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underlying assumptions regarding costs and emissions allocations.

7 *Keywords:* *MACC*, Material efficiency, Policy guidance

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## 8 **1. Introduction**

9       Marginal abatement cost curves (MACCS) seek to convert the cost of different green-  
10   house gas (ghg) emissions abatement measures into comparable, £/tco<sub>2</sub>, units. This is  
11   helpful for prioritising measures, but the application of the method has been heavily  
12   criticised. Concerns, expressed by Kesicki and Strachan (2011-12) and Ekins et al.  
13   (2011) amongst others, include the lack of transparency regarding underlying assump-  
14   tions (in particular in high profile work by McKinsey (2009)), the failure to account  
15   for the interaction between strategies (which can lead to double-counting in reduction  
16   potentials), and the limited representation of uncertainty. Despite their limitations,  
17   MACCS, as for example Figure 1, continue to be used to inform the policy community of  
18   the cost of disparate emissions abatement options. For example Eory et al. (2015) use a  
19   MACC to assess the potential contribution of measures in the agricultural sector to the UK  
20   5<sup>th</sup> Carbon Budget period and the UK government continues to estimate annual traded  
21   carbon values for the purpose of policy appraisal (DECC 2009, Department for Business,  
22   Energy & Industrial Strategy (BEIS) 2018 ). Given the emphasis on integrated assessment  
23   models in the IPCC process (Clarke and Jiang, 2014), measures that cannot be readily  
24   incorporated into these models in the form of MACCS may not be given due attention in  
25   the analysis of mitigation pathways to meet the international climate commitments set  
26   by the Paris Accord.

27       In this context, the challenge is not only to improve MACC transparency and methods  
28   but also to ensure that MACCS can be used to describe the full gamut of emissions options  
29   available. Strategies involving greater efficiency in the use of energy-intensive bulk ma-  
30   terials (such as steel) have been shown to offer significant mitigation potential but remain  
31   under-represented in MACCS. As explained by Allwood et al. (2011), steel accounts for a  
32   quarter of global industrial carbon emissions and there is ample opportunity to improve

the efficiency with which the metal is used, in particular in the construction sector (where approximately half of the steel in office buildings is surplus to requirements (Moynihan and Allwood, 2014; Dunant et al., 2018a) and the automotive sector (where 40 % of steel is scrapped along supply chains (Horton and Allwood, 2017)). Although model derived cost curves that explore the relationship between resource efficiency and aggregate GDP exist (Distelkamp and Meyer, 2014), to our knowledge there are no studies that draw on bottom-up engineering cost data to explore the implied marginal cost of abatement of specific material efficiency measures.

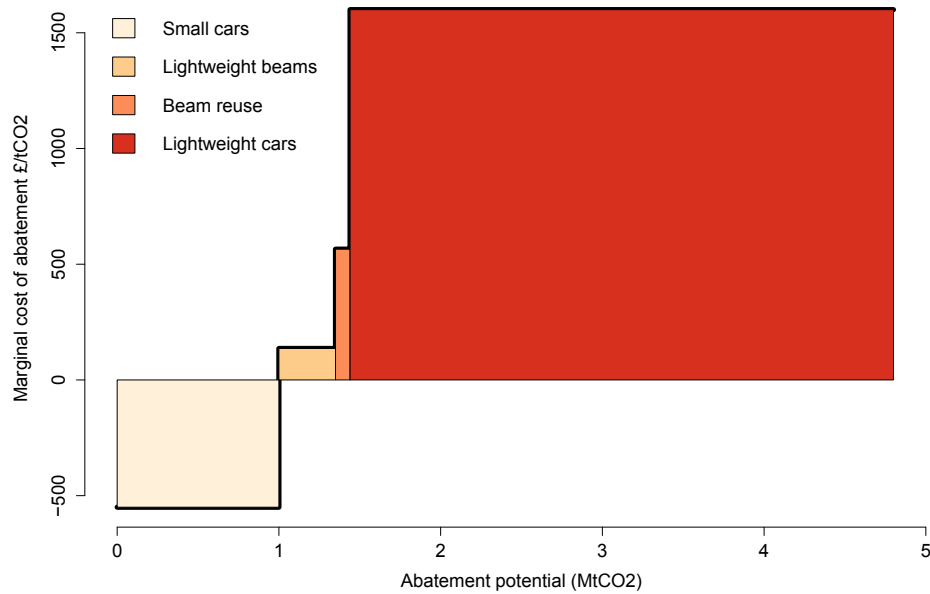


Figure 1: Material efficiency measures on a traditional MACC

In light of these findings, this paper seeks both to improve the MACC methodology and to extend the scope of MACCS to incorporate material efficiency measures. By proposing a new MACC methodology and applying it to assess the marginal cost of abatement of four strategies that improve material efficiency in the the use of steel in the UK, we hope to answer the following research questions:

- What information must be provided in order to be transparent about the assump-

- 47 tions underlying the proposed material efficiency  $MACC$ ?
- 48 • What effect does incorporating uncertainty and accounting for the interplay be-
- 49 tween strategies have on the material efficiency  $MACC$ ?
- 50 • How does the marginal cost of material efficiency strategies compare to the
- 51 reported cost of other abatement options?

## 52 2. Method

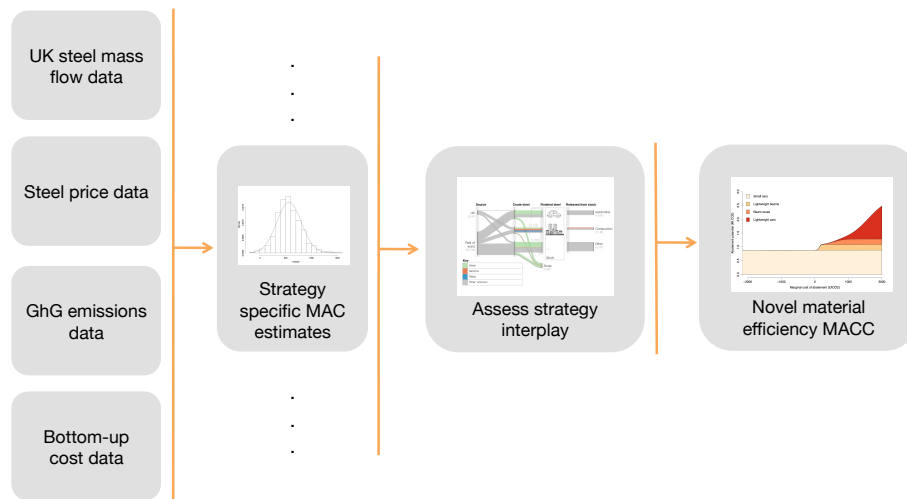


Figure 2: Proposed material efficiency  $MACC$  method

53 Figure 2 gives an overview of the proposed method. The following steps are used to

54 draw the curve.

- 55 1. For each material efficiency measure, we collect bottom-up data on measure
- 56 specific costs.
- 57 2. We verify whether these measures do not affect the use patterns of the final
- 58 products, and their effects are not dependent on social factors.
- 59 3. We combine these measure-specific cost assumptions with cross-measure assump-
- 60 tions.

- 61 4. To assess which measures interact with each other we map the material efficiency  
62 measures to be included in the MACC onto a Sankey diagramme and identify  
63 measures that relate to inter-dependent flows.
- 64 5. To account for the interactions between strategies, we express the potential for  
65 each strategy in terms of common parameters. We then estimate the degree to  
66 which measure  $a$  can be applied, for a given application of measure  $b$  ( $\eta_{a|b}$ ) and  
67 use this to restrict the emissions abatement potential.
- 68 6. Finally, to build the MACC we combine CDF cost curves for each of the strategies,  
69 taking into account the interplay between the strategies.

## 70 2.1. *Estimators, variability and uncertainty*

71 We lay out here how particular difficulties or ambiguities can be resolved, depending  
72 on the nature of the data.

73 *Choice of estimators.* To account for both the uncertainty in the data and its variability  
74 (price fluctuations over time, aggregation of technological variants), the cost and carbon  
75 data should be translated to probability distributions. The choice of the distributions  
76 can be done after inspection of the data, to provide the best fit in each case and have  
77 valid bounds. Provided a sufficiently large dataset, it can be preferable to use smoothed  
78 density estimators, which would exploit the real distributions in price and carbon, but  
79 for the purpose of this methodological paper, using simple univariate distributions is  
80 sufficient.

81 *Distinguishing between different types of variability and uncertainty.* A single MACC can  
82 only be drawn for a particular set of contextual parameters *e.g.* the underlying price of  
83 labour and material, the cost of capital and the state of technology. Given uncertainty  
84 over these contextual parameters, they must be fixed in order to draw a particular curve  
85 that describes a particular state of the world. Even when these parameters are fixed  
86 we would expect the cost of a particular strategy to vary to reflect any economies and

87 diseconomies of scale as the strategy is exploited. We therefore distinguish between  
88 the “variability” in strategy costs (to be taken into account in a particular MACC) and  
89 “uncertainty” in cross-strategy contextual parameters (to be taken into account across  
90 different curves). This distinction is particularly important for dealing consistently with  
91 interplay between strategies. If uncertain cross-strategy parameters are not fixed across  
92 strategies, there is a risk that incompatible facts are assumed to happen simultaneously  
93 *e.g.* that a high steel price application of one strategy is assumed to be exploited at the  
94 same time as a low steel price application of another strategy.

## 95 2.2. *Identifying the policy impetus within an economic paradigm*

96 The marginal cost of abatement depends in part on the policy impetus assumed. This  
97 could be an existing policy mechanism (*e.g.* the EU ETS — the European Union Emissions  
98 Trading Scheme), a theoretical construct (*e.g.* a universal carbon price on all emissions,  
99 globally) or a new form of regulation (*e.g.* specifying a maximum weight standard for  
100 car bodies). The chosen policy impetus has implications for the types of costs taken into  
101 account and for the way that these costs are passed on along supply chains. For example,  
102 we assume that the smaller car strategy is motivated by a regulation that sets a maximum  
103 weight for each vehicle type. As a result we only estimate the change in the price of the  
104 vehicle. The disutility due to constraining the choice of the consumer remains hidden.  
105 If instead this strategy were to be motivated by a carbon price this disutility would have  
106 to be taken into account and consumers would have to be compensated to overcome this  
107 loss in welfare.

108 If the strategy were to be motivated by a particular carbon pricing scheme, *e.g.* the  
109 EU ETS, then constraints on the way that this scheme is implemented (*e.g.* geographic  
110 jurisdiction and sectoral coverage) and the impact of related policies (*e.g.* the compen-  
111 sation for indirect carbon costs in heavy industries) should be taken into account in  
112 calculating the carbon price required to instigate change. Skelton and Allwood have  
113 shown that cost-pass-through of material efficiency in the EU ETS is inefficient, meaning

114 that simply converting the cost of implementing downstream material efficiency mea-  
115 sures into a carbon price (referred to as the shadow price of carbon) will under-estimate  
116 the costs of incentivising measures through this particular mechanism.

117 As explained by Skelton and Allwood, the rate of cost-pass-through depends in part  
118 on the economic paradigm assumed: firms operating under perfect competition have  
119 no choice but to fully pass on their costs whereas firms with some market power face  
120 a strategic decision over whether to absorb cost increases in profits or pass them on to  
121 their customers. Economic paradigm also has a large bearing on the way that costs are  
122 interpreted. For example, in estimating the cost choosing the lightest beams permitted  
123 by building codes we assume that designers are rational in their current decisions and  
124 consequently that the additional cost paid for steel that is not required in buildings must  
125 equal the benefit of excess steel (*e.g.* economies of scale in purchasing and flexibility  
126 in the face of possible future design changes). Thus the “cost” can be interpreted as a  
127 “benefit”.

### 128 **3. Estimating the material efficiency MACC – steel use in the UK**

129 To demonstrate the usefulness of the proposed approach, we apply it to a specific  
130 case not well captured by more traditional MACC: steel use in the UK. We focus on four  
131 specific material efficiency measures for our exemplar curve: reuse of steel sections in  
132 construction, choosing minimal steel beams, lightweight vehicles and choosing smaller  
133 cars. The measures were chosen to represent the two key steel end-use sectors in  
134 the UK: the automotive and construction industry. We combine measure-specific cost  
135 assumptions with cross-measure assumptions regarding steel prices, scrap prices and  
136 the emissions intensity of steel production to yield strategy specific marginal abatement  
137 cost (MAC) distributions.

138 The process of populating the curve for four material efficiency measures illustrates  
139 the types of assumptions that have to be made in order to build the material efficiency  
140 MACC. In the discussion section we draw together these assumptions to build a possible

standard for documenting MACC assumption, explore the value of the novel MACC method proposed and compare the resulting material efficiency abatement cost estimates to other ghg emissions abatement options.

### 3.1. Overview of strategy specific cost estimates

Table 1 gives a summary of the parameters used to estimate the marginal cost of abatement for each of these measures. The resulting marginal abatement cost distributions are given in Table 2. Full details of the assumptions and data sources that underpin these cost estimates are provided in the Supplementary Information and briefly summarised below.

Table 1: MAC cost assumptions. The distributions used are Uniform,  $U(\min, \max)$ , Triangular,  $Tri(\min, \max, \text{peak})$ , Normal,  $N(\mu, \sigma)$ , and Log-Normal  $LN(\mu, \sigma)$ .

Strategy	Cost Measure	Ab.	Units	Estimate
Beam reuse	Deconstruction	$c_d$	£/t fin. steel	$\sim U(70,147)$
	Reconditioning	$c_r$	£/t fin. steel	$\sim U(247,376)$
	Transportation	$c_t$	£/t fin. steel	$\sim U(44,50)$
	Location premia	—	Excluded	—
	CE marking costs	—	Excluded	—
	Scheduling costs	—	Excluded	—
Lightweight beam	Cost of excess steel	$\beta$	% of $p_s$	$\sim Tri(18,81,51)$
	Rationalisation benefit	—	Inferred	—
	Insurance change design	—	Inferred	—
hss car body	Lightweighting cost	$c_l$	£/t fin. steel	$\sim U(2490, 4270)$
	Use phase mass cost saving	$p_u$	£/t steel saved	$\sim U(-1500,-7000)$
	Powertrain cost savings	—	Excluded	—
Smaller car	Vehicle price	$p_v$	£/t steel	$\sim Tri(-240K, 52K, 43K)$
	Car body price	$\gamma$	% of $p_v$	$\sim Tri(1,6,3)$
	Use phase mass cost saving	$p_u$	£/t steel saved	$\sim U(-1500,-7000)$
All	Steel section price	$p_s$	£/t fin. steel	$\sim LN(6.1, 0.2)$
	Steel scrap price	$\alpha$	% of $p_s$	$\sim N(41, 9)$
	Emissions BF-BOF	$m_1$	tCO <sub>2</sub> /t cr. steel	$\sim N(2.25, 0.48)$
	Emissions EAF	$m_2$	tCO <sub>2</sub> /t cr. steel	$\sim N(0.41, 0.07)$
	Car use phase emissions	$m_u$	tCO <sub>2</sub> /t crude steel	$\sim U(0.52, 0.64)$

*Beam reuse.* The physical properties of steel beams do not deteriorate over time unless beams are exposed to extreme conditions such as fire. When a building is no longer required it can be deconstructed to extract the beams to be reconditioned for reuse in new



Table 2: Measure specific cost distributions. The detail of the formulae and the values for the various coefficients are found in the SI.

Measure	Sector	Emissions savings	MACC distribution	MACC equation
Beam reuse	Construction	Embodied	$\sim N(565, 238)$	$\frac{(p_s \alpha + c_d + c_r + c_l) - p_s}{m_2}$
Lightest beam	Construction	Embodied	$\sim N(136, 54)$	$\frac{\beta \cdot p_s}{(0.74 \cdot m_1 + 0.26 \cdot m_2)}$
hss car body	Automotive	Embodied	$\sim N(1600, 472)$	$\frac{c_l}{m_1}$
	Automotive	Embodied & use-phase	$\sim N(-338, 598)$	$\frac{c_l + c_u}{m_1 + m_u}$
Smaller car	Automotive	Embodied	$\sim N(-550, 864)$	$\frac{\gamma c_v}{m_1}$
	Automotive	Embodied & use-phase	$\sim N(-2135, 1150)$	$\frac{\gamma c_v + c_u}{m_1 + m_u}$

buildings. Only a small fraction of beams are currently reused in the UK. A survey of UK demolition contractors by Sansom and Avery (2014-06) revealed that 5 % of beams were reused in 2012. Instead the vast majority of buildings are demolished, damaging the beams, meaning that they have to be recycled rather than reused. This was the end-of-life route for 93 % of beams in the UK in 2012 (Sansom and Avery, 2014-06). The deconstruction premium, reconditioning costs and transportation premium reported in Table 1 were taken from Dunant et al. (2018b). These cost estimates are based on a set of 30 interviews with architects, structural designers, construction contractors, fabricators, steel stockists and demolition contractors. All costs are reported relative to a reference case: demolishing the unwanted building and recycling the beams, and specifying new beams for the new building.

*Lightweight beam.* Design codes set performance criteria for beams that make up steel buildings. These codes include safety margins that take into account the risk of failure. Buildings could be designed to use the minimum amount of steel required to meet these performance criteria but instead tend to exceed these criteria. Moynihan and Allwood assessed utilisation of over 12,000 beams and columns in 23 building designs, and found that on average 46 % of steel in beams was surplus to the requirements of design codes. More recent data on 3,600 beams in 30 commercial office and educational projects analysed for the Innovate UK Lightweighting Project found 53 % of steel to be surplus to requirements on average Dunant et al. (2018a). The average cost of the excess steel in

173 these buildings was £19 per beam ranging from £1 - 419 per beam. Structural engineers  
174 may choose to specify more steel than is technically required in order to reduce overall  
175 costs by simplifying design and fabrication requirements (a practice referred to as  
176 'rationalisation') or to allow for greater flexibility regarding the final design. Rather than  
177 evaluating these costs on a case-by-case basis, structural engineers tend to use rules of  
178 thumb to guide their design. For example Gibbons (1995) proposes that sections should  
179 be rationalised if the total increase in weight is less than 20 %, and, more conservatively  
180 Needham (1977) recommends rationalisation up to a 10 % weight increase for "small  
181 jobs" and 5 % weight increase for "medium sized jobs". To generate the MAC distribution  
182 in Table 2 we assume that designers behave rationally and so infer that at the margin,  
183 the cost of excess steel in the building must equal the benefit of rationalisation and the  
184 benefit of flexibility to make late alterations to designs.

185 *High strength steel car-body.* Innovations in metallurgy have improved the technical  
186 properties of steel, meaning that it is possible to make lighter vehicles. Current material  
187 choices in the automotive sector are driven by material costs, design vision and the  
188 desire to innovate. Given the different properties of materials, substituting one material  
189 for another requires full vehicle redesign. The Future Steel Vehicle project by the  
190 Automotive arm of the World Steel Association (World Auto Steel, 2011) developed full  
191 engineering designs for a lightweight steel-intensive electric vehicle using high strength  
192 steels (>500 MPa) and advanced high strength steels (>550 MPa). The project sought to  
193 achieve a 35 % body structure weight saving relative to the baseline vehicle. Focussing  
194 on manufacturing costs (excluding savings associated with the electric powertrain)  
195 the study found an average cost of weight saving of \$7.12/kg. A study by McKinsey  
196 (2012) estimates the cost of converting to high strength steels at €3/kg. Converting both  
197 the World Auto Steel (2011) and the McKinsey (2012) findings (converted to Pounds  
198 Sterling) gives a cost range of £2.49-4.27/kg. The upper limit of this range is given by the  
199 World Auto Steel (2011) result regarding changes in part cost. It excludes all powertrain

200 cost savings and is likely to be an over-estimate of vehicle costs for a lightweight internal  
201 combustion engine car as we would expect some cost savings resulting from a smaller  
202 internal combustion engine. Use-phase cost savings associated with the lighter vehicle  
203 weight can be included. European legislation takes these savings into account in setting  
204 “limit value curves” that define emissions standards as a function of kerbweight. The  
205 slope of the limit value curve is 0.0457 gco<sub>2</sub>/km/kg vehicle (European Environment  
206 Agency, 2016). The average car in the UK travels 12,700 km/year implying a 0.58 kgco<sub>2</sub>  
207 saving per year, per vehicle kg.

208 *Smaller car.* There are many different types of cars within the vehicle fleet. Demand  
209 for passenger kilometres could be met by small cars within the existing offering. In this  
210 section we explore the implications of customers buying the lightest weight steel option  
211 currently available within their chosen vehicle segment (*e.g.* sports car, large family  
212 car, city car). In reality consumers are free to choose from a range of vehicles offered  
213 by manufacturers depending on their preferences and budget constraints. McKinsey  
214 (2012) state that consumers have “limited willingness to pay for weight reduction”  
215 suggesting, that kerbweight is not an important determinant of choice. Combining data  
216 on car-body mass (from the Euro Car Body Conference), vehicle price (from various  
217 sources documented in the Supplementary Information) and on the composition of the  
218 UK vehicle fleet from Lansley (2016-01), reveals that downsizing to the lightest steel  
219 vehicle within the chosen segment would result in a 12 % reduction in average vehicle  
220 mass at an average cost saving of 43 £/kg. Only a fraction of the retail price of a vehicle  
221 is associated with the cost of the car body structure. von Thaden et al. (2017) estimate  
222 the cost of the body-in-white (biw) of a mass-produced European compact vehicle at  
223 approximately £630 per vehicle, which represents on average 3 % of vehicle price. Only  
224 taking into account this biw cost share would imply an average cost saving of 1.3 £/kg.  
225 This cost saving is consistent with assuming that customers buy vehicles with similar  
226 features to their first choice vehicle but a smaller body-in-white, meaning that they only

227 realise cost savings associated with the smaller car body.

### 228 3.2. Accounting for interaction between strategies

229 The Sankey diagram in Figure 3 is based on data from Serrenho et al. (2016-02) and  
 230 shows UK steel mass flows focussing on the two key sectors of interest: the construction  
 231 sector and the automotive sector. It shows which steel mass flows are affected by each  
 232 of the material efficiency measures. Mapping the measures onto the steel mass Sankey  
 233 is helpful as it reveals which measures inter-relate. Whether or not adjustments have to  
 234 be made to account for the interdependencies of these strategies then depends on the  
 235 specific case.

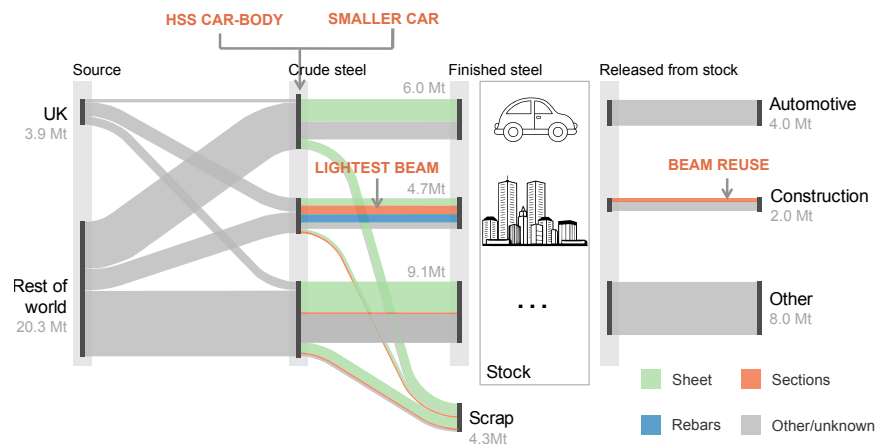


Figure 3: Material efficiency measures mapped onto the the UK steel mass flow sankey.

236 The lightest beam strategy and the beam reuse strategy both relate to steel section use  
 237 in the Construction sector. The effect of choosing the lightest beam on the potential for  
 238 reuse is mediated by the building stock. As the average life of a building is approximately  
 239 40 years and as both strategies relate to the use of standardised (as opposed to bespoke)  
 240 beams, we assume that the two strategies are independent. This means that we are  
 241 effectively assuming that the specification of beams that are released from stock for  
 242 reuse can be incorporated into lightweight new building designs.

243 In the automotive sector both strategies — choosing the smaller car in the chosen  
 244 vehicle segment, and specifying a high strength steel car body — relate to the same mass  
 245 flow. Both strategies depend on the mass of the average car and so the extent to which  
 246 one strategy can be applied depends on the extent to which the other strategy has been  
 247 applied. As the costs of the smaller car strategy are less than the cost of specifying high  
 248 strength steels, we assume that the smaller car strategy is implemented first. Assuming  
 249 that the smaller car strategy (A) can reduce the average weight of vehicles by 12 % the  
 250 extent to which the high strength steel strategy (B) can be applied is given by:

$$\eta_{B|A} = 1 - (\gamma_A \cdot 0.12) \quad (1)$$

251 Where  $\gamma_A$  is the fraction (ranging from 0 to 1) that denotes the extent to which the  
 252 smaller car strategy is applied. If strategy A is not applied at all, strategy B can be  
 253 applied in full; if strategy A is fully deployed, the gains of strategy B are at most 88 %  
 254 of its theoretical maximum.

### 255 3.3. Allocating emissions to steel savings

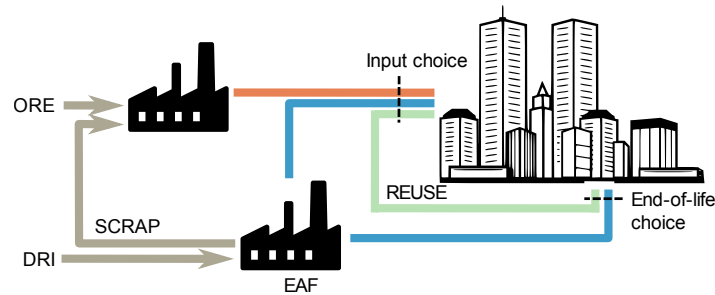


Figure 4: Schematic showing emissions savings associated with reuse of steel sections

256 There are multiple methods that can be used to allocate emissions savings to material  
 257 efficiency strategies. Like costs, all emissions savings must be measured relative to a  
 258 reference case that represents what would have happened in the absence of the strategy  
 259 being applied. By way of example, Figure 4 gives an overview of the steel flows

260 associated with replacing a building. The figure shows that when a building is built, steel  
261 can be specified from three different sources: primary steel from a blast furnace-basic  
262 oxygen furnace(BF-BOF), secondary steel from an electric arc furnace (EAF) or reused  
263 steel. At the end of a building's life the choice is more constrained: steel can either be  
264 sent for reuse or for recycling. Based on Figure 4, there are different ways to allocate  
265 emissions savings to steel reuse in buildings:

- 266 • Displaced input method: if the input choice is considered in isolation, increasing  
267 the share of reused steel that is specified would displace both steel from iron ore  
268 and from recycled scrap
- 269 • Displaced scrap method: taking into account the more constrained choice at the  
270 end of a building's life, steel reuse can only displace steelmaking from recycled  
271 scrap and not steelmaking from iron ore
- 272 • Future reuse potential method: steel has the potential to be reused indefinitely  
273 therefore the choice to specify steel (rather than other materials such as concrete  
274 that has no current viable route for reuse) facilitates future reuse and/or recycling.  
275 Methods such as BS EN 15804 (2012) 'Module D' and PAS 2050 (2008) attempt  
276 to attribute future potential savings to the current decision.

277 We use the displaced scrap method for the beam reuse strategy as this method does  
278 not rely on uncertain future events and as it takes into account the more constrained  
279 choice at the end of a building's life, in line with Sansom and Avery (2014-06) findings  
280 that over 90 % of structural steel in buildings is recycled or reused at the end-of-life. The  
281 remaining material efficiency strategies examined in this paper relate to input decisions  
282 and so we use the displaced input method for these measures. Table 3 gives a summary  
283 of the maximum potential material and so emissions savings that can be achieved by  
284 each of the measure. In order to allow measures to be compared, all steel savings are  
285 calculated in crude steel equivalent units. This means that any measures that occur

286 further downstream along the mass sankey diagram in Figure 3 save not only the finished  
 287 steel in the relevant product but also the yield losses along the supply chain making  
 288 those products.

Table 3: Measure specific material and ghg emissions savings. Sources for these values can be found in the sr  
 in the the sections corresponding to each strategy.

Measure	Material saving (Mt cr. steel eq.)	Emissions displaced	Emissions saving (Mtco <sub>2</sub> )
Beam reuse	0.22	100 % EAF	0.09
Lightest beam	0.20	26 % EAF; 74 % BF-BOF	0.35
hss car body	1.50	100 % BF-BOF	3.40
Smaller car	0.44	100 % BF-BOF	1.00

### 289 3.4. Building the new MACC

290 Figure 5 shows the resulting marginal abatement cost curve for the four material  
 291 efficiency measures. The top panel shows the graph which only account for emissions  
 292 savings associated with reduced demand for steel. The bottom panel shows the same  
 293 MACC when also taking accounting for use-phase costs and emissions. These only affect  
 294 the automotive sector strategies as the use-phase emissions of buildings is not affected by  
 295 the proposed changes in frame construction. The marginal abatement cost distributions  
 296 used as input are given in Table 2 and the greenhouse gas emissions abatement potentials  
 297 in Table 3. Possible double counting due to the interdependence between the high  
 298 strength steel car-body measure and the smaller car strategy is corrected for as per  
 299 Section 3.2. Removing double-counting reduces the abatement potential by 0.38 Mtco<sub>2</sub>  
 300 in the steel emissions only case and 0.75 Mtco<sub>2</sub> when accounting for use phase savings,  
 301 equivalent to 8 % and 15 % respectively of the total abatement potential.

302 Figure 6 shows a zoomed in version of three material efficiency MACCs that assume  
 303 different steel prices ranging from £640 in the high price scenario to £310 in the low  
 304 price scenario (covering for 95 % of cases in the assumed cost distribution). The graph  
 305 shows that the beam reuse strategy becomes more preferable in the high steel price  
 306 scenario. This is to be expected as, in accordance with the beam reuse equation in

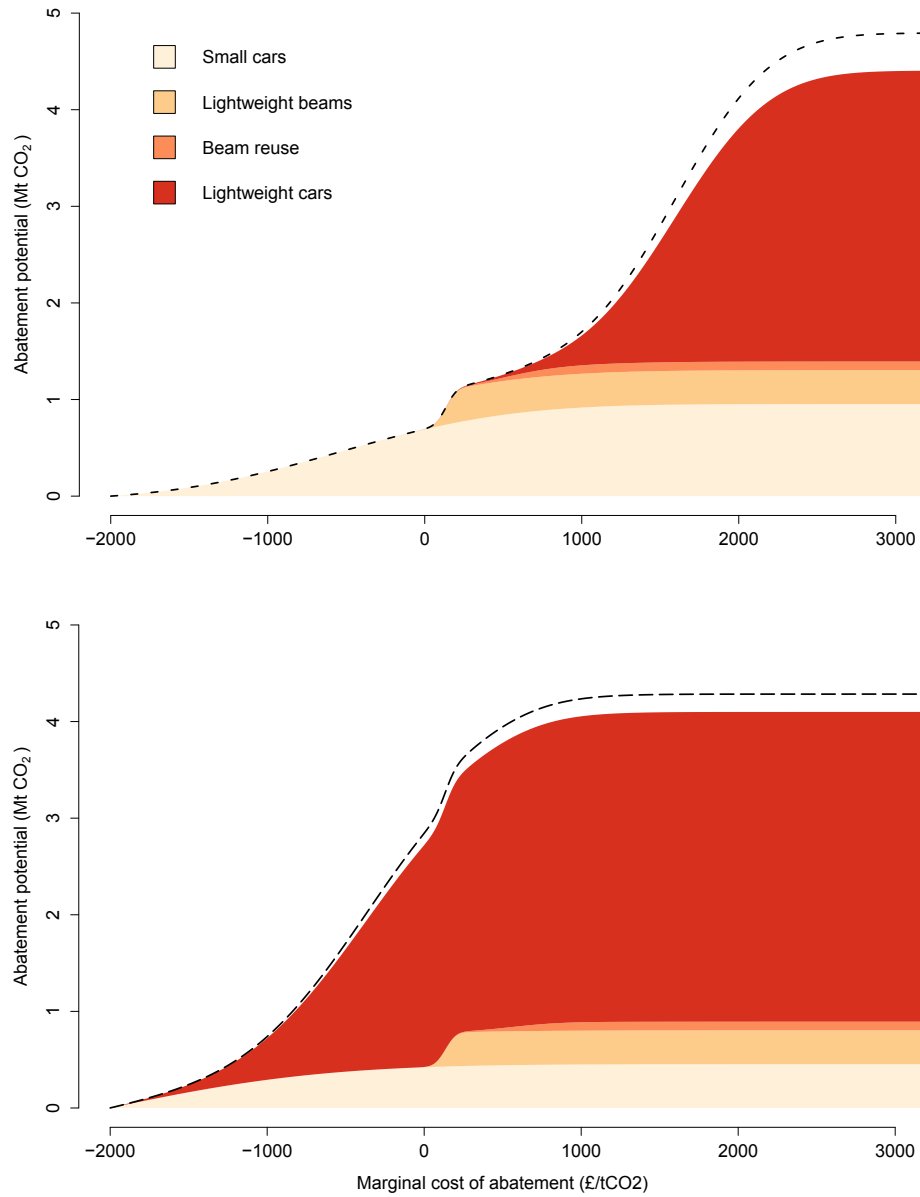


Figure 5: Novel material efficiency *MACC* accounting for the interdependence between strategies (steel emission savings only on top; including use-phase cost and emissions savings at the bottom). The dashed line indicates the emissions when the interdependency between strategies is not accounted for. Example code to generate these figures is given in 5.

307 Table 2, a higher steel price raises the cost of the reference case strategy (specifying  
 308 primary steel), increasing the incentives for reuse. Rather counter-intuitively, Figure 6



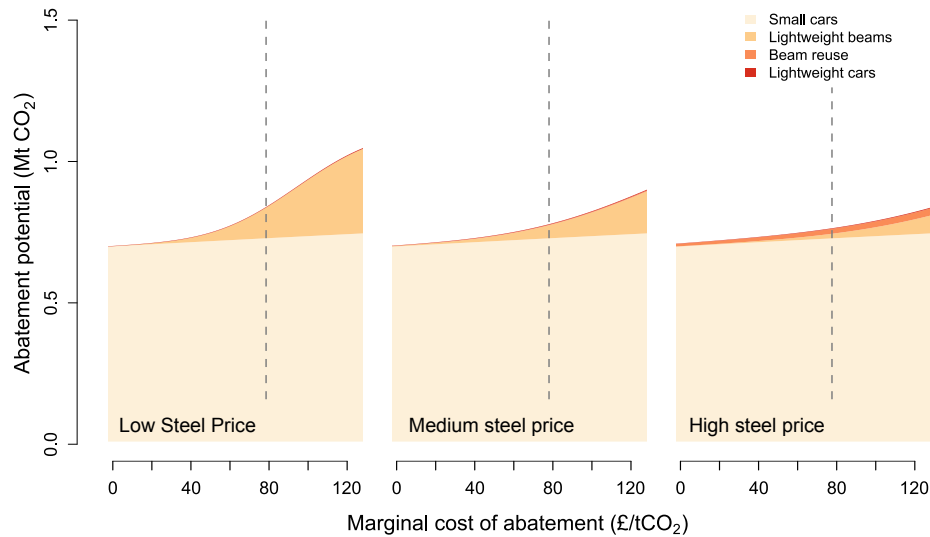


Figure 6: A selection of material efficiency MACCS under different steel price scenarios

shows weaker incentives for the lightweight beam strategy in the high steel price scenario. This is unexpected as a high steel price would increase the incentives for structural engineers to take greater care to avoid over-specifying the amount of steel in beams in excess of the requirements of building codes. This result is caused by the simplicity of the cost model assumed for this strategy. By assuming that the cost of excess steel must equal the benefit of rationalisation and flexibility to react to future design changes we force the unwanted result that the higher the steel price, the higher the benefits of rationalisation and flexibility, and so the lower the incentives to pursue this strategy. This suggests that it is only meaningful to explore price sensitivity if the underlying cost models are sufficiently sophisticated to respond to these price changes sensibly. It is not possible in the scope of this work to develop such a model, which would need to include considerably more information, notably the long-term interest rate, the futures market for steel, as well as predictions for the construction sector.

Rather, such apparently contradictory result highlights where complex behaviour by the actors is the likely underlying cause of inefficient use of materials, and where intervention is likely the hardest.

325 3.5. Discussion – material efficiency strategies

Table 4: Measure specific material and ghg emissions savings

Measure	Total potential (Mtco <sub>2</sub> )	Exploited at 79 £/tco <sub>2</sub>			
		Steel only (Mtco <sub>2</sub> )	( %)	Steel & use phase (Mtco <sub>2</sub> )	( %)
Smaller car	1.00	0.72	72 %	0.42	42 %
Lightest beam	0.35	0.05	14 %	0.05	14 %
Beam reuse	0.09	0.002	2 %	0.002	2 %
HSS car body	3.40	0.002	0.05 %	2.40	70 %

326 Table 4 shows the share of abatement that would be considered to be cost effective  
327 under the BEIS (2018) 79 £/tco<sub>2</sub> 2030 carbon value for policy appraisal. This value is  
328 the projected carbon cost under the EU emissions trading scheme which is believed by  
329 the BEIS to lead to the mitigation targets being met. The table shows that, when only  
330 emissions savings due to reduced demand for steel are taken into account, the cheapest  
331 strategy (choosing smaller cars) is largely exploited but the more expensive strategies  
332 (steel reuse and high strength steel body in white in this case) are only just starting to  
333 come into play. Once use-phase cost and associated emissions savings are taken into  
334 account the costs of the two lightweighting strategies in the automotive sector reduced  
335 dramatically, increasing incentives for the HSS car body strategy and reducing the efficacy  
336 of the smaller car strategy due to the double counting restriction.

337 The novel material efficiency MACCS in Figure 5 shows that, once double-counting  
338 is removed, the four proposed material efficiency measures could save in the order of  
339 4.5Mt co<sub>2</sub>. This represents 35 % of UK direct emissions due to industrial processes  
340 DECC (2016). The emissions savings would occur across global supply chains. Cabrera  
341 Serrenho et al. (2015) estimate that 20 Mt of steel was used to meet UK demand  
342 in 2007, of which 13 Mt was imported. As shown in Table 3, the proposed strategies  
343 would reduce steel demand by 2.4 Mt, equating to a 12 % reduction in steel demand and  
344 associated emissions. The two MACCS show a wide range of costs of abatement, with the  
345 average cost of abatement for each of the strategies ranging from –705 £/tco<sub>2</sub> for the

346 smaller car strategy to 1600 £/tco<sub>2</sub> for high strength steel car body strategy in Figure 5  
347 (top) and –2, 135 £/tco<sub>2</sub> for the smaller car strategy to 565 £/tco<sub>2</sub> for the reuse strategy  
348 in Figure 5 (bottom).

## 349 **4. Discussion**

350 In this paper we have presented a novel method for building a marginal abatement  
351 cost curve (MACC) to take into account material efficiency measures and applied this  
352 method to build a marginal abatement cost curve for four material efficiency measures  
353 in the UK. In response to calls for greater transparency on MACC assumptions, in the next  
354 section (Section 4.2) we set out a standard for documentation for documenting MACC  
355 assumptions based on the experience of populating the material efficiency MACC. We  
356 then identify how the novel MACC method proposed here improves on the traditional  
357 MACC (Section 4.1).

### 358 *4.1. Methodological improvements*

359 Figure 1 shows the four material efficiency measures in the traditional MACC format.  
360 This format has many shortcomings in particular:

- 361 • The assumption that there is a single cost for each measure set equal to the average  
362 cost for that measure;
- 363 • The assumption that measures will be chosen in sequence (from least to highest  
364 average cost) rather than in parallel;
- 365 • The assumption that measures are independent and so that the abatement potential  
366 of individual measures can be summed to reveal the total abatement potential.

367 The novel material efficiency MACC in Figure 5 addresses these shortcomings by:

- 368 • Depicting a cost distribution for each measure;

- 369 • Identifying parameters that are common across measures, and allowing measures  
370 to occur in parallel, where appropriate, for a given cost of carbon under a consistent  
371 set of cross-strategy parameters;
- 372 • Taking into account the interaction between strategies and so removing double  
373 counting of emissions potentials.

374 Comparing the traditional (Figure 1) and novel (Figure 5) is complicated slightly  
375 by the fact that the axes are reversed in the novel MACC as compared to the traditional  
376 MACC. The benefit of this modification is that cumulative distribution function (CDF) for  
377 different carbon prices can be stacked taking into account the interdependency between  
378 strategies. Although this makes it slightly more cumbersome to compare the two MACCs  
379 it does not detract from the ease of interpreting the novel MACC when viewed in isolation.

#### 380 *4.2. Assumptions verification*

381 The process of estimating the marginal cost of abatement for a range of material  
382 efficiency measures is helpful not only for populating the MACC but also for revealing  
383 the types of assumptions that have to be made to estimate a MACC. What becomes clear  
384 is that there can be no definitive MACC, there can only be a particular representation  
385 of costs based on a particular set of assumptions. The challenge then is to state the  
386 assumptions transparently in order to avoid mis-representation and to be as consistent  
387 as possible in the treatment of different strategies in order to allow comparison. Figure 7  
388 gives an overview of the types of assumptions that have to be made in order to populate  
389 a material efficiency MACC. The assumptions are broken into three categories: cross-  
390 strategy assumptions, strategy specific assumptions and curve specific assumptions.  
391 Any MACC, whether the novel MACC proposed here, or a traditional MACC, includes these  
392 different types of assumptions although they may not be clearly stated or dealt with  
393 consistently.

394 Identifying cross-strategy assumptions helps to ensure consistency across the emis-  
395 sions abatement strategies considered in the MACC. The key here is to distinguish between

assumptions that apply across all strategies and must be consistent as opposed to those that apply across all strategies but may differ. For example we would expect the steel price level to be consistent across scenarios (it would be unfair to compare an abatement cost that assumes a low steel price for one strategy to one that assumes a high steel price for another), but allow the emissions intensity of steel to vary across strategies to reflect the range in emissions intensities of current steel plants (as it is possible that steel is sourced from a high emitting source in one case but a lower emitting source in another). The interdependence of cross-strategy assumptions must also be taken into account: for example the steel scrap price should be modelled as a function of the virgin steel price, rather than modelled independently, as the two prices tend to move together.

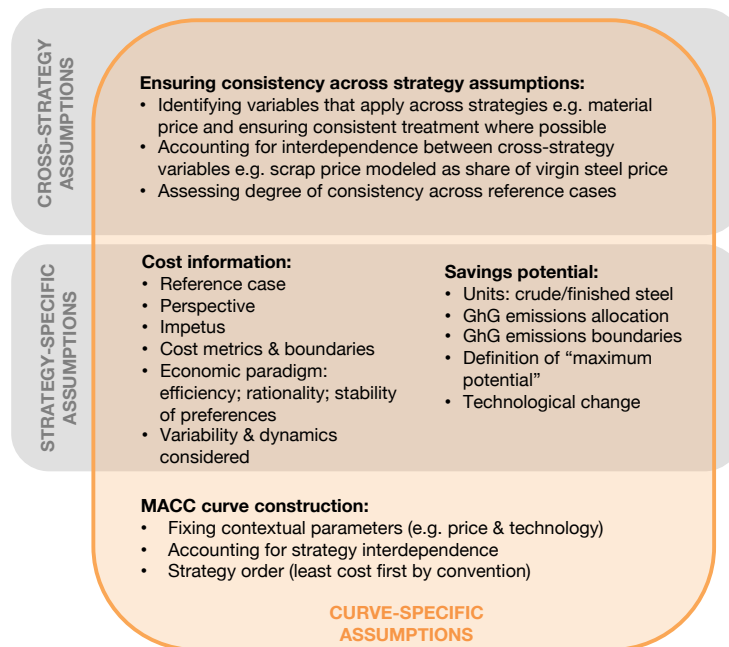


Figure 7: Standard for documentation of the assumptions behind the creation of a MACC for logging material efficiency MAC assumptions

The strategy specific assumptions in Figure 7 break down some of the elements that make up different, at times competing, notions of cost. These are the types of features of costs that researchers should be mindful of when building a MACC. They relate both

409 to the data that are collected to populate the `MACC` and to the way that these data are  
410 interpreted and, as explained in Section 2.2 the interpretation cause as much influence  
411 on the magnitude of costs as the underlying data.

412 Finally, there are a set of curve specific assumptions. These include the cross-  
413 strategy and strategy specific assumptions mentioned above, as well as assumptions that  
414 relate to the construction of the particular curve itself. In order to construct a single  
415 cost curve (as opposed to a cost fan) all contextual parameters (such as steel prices  
416 in this case) must be held constant. The curve can then be constructed for the given  
417 set of contextual parameters by stacking the `CDF` for cost assumed for each strategy.  
418 Assumptions regarding the nature of the interdependence between strategies are then  
419 required in order to remove any double-counting of abatement potential from the curve.  
420 Given the nature of the curve, the convention is to assume that lower cost measures are  
421 pursued first.

## 422 5. Example R code

```
423 library( ' DescTools ' )  
424 points<-seq( from=-2000, to=4000, by=1)  
425 pointsy = seq(from=0, to = 4, by =0.0001) ;  
426 psmallcars = cumsum(dnorm(points ,-2135, 1150))  
427 plightbeams = cumsum(dnorm(points ,136, 54))  
428 preusebeam = cumsum(dnorm(points ,565, 238))  
429 plightcars = cumsum(dnorm(points ,-338, 598))  
430  
431  
432 vals <- cbind(points ,  
433                psmallcars ,                               # Small cars  
434                plightbeams*0.35 ,                         # Lightweight beams  
435                preusebeam*0.09 ,                           # Beam reuse
```

```

436         (1-(psmallcars)*.12)*plightcars*3.4 # Lightweight vehicle
437     )
438     PlotArea(as.data.frame( vals ),
439             xlab="Marginal_cost_of_abatement_(Pounds/tCO2)",
440             ylab="Abatement_potential_(Mt_CO2)",
441             xlim=c(-2000,3000), ylim=c(0,5),
442             col=c("#f0f9e8", "#a8ddb5", "#43a2ca", "#0868ac")
443     )
444     legend("topleft",
445         fill=c("#f0f9e8", "#a8ddb5", "#43a2ca", "#0868ac"),
446         legend=c("Small_cars",
447             "Lightweight_beams",
448             "Beam_reuse",
449             "Lightweight_cars"),
450         bty="n"
451     )

```

### 452 *5.1. Interpreting of the new curve*

453     MACCS have been used to guide policy. They provide context for possible abatement  
454     measures, and provide a simple mean to estimate economic impacts and pathways.  
455     Unfortunately, because they do not account for the variability and uncertainty of the  
456     estimations, nor the interactions between the measures considered, they are a poor guide.  
457     The new type of curve proposed here should give a more robust answer to the question  
458     ‘how much carbon can be abated for what marginal price?’

459     In the original McKinsey curve, as in our example, some of the measures have a  
460     negative cost. This does not mean that the abatement measures should have already  
461     been implemented, or that the assumptions are (necessarily) false, Rather, this may  
462     reflect uncertainties or the relative novelty of the possible measures: this curve does

not represent an equilibrium, but rather the driving potential for change on a range of carbon costs.

The new approach requires more data than the traditional one: material flow maps are required to robustly assess the interaction between the abatement measures. These data can be time-consuming to acquire and be somewhat uncertain. Nonetheless they are central to calculating the interactions between measures, and we believe this to be necessary for the curve to be a meaningful predictive tool. Importantly, collecting them informs on the uncertainty and variability of the underlying data, both aspects reflected in the proposed methodology, and notably absent in traditional MACCS.

## 6. Conclusions

This paper has set out a novel method for building a marginal abatement cost curve (MACC). Applying this method to four material efficiency measures in the UK shows that these strategies could deliver significant abatement potential at costs that become competitive once use-phase savings are taken into account. The process of populating the MACC revealed the types of assumptions that have to be made in order to populate a MACC. These assumptions were summarised into a structured assumptions guide to aid MACC transparency. This novel approach allowed us to lay out an abatement strategy focused on material use, accounting for the uncertainty and variability of the underlying data.

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