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USING BUILDING SIMULATION TO CREATE MARGINAL ABATEMENT COST CURVES OF INDIVIDUAL BUILDINGS

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ABSTRACT

This paper explores a technique for generating marginal abatement cost curves for individual buildings. It makes use of sequential optimisation and exhaustive search of building refurbishment options based on a custom building energy model developed previously by the authors.

INTRODUCTION

In the energy efficiency and carbon-reduction sectors, there have been long-standing and well-studied drivers and barriers to investments in building retrofit projects (Ürge Vorsatz et al., 2009). It was also towards the end of the last decade that widespread building refurbishments were becoming one of the more prominent focus areas of government actions in these sectors, particularly in Europe and North America (EU, 2010; The White House; Office of the Press Secretary, 2011). This momentum has only recently been tempered by the realities of the post-Kyoto, post-Copenhagen, and post-financial crisis world. Though energy costs and emissions have continued to increase in many countries, adding to the long-term financial drivers for retrofits, so too have building owners' and investors' fears of short-term risks and low rates of returns.

Some of these risks also rest on the shoulders of consulting companies and retrofit providers. These entities are tasked with soliciting consumers (e.g., building owners) who may request preliminary assessments to be undertaken for very little, or negligible, initial costs. Responding to this, a consulting engineer must balance the cost of providing analysis to the prospective client against the intrinsic value of that analysis. In other words, does it warrant an engineer to spend considerable time modelling a building if there is limited chance that the client will continue pursuit of the project? Does it warrant the engineer to spend little time in developing simple recommendations, given that the client may feel considerable analysis is required to alleviate his/her perceived risks? Acknowledging that this a complex issue, and not completely addressable by a single discipline or paper, this particular study proposes only a partial solution to the information cost barrier. We suggest that building-tailored marginal abatement cost curves (MACCs) may be a useful way to visualize investment costs/benefits at early project design stages. We also suggest that existing dynamic building simulation tools can be adapted to generate optimised MACCs in a relatively short time-frame. Whilst the focus here will be principally on non-domestic buildings, the discussed methodology is applicable to domestic buildings as well.

MARGINAL COST CURVES FOR BUILDING RETROFITS

The combined modelling of the cost and GHG-mitigation potential of building technologies is no longer an emerging field. In addition to being a specialized practise in the consulting sector, it has also been taken-up by governments seeking macro-level analyses of building stocks (Weiner, 2009), by various international organizations (OECD/IEA, 2009), and - of course - by the research community at large (Harvey, 2009; Ürge Vorsatz and Novikova, 2006; Marnay et al., 2007; Anderson et al., 2006; Ren and Gao, 2010)[1]. In the UK, one of the most visible outputs of macro-level studies has been the marginal abatement cost curve for the reduction of GHG emissions in the country's entire domestic and non-domestic buildings stocks (Pye et al., 2008). Illustrated in figure 1 for the non-domestic building stock, the MACC depicts the total, national-level GHG mitigation potential of key emissions-reduction measures against their marginal abatement cost (£ per tonne-CO_2 saved). Negative costs reflect positive returns-on-investment and are thus the most favourable technologies to support.

The MACC in figure 1 also seemingly depicts the cost and GHG-mitigation potential of a large number of technologies in a very simple format, relevant particularly for policy-makers. Using such a curve, analysts can presumably assess the approximate societal costs of meeting carbon reduction targets as well as provide benchmarking for carbon pricing schemes. They can identify which measures work best towards achieving a set target (e.g., emissions reductions) and which measures may require further financial incentives. For similar reasons, a MACC developed at the individual building-level may be helpful during initial retrofit planning stages. Just as a policy-maker would do so, individual building managers could use a tailored MACC to pinpoint the specific retrofit measures

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[1] These are only to name a few. The authors recognize many others have contributed to this field but cannot all be named here.

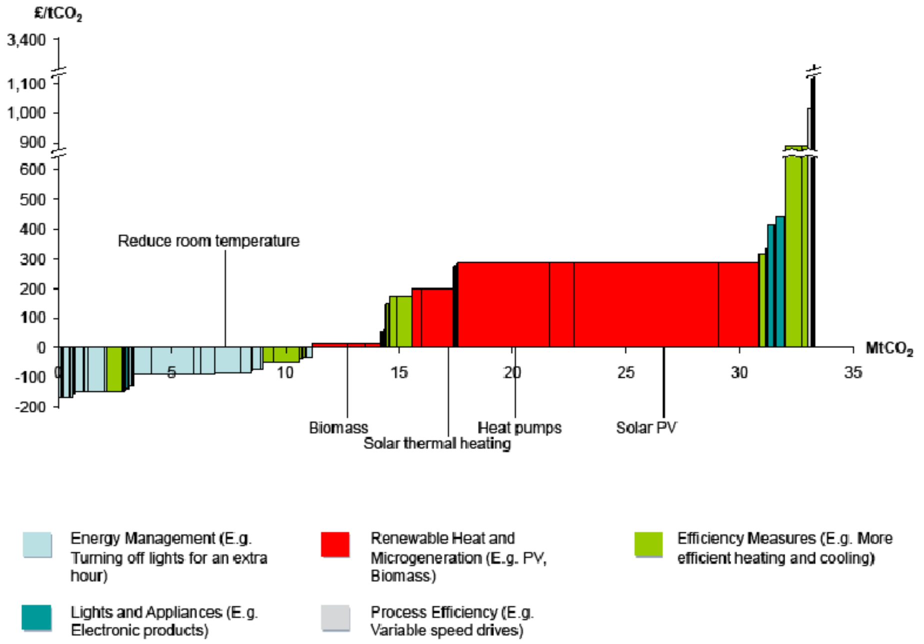

Figure 1: Marginal GHG abatement cost curve of the UK's non-domestic buildings sector, 2008 data, 20 year time horizon (Produced by Committee on Climate Change (Weiner, 2009))

that would meet targeted investment returns and GHG emissions reductions. In addition, a MACC would show the decision-maker the potential impacts of pursuing more or less ambitious interventions, a particularly useful feature. So far, there seems little evidence of MACCs being developed and used effectively for such purposes.

This may be due particularly to one factor. As will be discussed in the following sections, generating a true MACC requires extensive engineering modelling of numerous retrofit options as well as cost optimization to some degree. It is only recently that advances in building simulation optimizers and reductions in computational costs have made this feasible. It is also the result of this issue that existing methodologies for devising macro-level MACCs, which pre-date these recent advances, have required far-reaching engineering and cost assumptions that would not be appropriate for a single building study (Weiner, 2009).

GENERATING TRUE MARGINAL COST CURVES: AN OPTIMIZATION PROBLEM

In this work, we distinguish between the creation of - what we call - *true* and *illustrative* marginal abatement cost curves. For a discrete decisions problem, *true* MACCs are created by sequential optimisation of each step along a curve, as depicted by the example in figure 2. Starting from the zero-investment point, each step reflects the least-cost additional measure when combined with all preceding steps. The depicted costs from this process are *truly* marginal because their additionality to prior measures is explicitly considered. The figure also provides some explanation as to why such MACCs require larger simulation datasets to construct; one may need the modelling capability to simulate nearly all combinations of retrofit measures.

Illustrative MACCs differ in that they simplify interactions between measures in order to circumvent any requirement for large-scale optimisation and/or physical simulation. The UK MACCs, such as the one shown previously in figure 1, are an example of such curves. They were developed by assuming that the accepted marginal abatement cost of each plausible retrofit measure would be the most pessimistic value of two cases: 1) when no other measures would be installed; or 2) when all other measures would be installed. Because the additionality of measures along the MACC is not explicitly assessed, the costs and GHG mitigation potentials on such curves cannot be considered truly marginal.

TARGET-ORIENTED MARGINAL COST CURVES

Whilst the *true* MACC of figure 2 may be more accurate than any illustrative MACC, it may not be sensible, from the retrofit decision-maker's point of view, to generate a true MACC in such a manner only. Generating a MACC without establishing key investment targets, or economic constraints, may be either unwise or ineffective. For instance, an investor may be principally concerned with determining the best retrofit *option*[2] which meets some pre-established capital cost constraints and energy- or cost-reduction targets. The best (or optimum) option to achieve these goals may

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[2] a combination of one or more measures

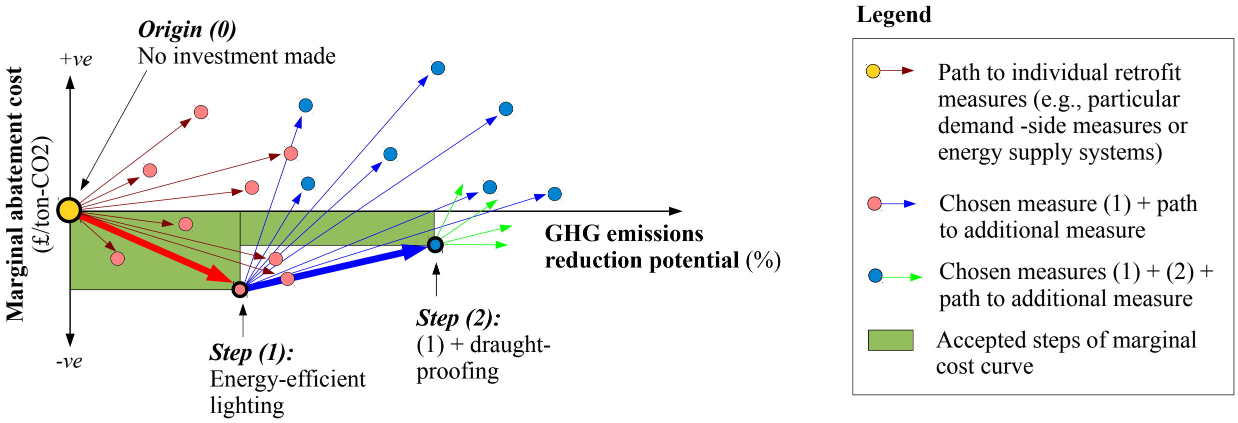

Figure 2: Process of creating true marginal abatement curves through sequential optimisation

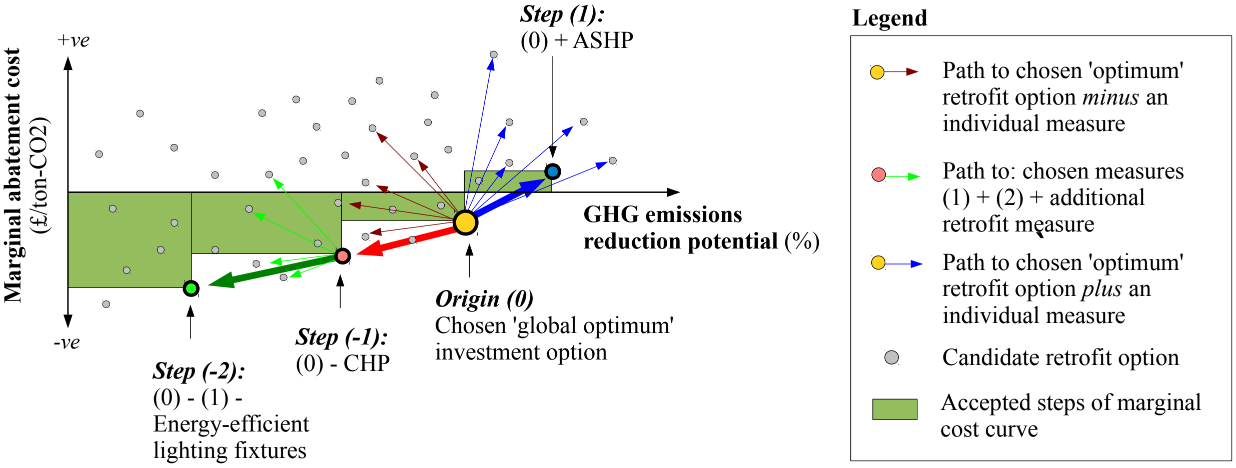

Figure 3: Process of creating true marginal abatement curves based on known targets

not necessarily include retrofit measures that would be identified using the sequential process described above and shown in figure 2.

The reason for this stems largely from the technical interactions between various retrofit measures. For instance, one may estimate that retrofitting a particular building's lighting fixtures with more efficient equipment would be a good individual measure from a cost perspective, though maybe not the best. Perhaps draught-proofing would be predicted as the single-best retrofit measure. However, one of the technical impacts of both measures - though to differing degrees - would be a change to the building's transient ratio of heating-to-electricity demand. This would impact the feasibility of a co-generation energy supply system, for better or worse. It could turn out, for instance, that a CHP system, when combined with energy-efficient lighting fixtures, would be more cost-effective than any option which includes draught-proofing.

Given this possibility, we propose an alternative approach to generating a MACC for constrained optimisation problems. Shown in figure 3, the process starts by first determining the best retrofit option that would meet the decision-maker's targets and then establishing this option as the origin data point of the MACC. Upon this step, the downstream and upstream portions of the cost curve would be found by removing and adding installed measures, repeating the sequential search process described earlier. The output curve would illustrate the marginal contribution of all retrofit measures required to meet the target, and would allow the decision-maker to view the impact of investing in measures beyond the target.

We will explore in the following sections how the various types of MACCs discussed in this paper compare to one another for a single building.

ENGINEERING AND COST OPTIMISATION MODEL

The energy and cost modelling undertaken for this paper has been done using the Decoupled Building Energy Retrofit Assessor (DeBERA), developed previously by the authors (Rysanek and Choudhary, 2012, 2013). The tool represents a set of sequential models designed to exhaustively simulate building retrofit options using dynamic building simulation software.

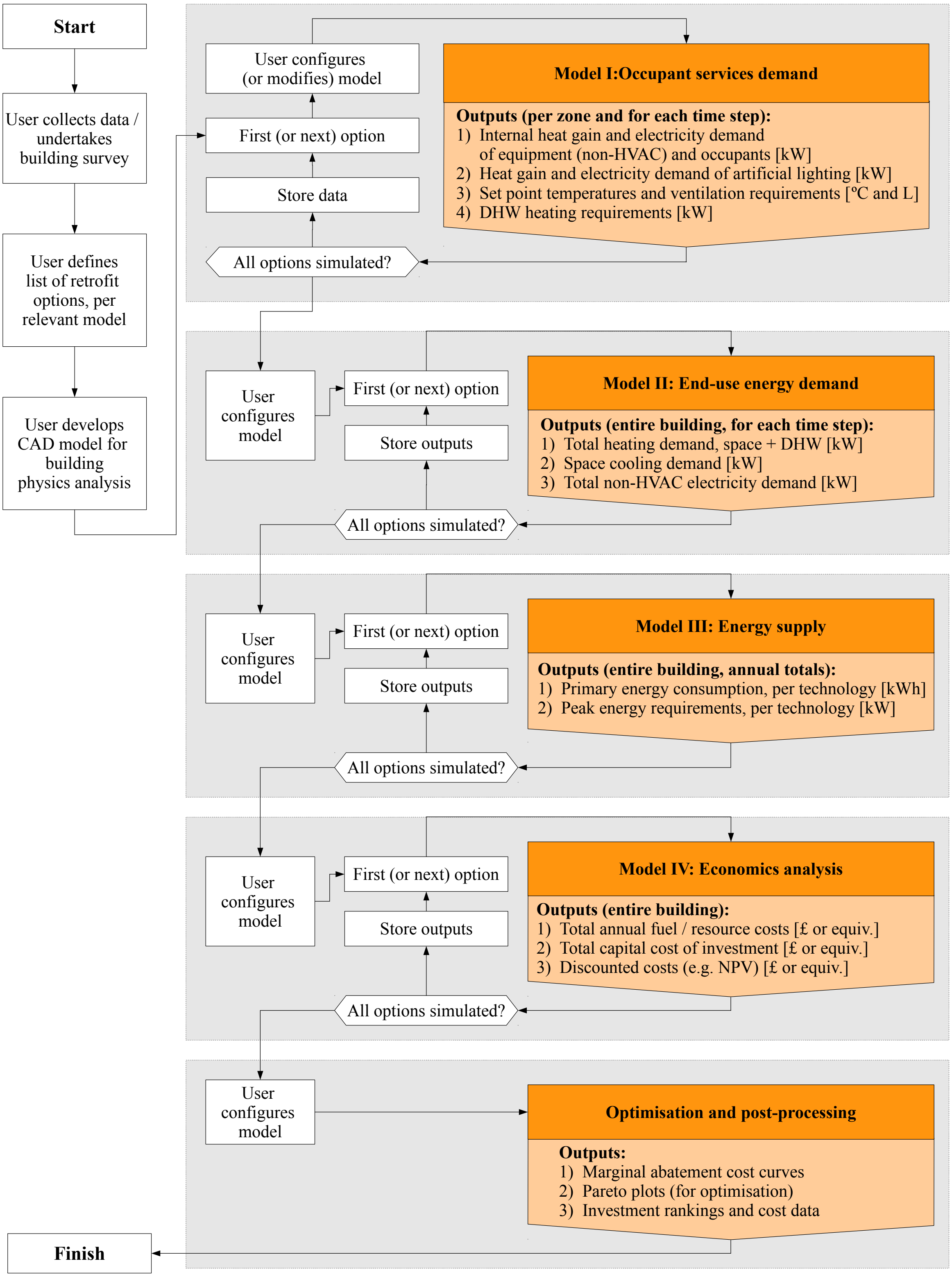

Figure 4: Process flow diagram of the Decoupled Building Retrofit Assessor (DeBERA); Methodology available in (Rysanek and Choudhary, 2012, 2013).

The tool separates the simulation of occupant behaviour, energy supply, and economics from the conventional building energy modelling environment, essentially reducing the number of simulation runs required by the multi-zone building physics engine (the most computational expensive component of the simulation process). A simulation flow diagram for DeBERA is provided in figure 4. DeBERA's development has been greatly influenced by a number of other research projects which have explored simulation and economic optimisation of building retrofit and design options in a similar manner. We highlight particularly the work of Horowitz et al. (2008) and their development of the BEopt and Opt-E-Plus packages.

EXAMPLE OF BUILDING-TAILORED MARGINAL COST CURVES

In the following pages, we will illustrate various types of MACCs generated for a particular, real-world building. The building, representing an ageing non-domestic office building in the UK, is described in table 1 and is depicted in its model format in figure 5.

Candidate refurbishment measures

A selection of candidate refurbishment measures is isolated and presented in table 2. Approximate costs are also shown, having been estimated from related literature and heuristic data sources, see (Rysanek and Choudhary, 2013).

Economic conditions

The retrofit analysis, which will examine the cost/benefits of all feasible combinations of retrofit measures, is governed by a set of economic conditions which are outlined in table 3.

Results

From the 15 candidate retrofit measures defined in table 2, approximately 38,000 combinations of measures are deemed feasible by the DeBERA model. With each combination, or option, carrying a unique marginal abatement cost and GHG mitigation potential, a scatter of the data - illustrated in figure 6 - depicts the range of values obtainable.

There can be numerous ways to parse the data presented in figure 6. As we aim in this paper to compare various techniques for constructing MACCs out of building simulation data, we begin by depicting the representative *illustrative* MACC of the given dataset. This is shown in figure 9, where the costs and GHG mitigation potentials of each measure have been assessed in isolation - ignoring any interactions with neighbouring measures. Carrying on, in figure 7, we depict the corresponding *true* MACC of the dataset, based on a sequential search of measures starting from the zero-investment point (see figure 2).

Figure 8 illustrates the effect of generating MACCs outward from an established target, as shown earlier by the process given in figure 3. Figure 8 depicts the least-cost pathway towards the retrofit option with the greatest GHG mitigation potential overall.

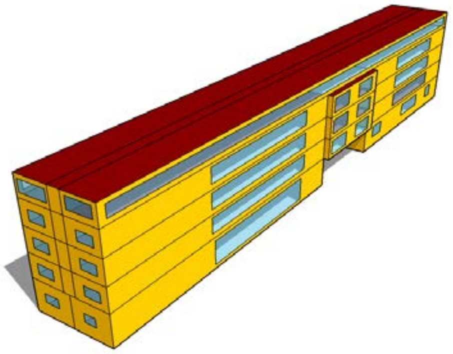

Figure 5: Representative TRNSYS3D model of study building

Table 1: Description of building and existing systems

Characteristic
Construction date: Between 1960-1961
Number of floors: Four
Total occupied floor area: 3,265 m^2
Building type: Mixed-use office building, with approximately 85 private office, 3 lecture rooms, one computer laboratory, a small cafeteria and library, meeting rooms and various IT/administrative areas.
Existing HVAC: Heating only, with centrally-controlled LTHW radiator system. A high-efficiency non-condensing boiler was installed in the late 1990s.
Building fabric: Limited insulation throughout, as per original construction; single-pane metal-framed glazing without weather-stripping.
Lighting: T8 fluorescent lighting is installed throughout, with manual control only. Public corridor lighting is left on usually 24/7.
Occupancy habits: Occupants work typical weekday hours, with modest overtime. Approximately 50% of computing equipment is left switched on 24/7.

Table 3: Economic conditions and constraints to analysis

Measure and description
Energy prices: 'Pessimistic' energy price projections, as set out in Rysanek and Choudhary **Tariffs:** Constant carbon tarriff of £12 / ton-CO$_2$
Subsidies: Via the UK Feed-in Tarriffs and Renewable Heat Incentives, a subsidy of £0.026/kWh is provided for thermal energy delivered by biomass and £0.13/kWh for solar PV
O&M costs: Included, as set out in Rysanek and Choudhary (2013)
Investment time horizon: 10 years (2012-2022)
Discount rate: 6%
Service life of retrofit measures: We assume the service life of all new equipment to be greater than 10 years

DISCUSSION

The illustration of MACCs in figures 7 to 9 provide an interesting perspective on the relevant costs and im-

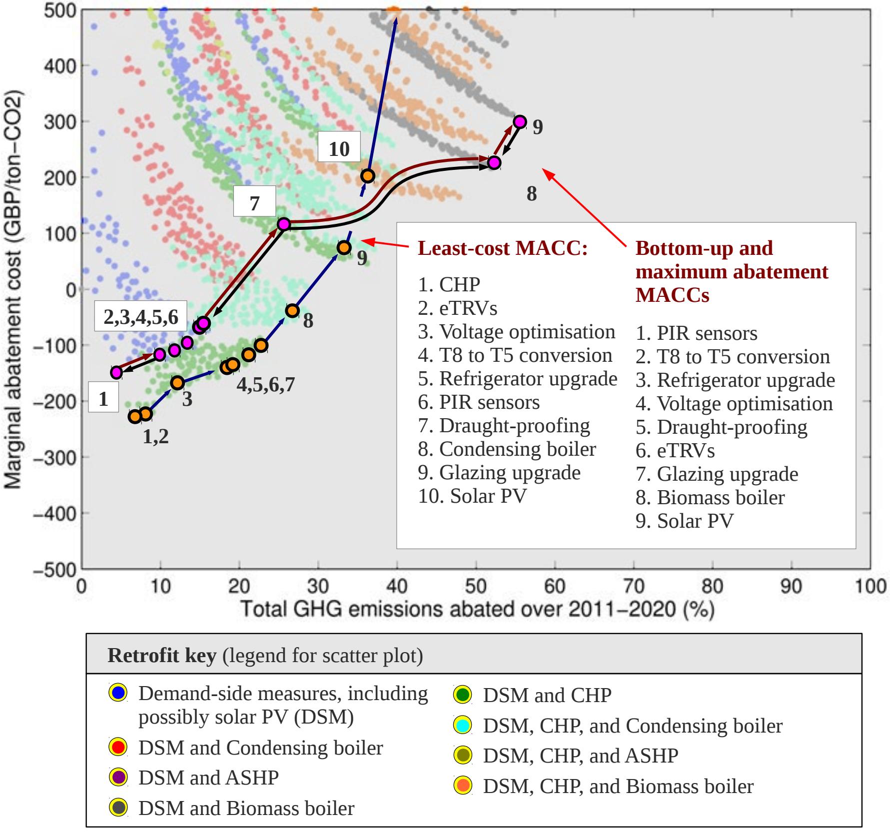

Figure 6: Comparison of chosen, true MACC pathways against scatter plot of all simulated options

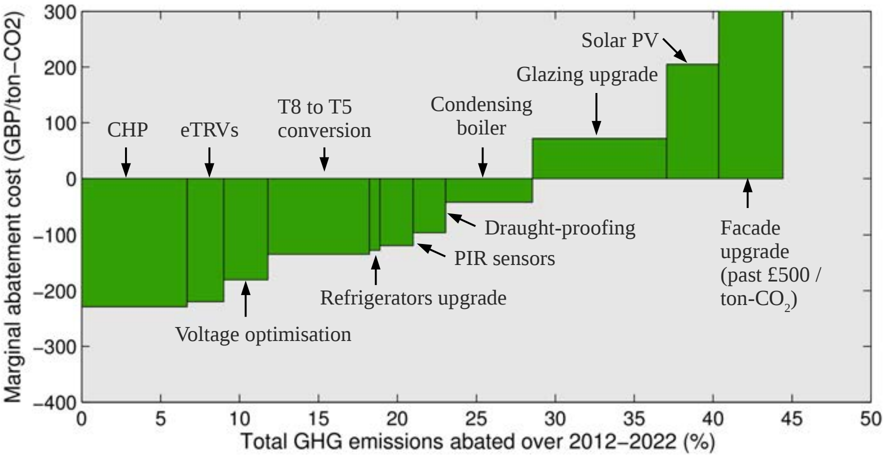

Figure 7: True marginal abatement cost curve, whether starting from no-investment or from option with maximum GHG abatement

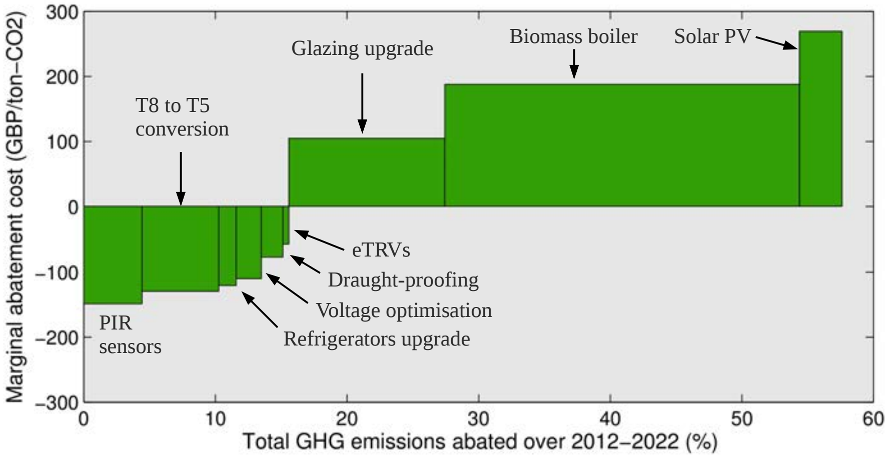

Figure 8: True marginal abatement cost curve, based on option with greatest GHG mitigation potential under £ 0/ton-CO$_2$

Table 2: Candidate refurbishment measures

Measure	**Description**	**Cost**
PIR sensors	Install PIR sensors in public areas	£5,000
T8 to T5	Convert all T8 lighting fixtures to T5 high ballasts	£14,000
Refrigeration	Upgrade all servery food refrigeration units with high-efficiency appliances	£4,000
Centralize IT	Create single, central facility for document printing and photocopying	£3,000
Replace roof	Decreases roof U-value from 1.1 W/m^{2}K to 0.22 W/m^{2}K	£80,000
Replace glazing	Decreases glazing U-value from 5.7 W/m^{2}K to 1.4 W/m^{2}K	£150,000
Refurbish façade	Decrease external wall U-value form 0.77 W/m^{2}K to 0.35 W/m^{2}K	£500,000
eTRVs	Adapt all building radiators with electronically-regulated TRVs, providing zone heating control	£18,000
Draught-proof	Inspect build air leakages and apply weather-stripping where needed	£10,000
Boiler	Maintain existing high-efficiency boiler	-
Biomass	Install biomass pellets boiler with automatic feeder	£420/kW
Condens. boiler	Install condensing boiler	£90/kW
CHP	Install small-scale co-generation plant without thermal storage	£350/kW
ASHP	Install air-source heat pump	£250/kW
Solar	Install 35-kW rooftop solar photovoltaic system	£4000/kW

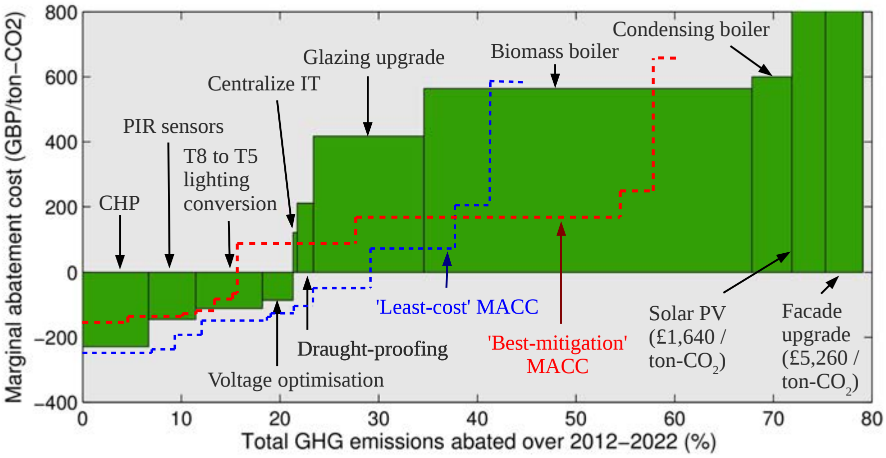

Figure 9: Illustrative marginal abatement cost curve (no technical interactions between measures

pacts of retrofit measures in achieving particular decarbonisation targets. Whilst it was expected to see the *illustrative* MACC differing greatly from the *true* cost curves - due to the lack of incorporating technology interactions between measures - the differences amongst the various *true* curves are more striking. For instance, whilst combined heat-and-power (CHP) is identified to be the least-cost measure in figure 7, it is interesting that combining CHP with eTRVS would provide greater cost savings than both in isolation (see figure 9, for which eTRVs are not even considered a GHG-saving measure in isolation). This is likely due to the effect eTRVs would have on transient thermal energy demand, making the building's ratio of heating-to-electricity demand more favourable for CHP applications. We also see in the *true* MACCs that cost savings attributed to low-hanging fruit can be put towards more expensive carbon reduction measures. This suggests that, when examining multiple retrofit options *and* including the effects of technology interactions, one may better identify deeper energy and GHG emissions savings. Granted, we have not examined the effect of high capital costs - and the access to capital - as a barrier to investment, nor other similar barriers in this study.

Overall, two discussion points emerge from these initial examples of building-tailored MACCs. *The first point* refers to the relevance of using a single MACC for any type of cost analysis. It was shown that, for one building alone, there can be multiple possible pathways to reducing GHG emissions cost-effectively. Two different *true* MACCs were produced to show this, though many more could have been generated had we introduced further sets of investment targets and constraints. *The second point* refers to the value of MACCs generated from detailed building simulations. Figure 9 showed the creation of an illustrative MACC based on a similar methodology to that used by the CCC/BRE/AEA in their generation of MACCs for the UK building-stock[3]. When compared to the true MACCs generated in this study, there is a striking difference between all results; the true MACCs correlate poorly to the illustrative MACC depicted. Whilst this information relates only to a single building versus an entire building stock, it suggests that one would be ill-advised to explicitly ignore the technology interactions of retrofit measures when generating such MACCs.

CONCLUSIONS

In a simple study, we have illustrated how there can exist multiple technology pathways for meeting deep energy and emissions reduction targets in buildings. What we hope has been particularly highlighted in this paper is the value of constructing marginal abatement cost curves using methodologies which explicitly consider both engineering interactions between refurbishment measures and the impact of long-term economic targets or constraints.

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[3] see figure 1