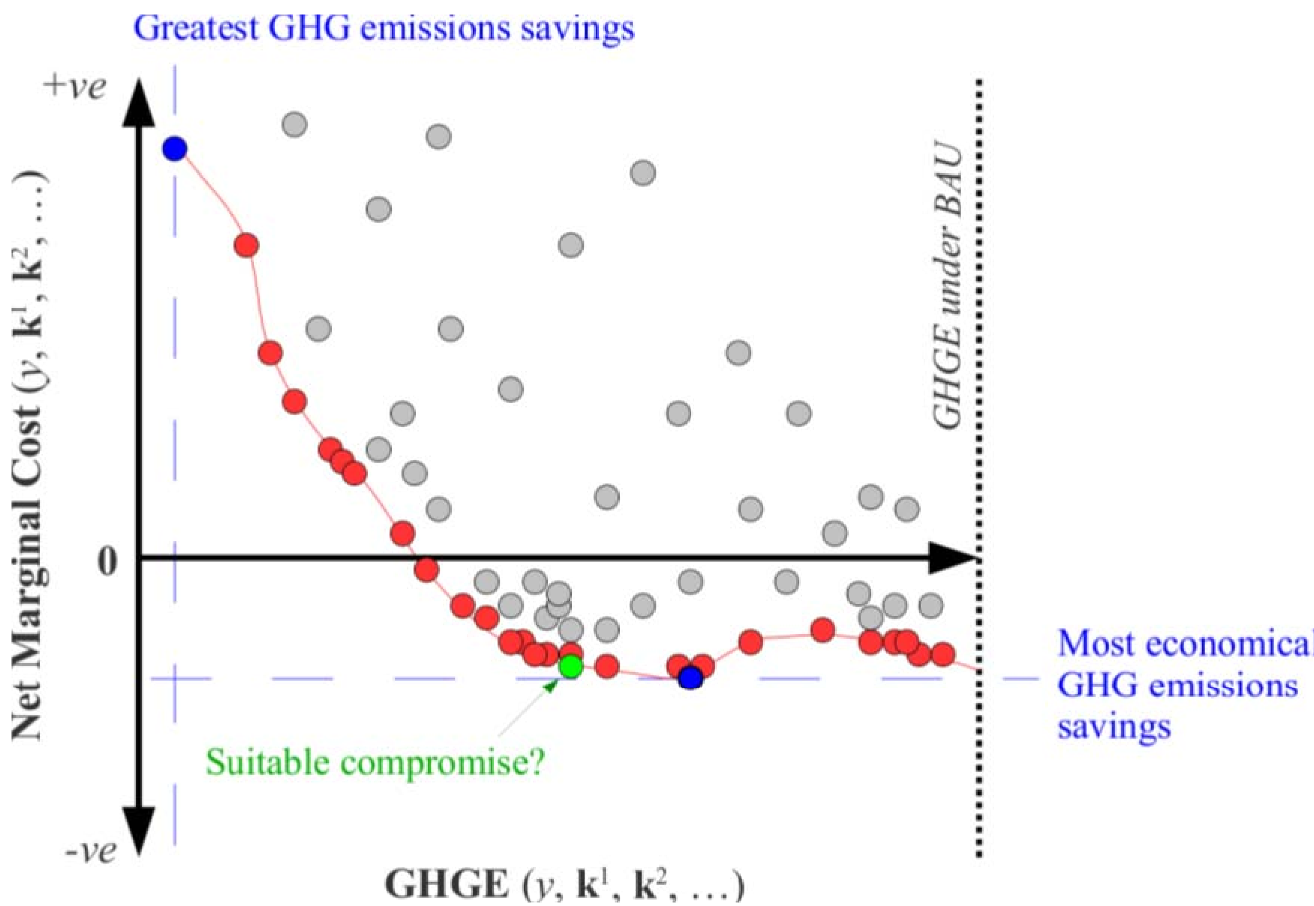
** 'Best-case' scenario means: low energy prices, low carbon intensity of the grid, low system costs, high subsidies and high carbon taxes

*** 'Worst-case' scenario means: high energy prices, high carbon intensity of the grid, high system costs, low subsidies and low carbon taxes

† In the 'best-case' scenario, CRC is expanded to all buildings, starting at £12/ton-CO_2 and expanding to £20/ton-CO_2 by 2020. (This is an approximate low-end projected price of EU ETS by 2020

The Goal: Optimization

We wish to choose an investment option that: **Minimizes:** {-NPV, GHGe}

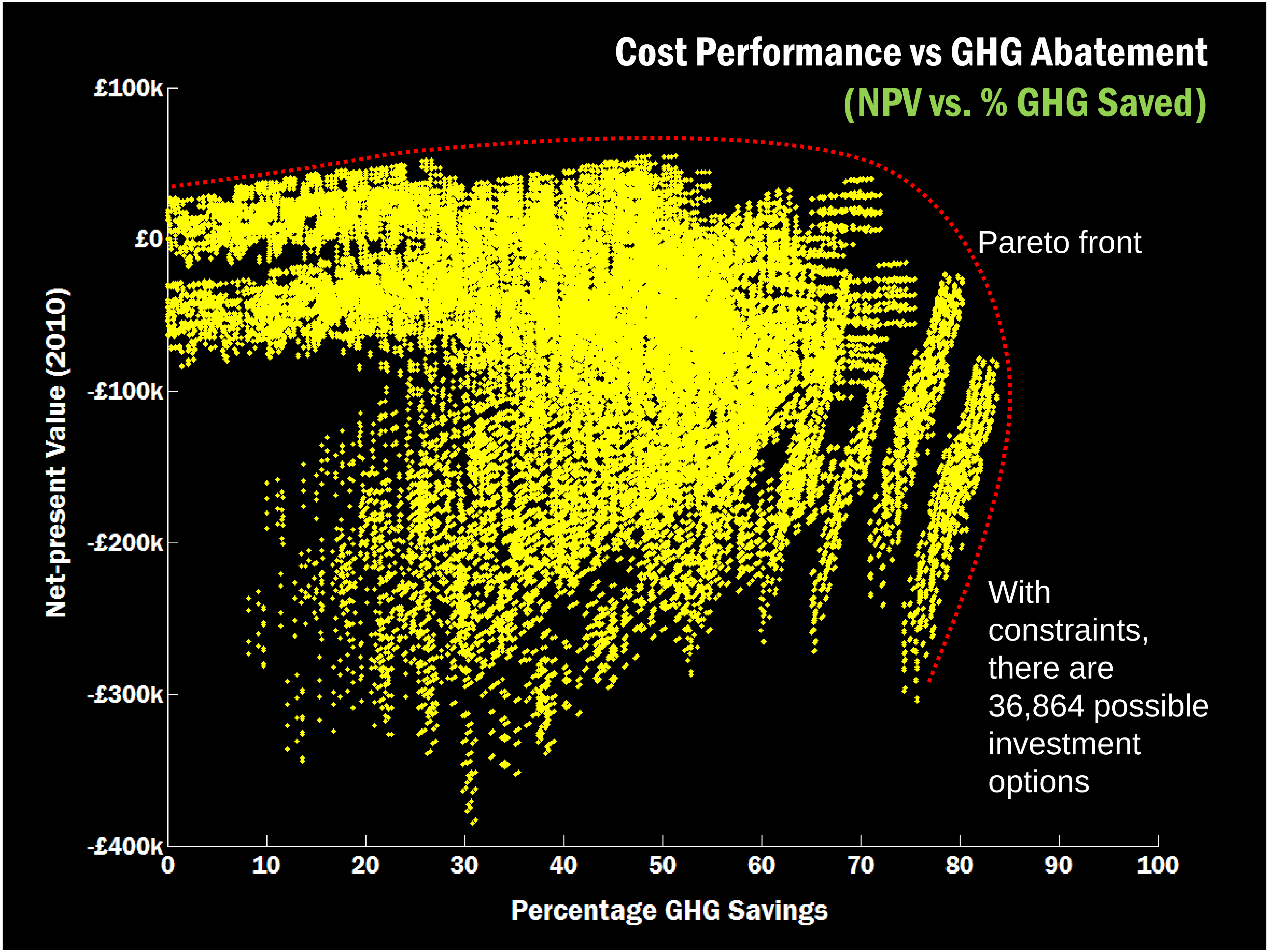


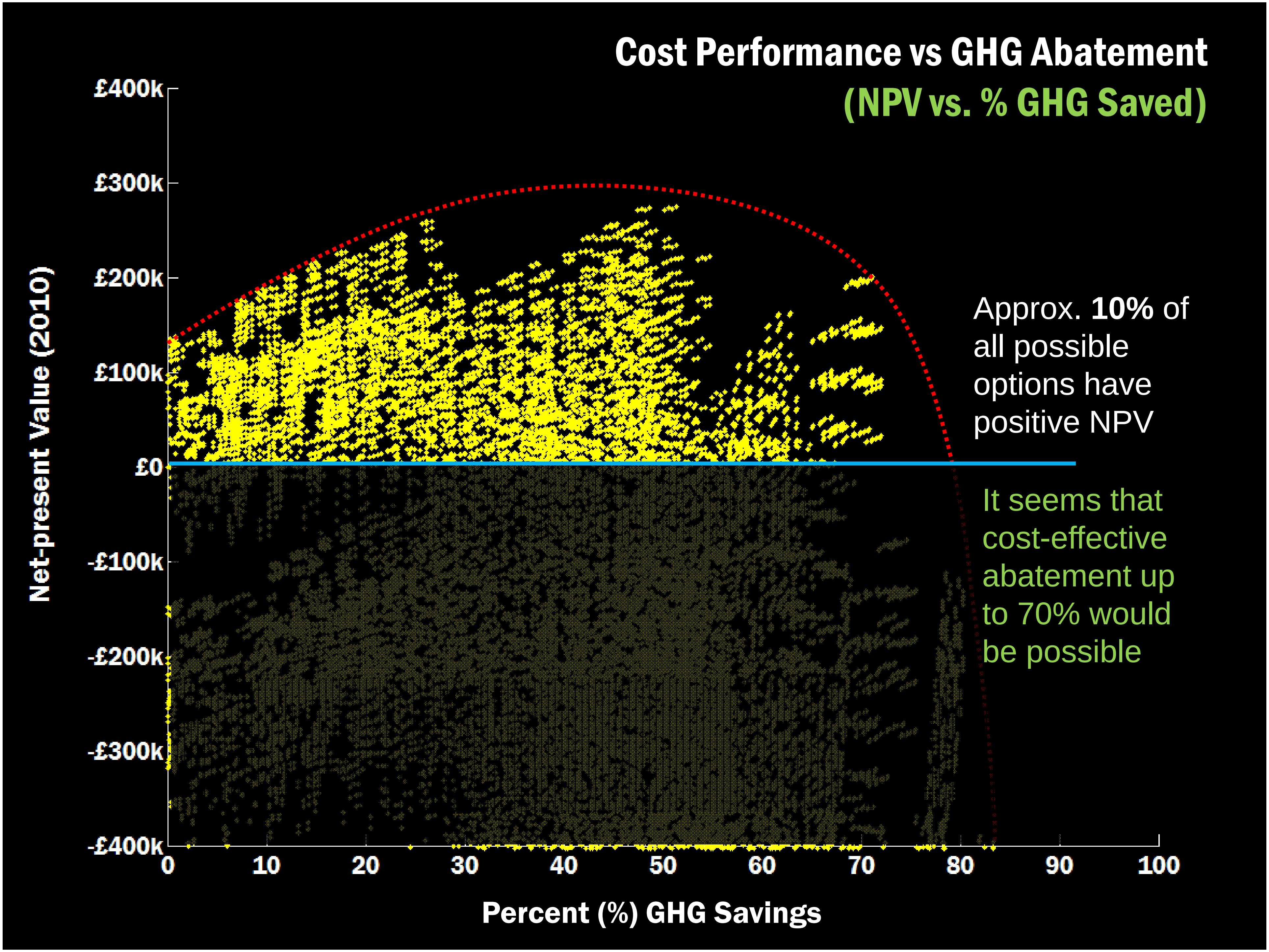
Marginal abatement cost shown here

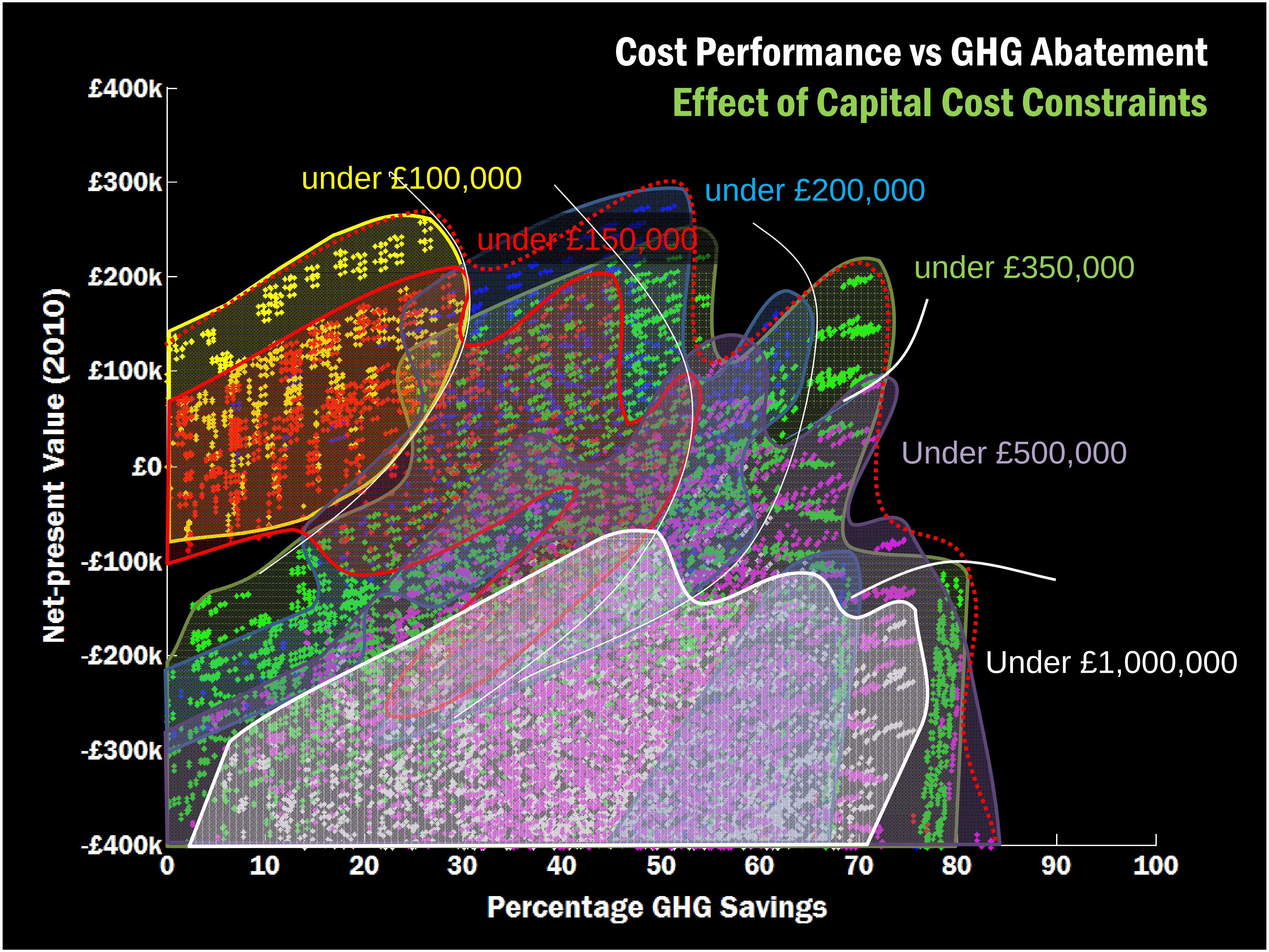
Energy Efficient Cities initiative

UNIVERSITY OF CAMBRIDGE

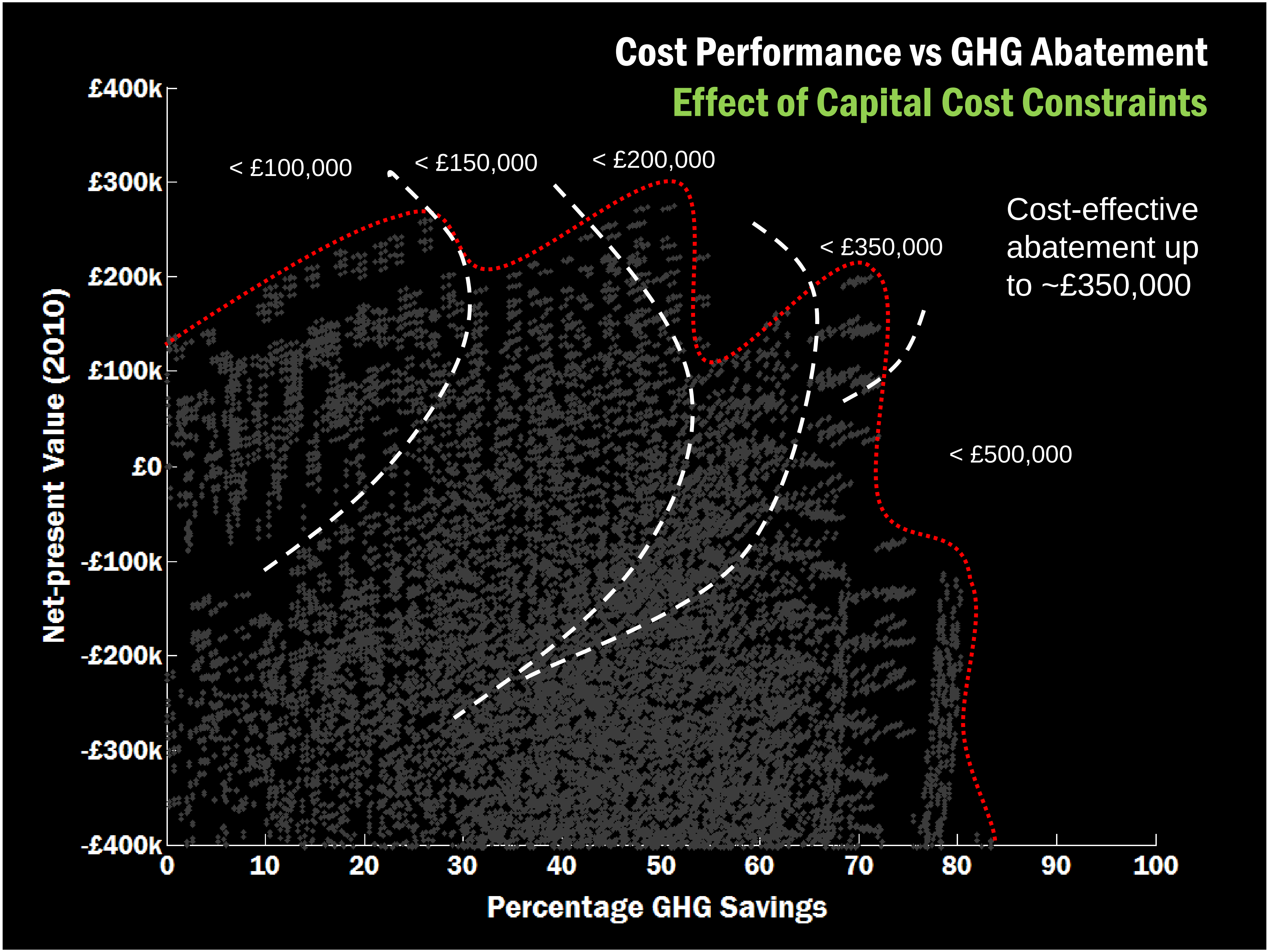
The Results

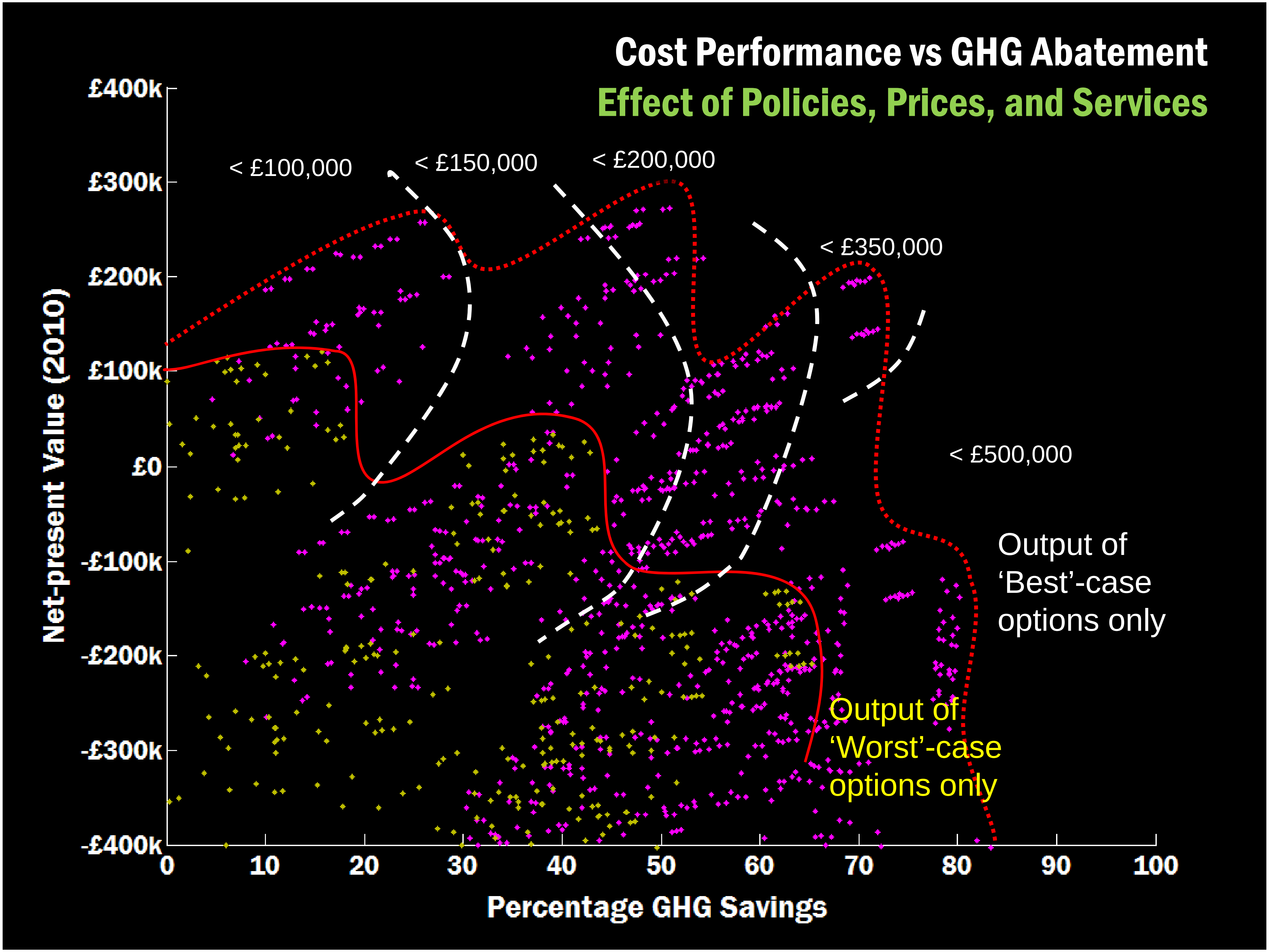

Cost Performance vs GHG Abatement
(NPV vs. % GHG Saved)
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings
Pareto front
With constraints, there are 36,864 possible investment options


Cost Performance vs GHG Abatement
(NPV vs. % GHG Saved)
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percent (%) GHG Savings
Approx. 10% of all possible options have positive NPV
It seems that cost-effective abatement up to 70% would be possible



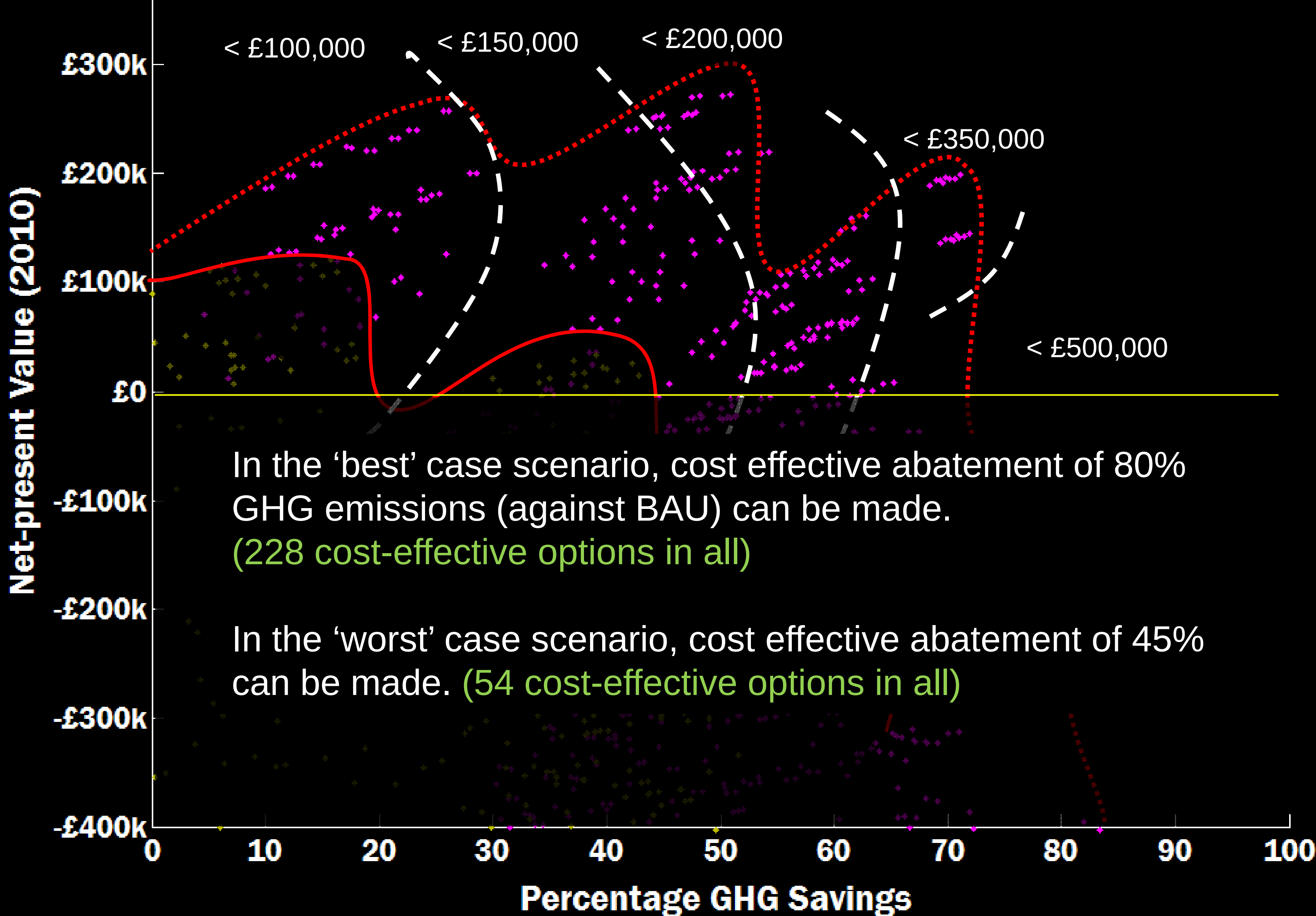
Cost Performance vs GHG Abatement
Effect of Capital Cost Constraints
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings
under £100,000
under £150,000
under £200,000
under £350,000
Under £500,000
Under £1,000,000


Cost Performance vs GHG Abatement
Effect of Capital Cost Constraints
< £100,000
< £150,000
< £200,000
< £350,000
< £500,000
Cost-effective abatement up to ~£350,000
Net-present Value (2010)
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings


Cost Performance vs GHG Abatement
Effect of Policies, Prices, and Services
< £100,000
< £150,000
< £200,000
< £350,000
< £500,000
Output of 'Best'-case options only
Output of 'Worst'-case options only
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings

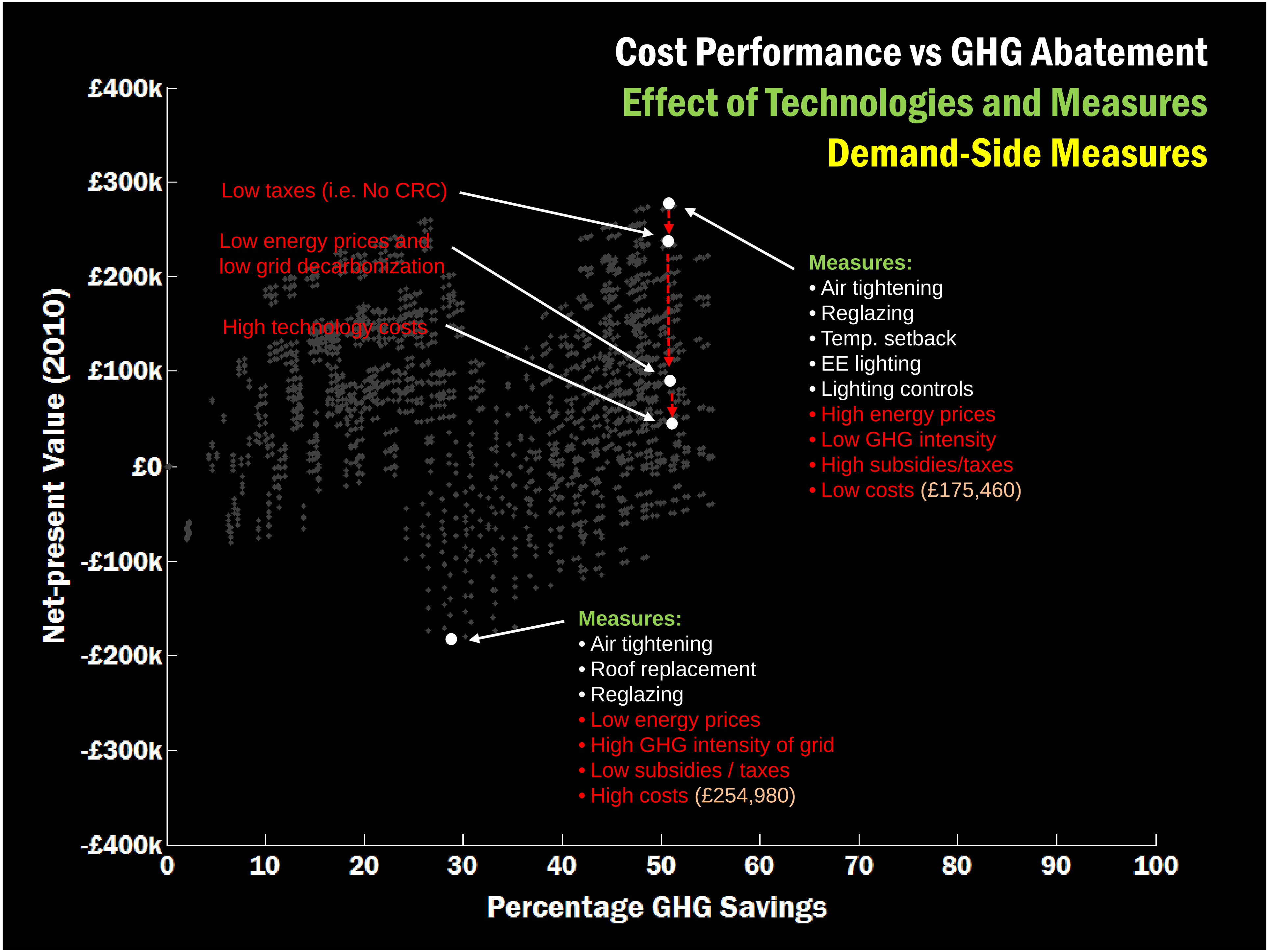
Cost Performance vs GHG Abatement

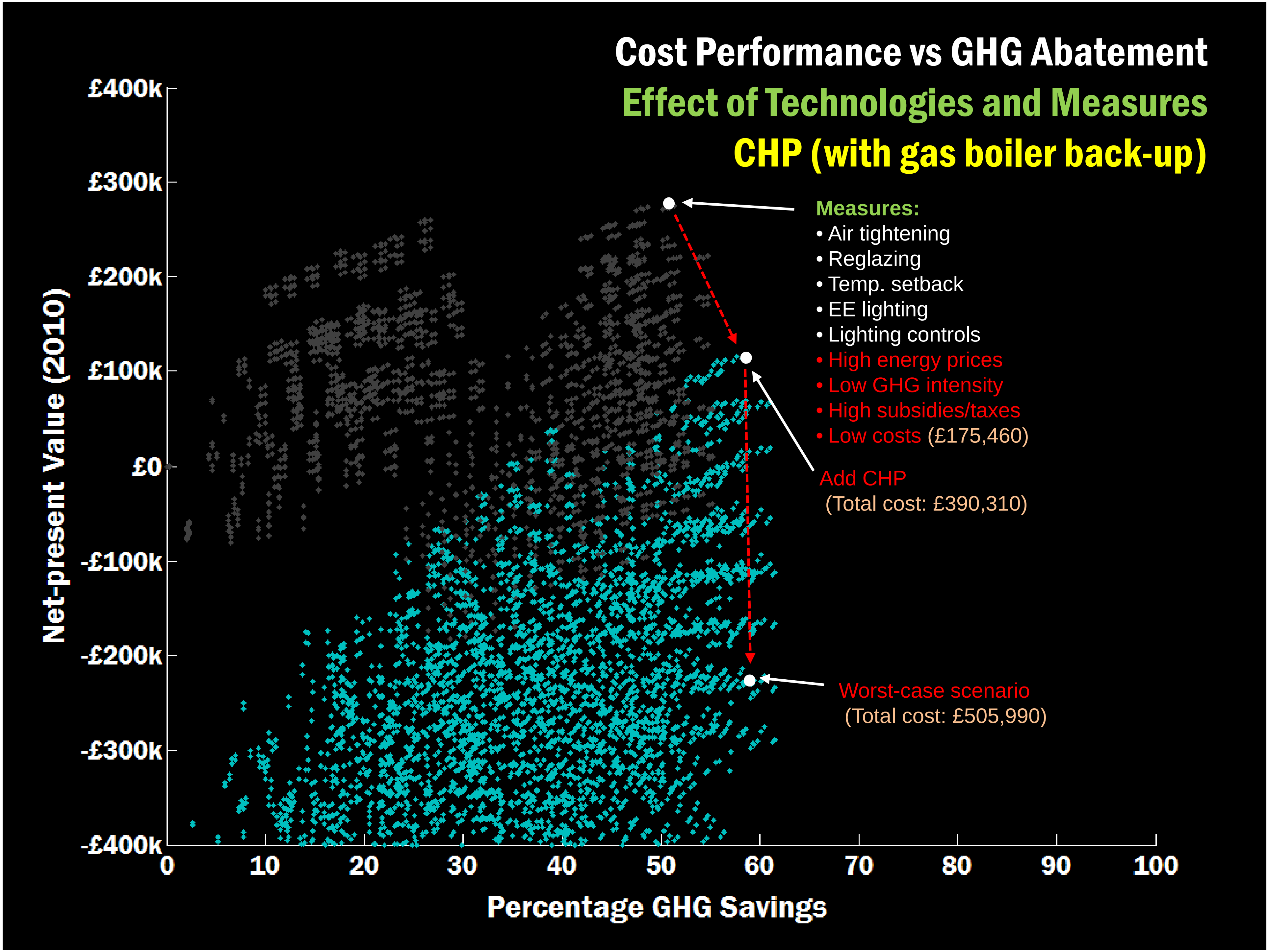
Distribution of Technologies

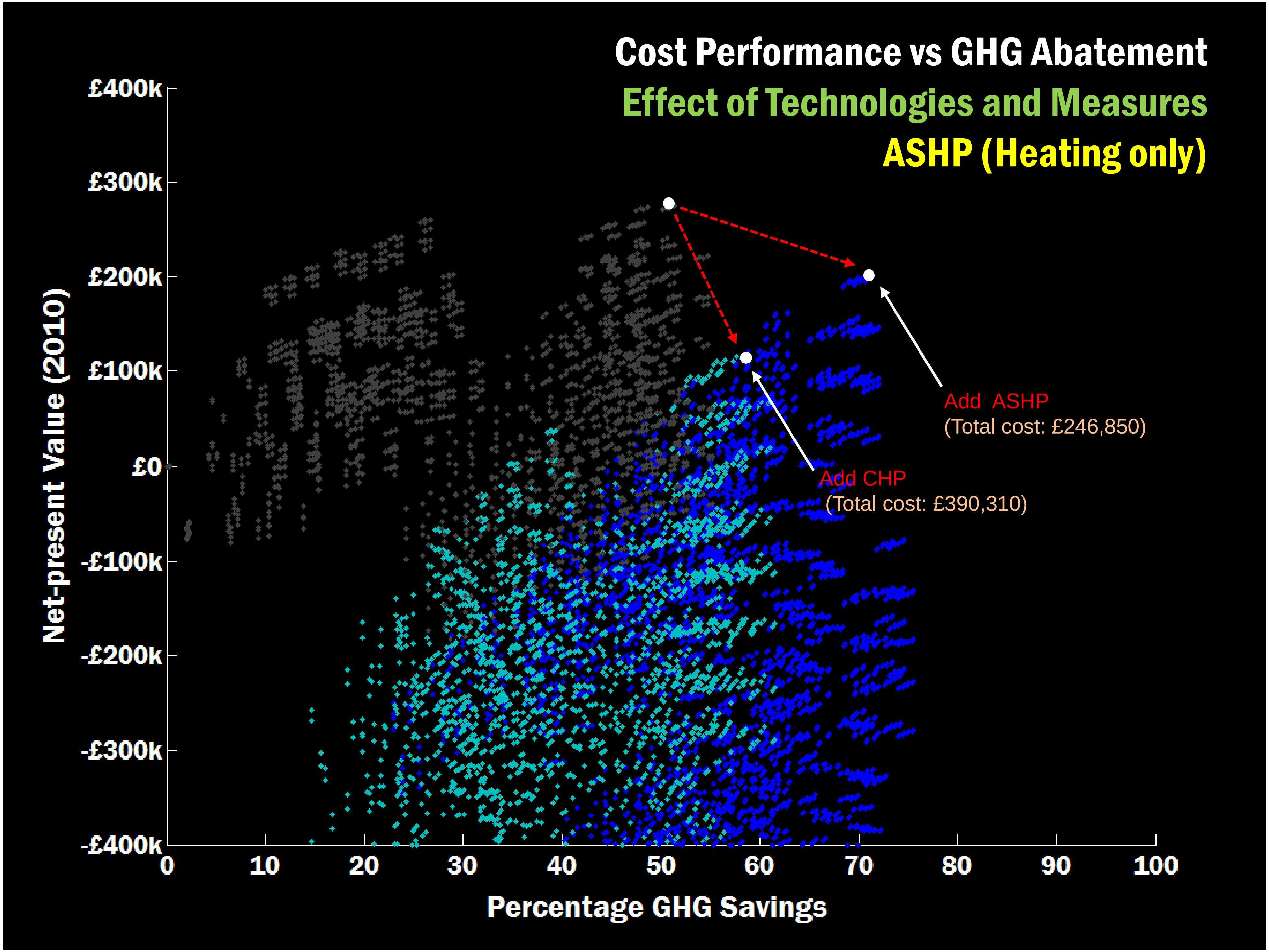


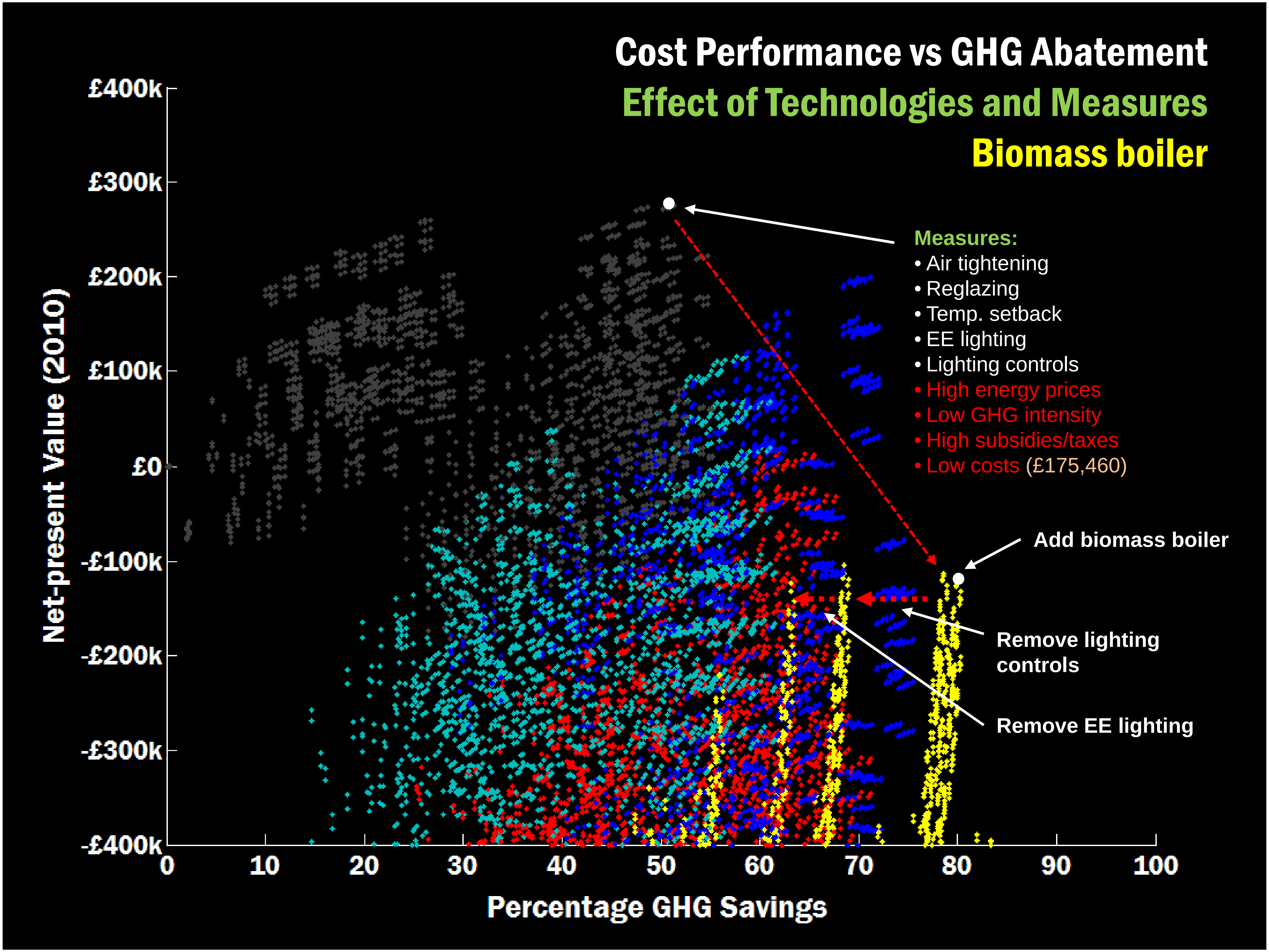
In the ‘best’ case scenario, cost effective abatement of 80% GHG emissions (against BAU) can be made.
(228 cost-effective options in all)

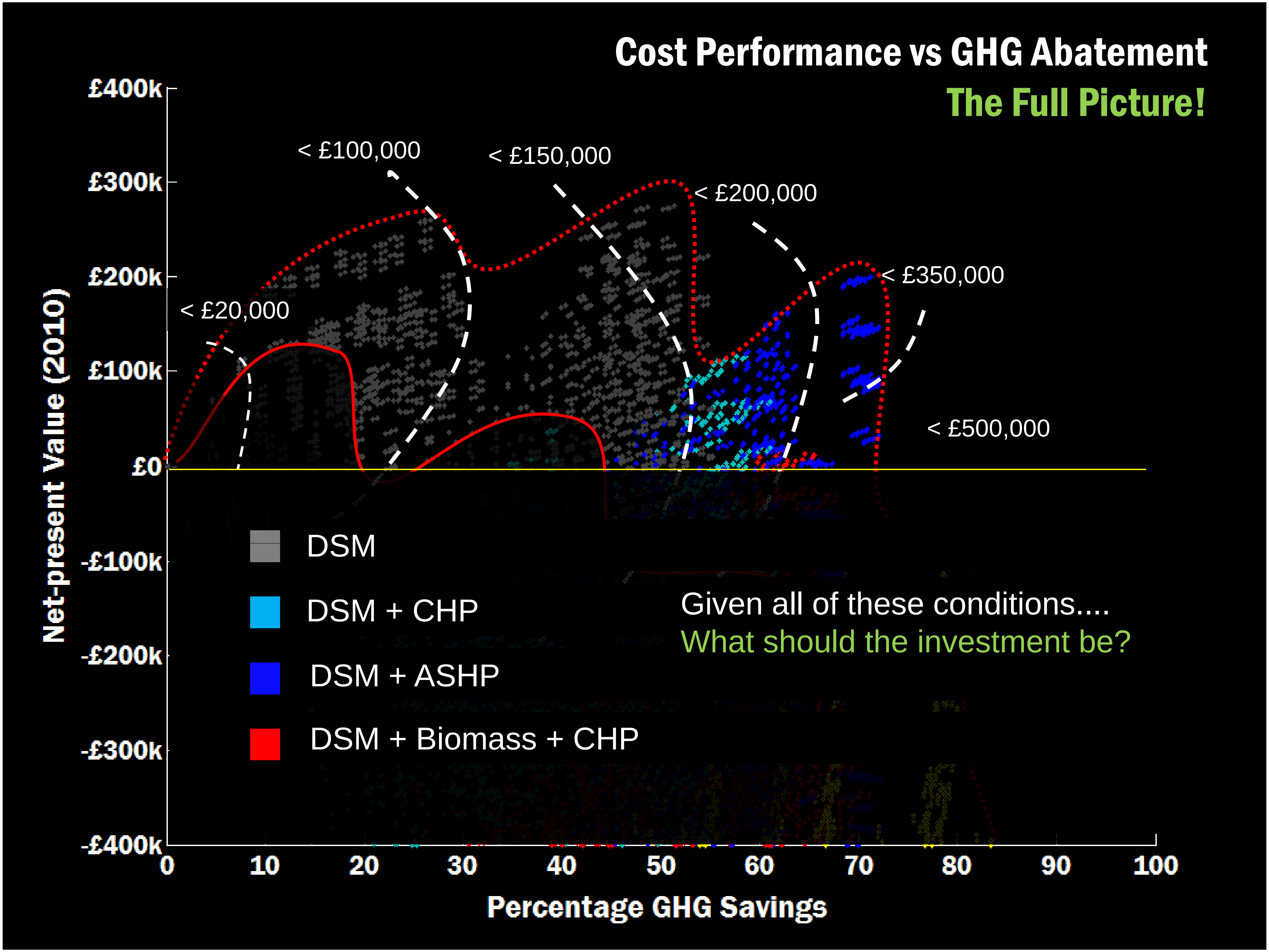
In the ‘worst’ case scenario, cost effective abatement of 45% can be made. (54 cost-effective options in all)

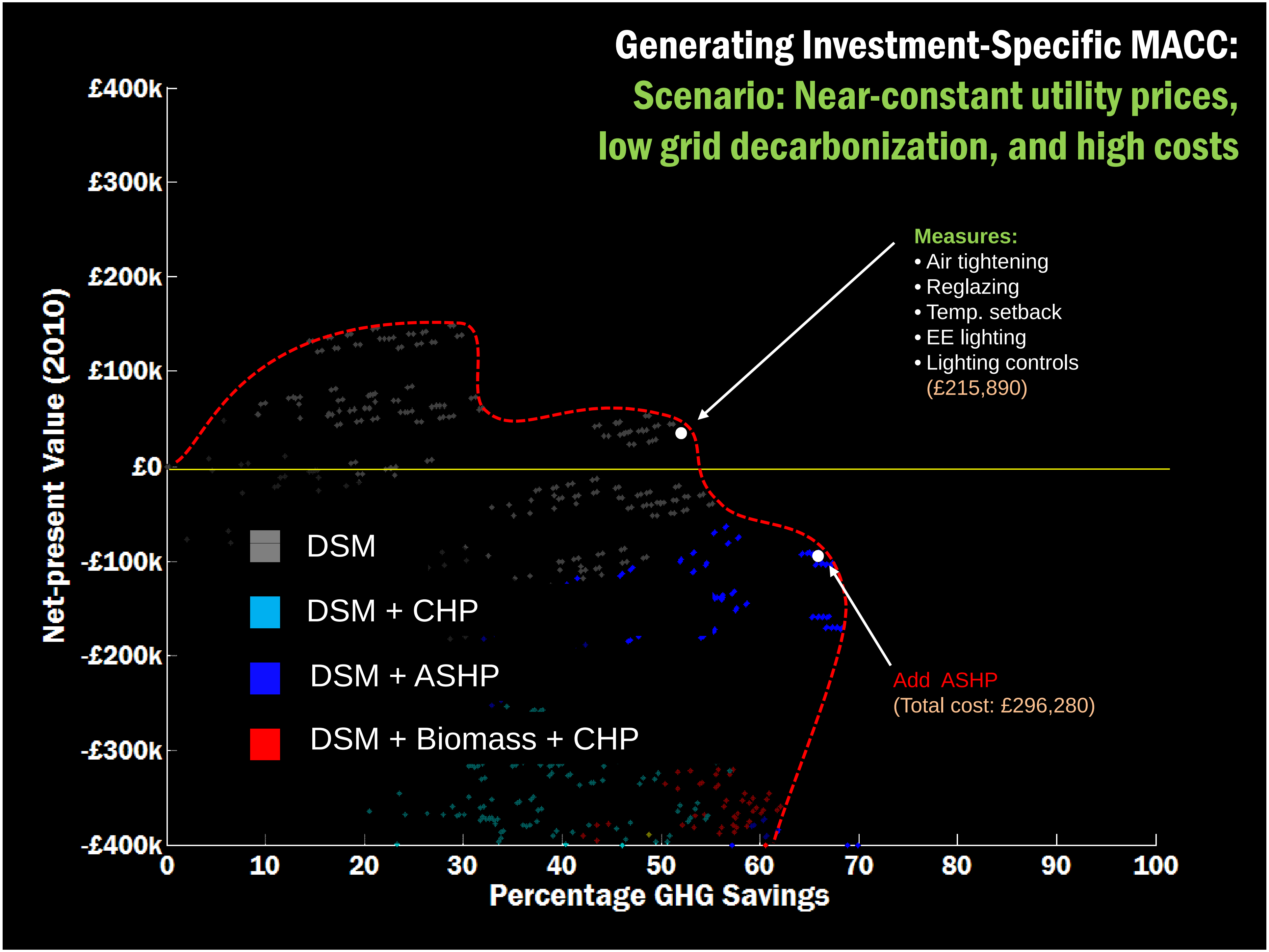

Cost Performance vs GHG Abatement
Effect of Technologies and Measures
Demand-Side Measures
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings
Low taxes (i.e. No CRC)
Low energy prices and
low grid decarbonization
High technology costs
Measures:
• Air tightening
• Reglazing
• Temp. setback
• EE lighting
• Lighting controls
• High energy prices
• Low GHG intensity
• High subsidies/taxes
• Low costs (£175,460)
Measures:
• Air tightening
• Roof replacement
• Reglazing
• Low energy prices
• High GHG intensity of grid
• Low subsidies / taxes
• High costs (£254,980)


Cost Performance vs GHG Abatement
Effect of Technologies and Measures
CHP (with gas boiler back-up)
Measures:
• Air tightening
• Reglazing
• Temp. setback
• EE lighting
• Lighting controls
• High energy prices
• Low GHG intensity
• High subsidies/taxes
• Low costs (£175,460)
Add CHP
(Total cost: £390,310)
Worst-case scenario
(Total cost: £505,990)
Net-present Value (2010)
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings

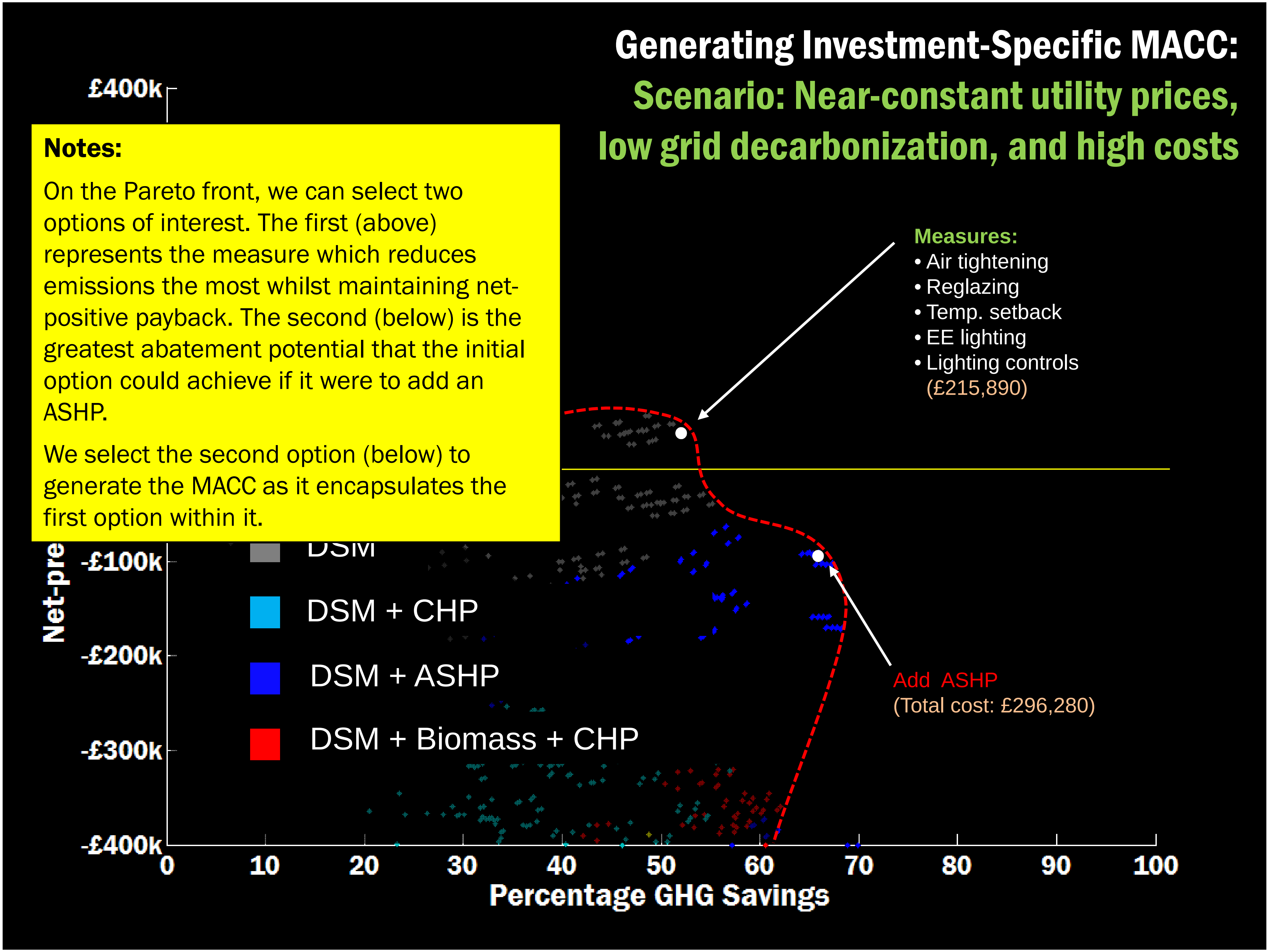

Cost Performance vs GHG Abatement
Effect of Technologies and Measures
ASHP (Heating only)
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings
Add ASHP
(Total cost: £246,850)
Add CHP
(Total cost: £390,310)


Cost Performance vs GHG Abatement
Effect of Technologies and Measures
Biomass boiler
Measures:
• Air tightening
• Reglazing
• Temp. setback
• EE lighting
• Lighting controls
• High energy prices
• Low GHG intensity
• High subsidies/taxes
• Low costs (£175,460)
Add biomass boiler
Remove lighting controls
Remove EE lighting
Net-present Value (2010)
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings

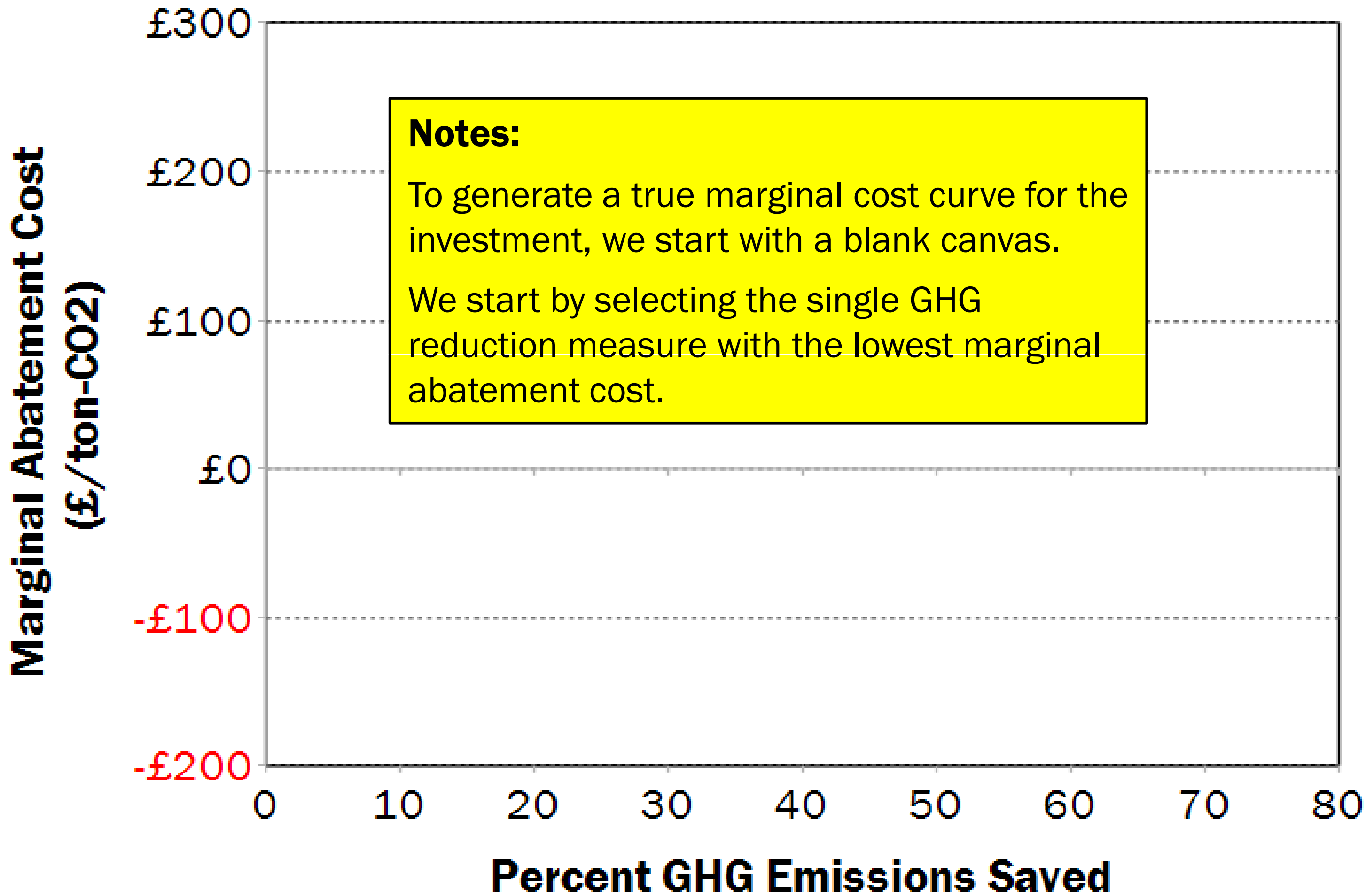

Cost Performance vs GHG Abatement
The Full Picture!
< £20,000
< £100,000
< £150,000
< £200,000
< £350,000
< £500,000
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
Net-present Value (2010)
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings
DSM
DSM + CHP
DSM + ASHP
DSM + Biomass + CHP
Given all of these conditions....
What should the investment be?



Generating Investment-Specific MACC:
Scenario: Near-constant utility prices, low grid decarbonization, and high costs
Net-present Value (2010)
£400k
£300k
£200k
£100k
£0
-£100k
-£200k
-£300k
-£400k
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings
Measures:
• Air tightening
• Reglazing
• Temp. setback
• EE lighting
• Lighting controls
(£215,890)
DSM
DSM + CHP
DSM + ASHP
DSM + Biomass + CHP
Add ASHP
(Total cost: £296,280)


Generating Investment-Specific MACC:
Scenario: Near-constant utility prices, low grid decarbonization, and high costs
Notes:
On the Pareto front, we can select two options of interest. The first (above) represents the measure which reduces emissions the most whilst maintaining net-positive payback. The second (below) is the greatest abatement potential that the initial option could achieve if it were to add an ASHP.
We select the second option (below) to generate the MACC as it encapsulates the first option within it.
Measures:
• Air tightening
• Reglazing
• Temp. setback
• EE lighting
• Lighting controls
(£215,890)
Add ASHP
(Total cost: £296,280)
DSM
DSM + CHP
DSM + ASHP
DSM + Biomass + CHP
£400k
-£100k
-£200k
-£300k
-£400k
Net-pre
0
10
20
30
40
50
60
70
80
90
100
Percentage GHG Savings

Generating a optimized MACC of an investment set

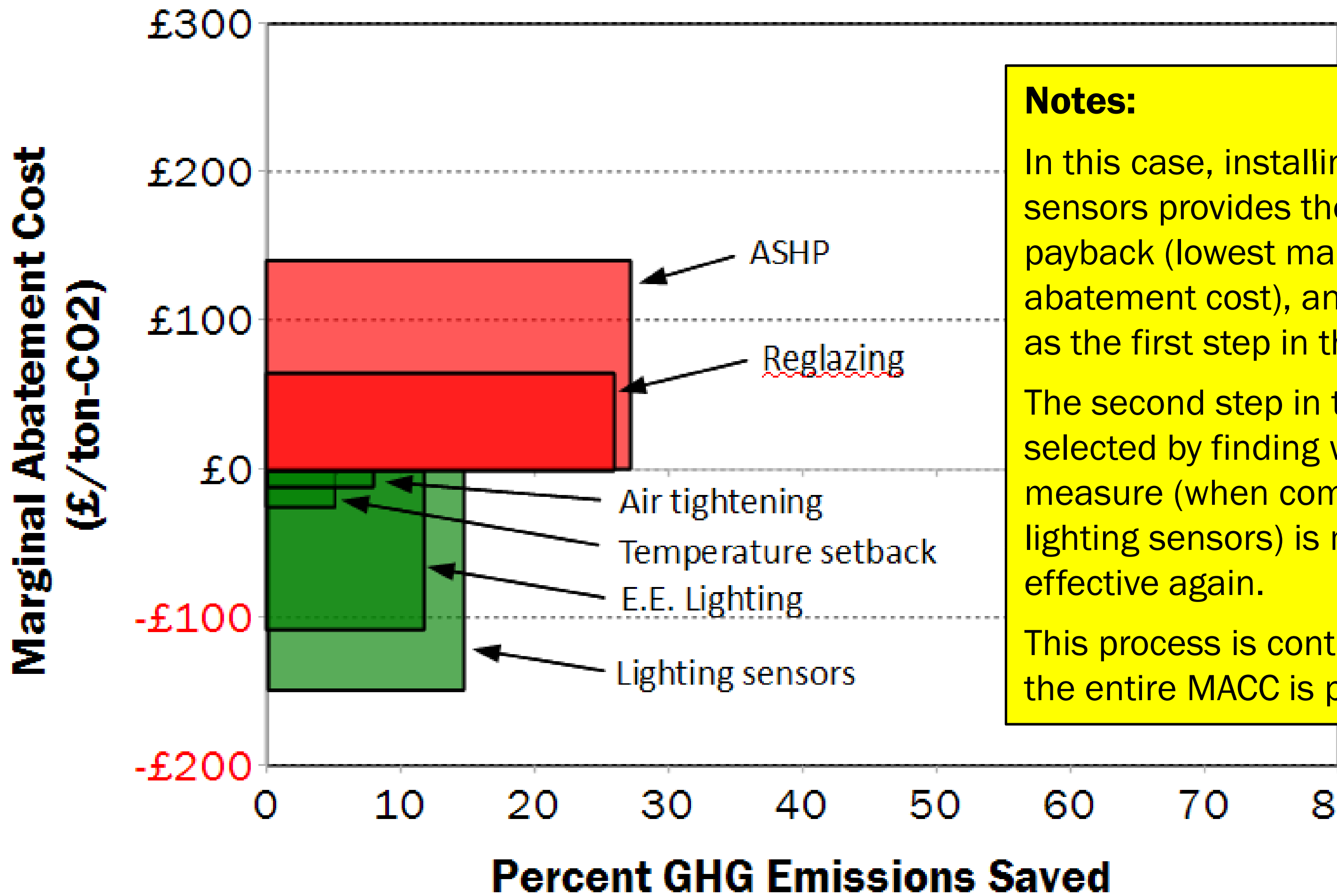


Notes:

To generate a true marginal cost curve for the investment, we start with a blank canvas.

We start by selecting the single GHG reduction measure with the lowest marginal abatement cost.

Generating a optimized MACC of an investment set



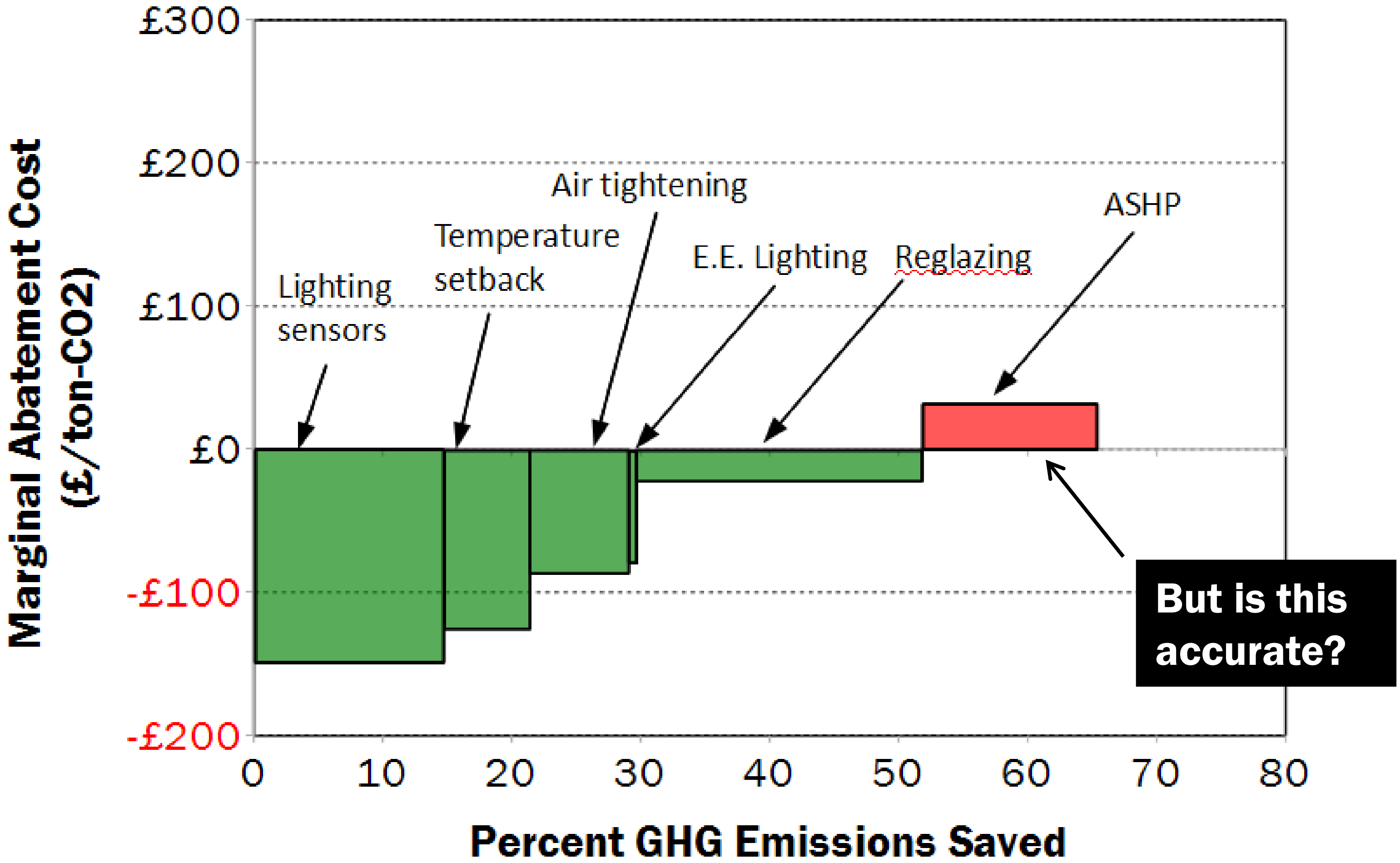
Notes:

In this case, installing lighting sensors provides the greatest payback (lowest marginal abatement cost), and is selected as the first step in the curve.

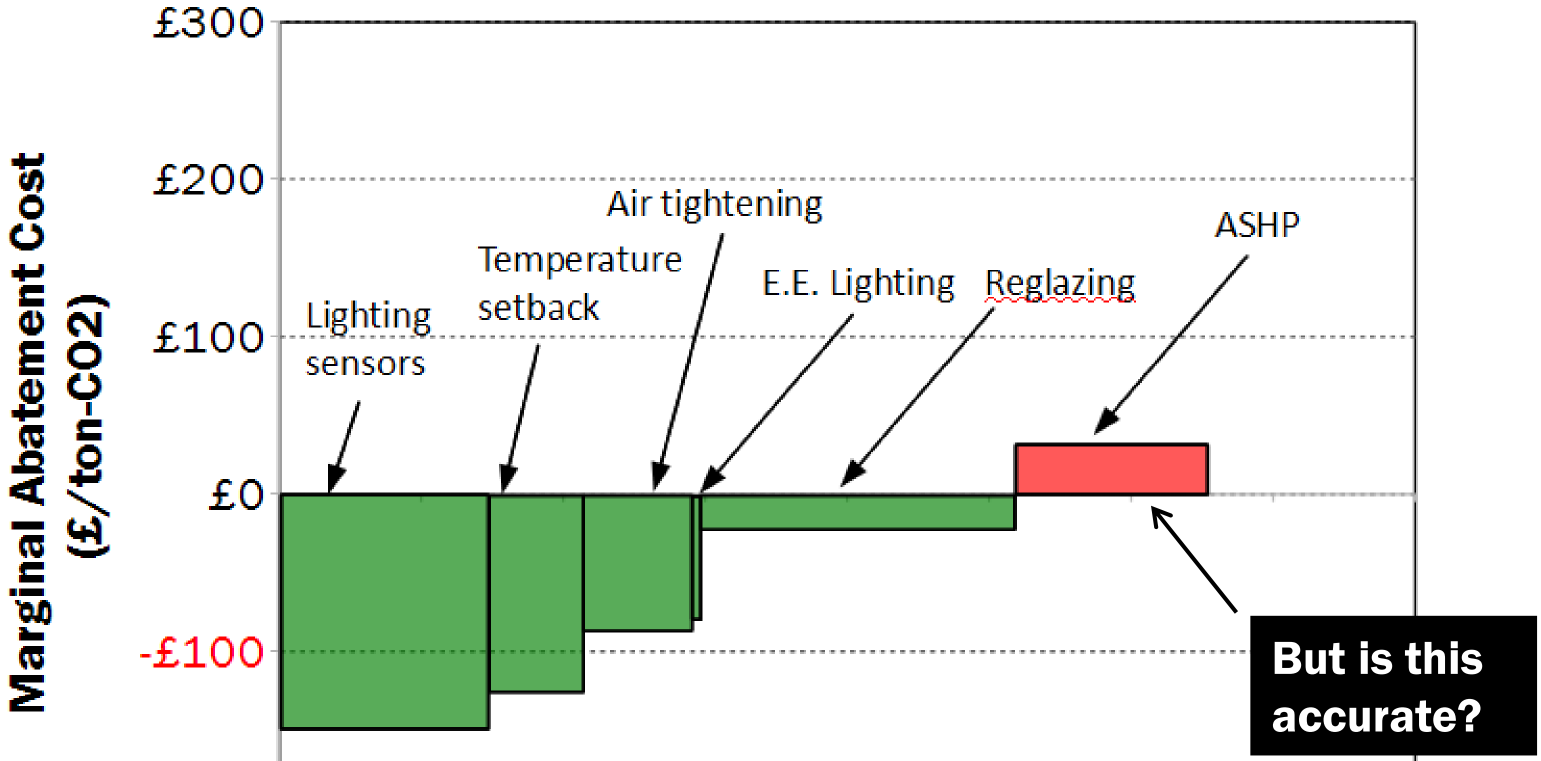
The second step in the curve is selected by finding which measure (when combined with lighting sensors) is most cost-effective again.

This process is continued until the entire MACC is produced.

Generating a optimized MACC of an investment set



Generating a optimized MACC of an investment set



Notes:

The answer, is yes and no. If the MACC is used to determine whether it's better to invest only up until 'reglazing', then yes.

However, if investment in ASHP is to be delayed, then the existing gas boiler must be replaced. This changes the total capital cost of the investment set, and thus provides a key reason why long-term investment decisions warrant multi-period optimization (to be done in the next stage of this research).

Final Points and Future Work

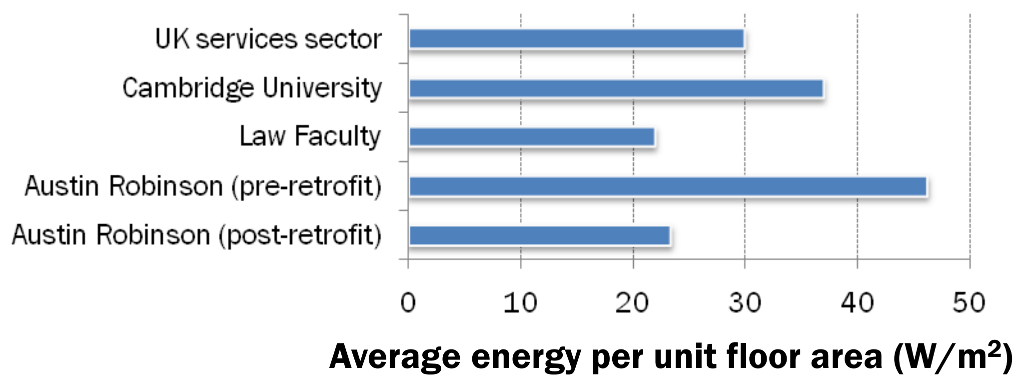
The case for multi-period optimization
Life-cycle of energy supply systems vs. Investment triggers

‘De-gassification’ as good as ‘decarbonization’?
If a building can economically de-gassify, is this sufficient given the future decarbonization of the grid?

Between the ‘best’ practise and ‘worst’ policy scenarios, cost-effective abatement can differ by as much as 40%.

Changes to services demands can and will have an impact but maybe not as much as technology cost reduction.

Additional building case studies are now in the pipeline.
The model stands as a general tool applicable to all buildings.



Source: (Mackay 2008)

Thank You!

For references or questions please contact:

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