

1 **Carbon Brainprint – an estimate of the intellectual contribution of research**
2 **institutions to reducing greenhouse gas emissions**

3 Julia Chatterton^a, David Parsons^{a*}, John Nicholls^a, Phil Longhurst^a, Mike Bernon^a, Andrew
4 Palmer^a, Feargal Brennan^a, Athanasios Kolios^a, Ian Wilson^b, Edward Ishiyama^c, Derek
5 Clements-Croome^d, Abbas Elmualim^d, Howard Darby^e, Thomas Yearley^f, Gareth Davies^g

6 ^a Cranfield University, Cranfield, Bedford, MK43 0AL, UK (j.chatterton@cranfield.ac.uk,
7 d.parsons@cranfield.ac.uk, J.R.Nicholls@cranfield.ac.uk, P.J.Longhurst@cranfield.ac.uk,
8 m.p.bernon@cranfield.ac.uk, a.palmer@Cranfield.ac.uk, f.brennan@cranfield.ac.uk,
9 a.kolios@cranfield.ac.uk)

10 ^b Department of Chemical Engineering and Biotechnology, University of Cambridge, New
11 Museums Site, Cambridge CB2 3RA, UK (diw11@cam.ac.uk)

12 ^c Downstream Research, IHS, 133 Houndsditch, London, EC3A 7AH
13 (ishiyama.edward@googlemail.com) Formerly at University of Cambridge

14 ^d School of Construction Management and Engineering, University of Reading, PO Box 220,
15 Reading, RG6 6AY, UK (d.j.clements-croome@reading.ac.uk, a.a.elmualim@reading.ac.uk)

16 ^e Technologies for Sustainable Built Environments Centre, University of Reading, PO Box
17 220, Reading, RG6 6AY, UK (HDarby@peterbrett.com)

18 ^f Estates and Facilities, University of Reading, PO Box 220, Reading, RG6 6AY, UK
19 (t.yearley@reading.ac.uk)

20

21 ^g Icon Print Innovations P/L, Wentworthvill, NSW, Australia (gareth@icon2100.com)

22 (Formerly at Newera Controls Solutions Limited).

23 * Corresponding author. Tel: +44 1234 750111; Fax: +44 1234 752971. E-mail address:

24 d.parsons@cranfield.ac.uk (D. J. Parsons)

25

26 **Carbon Brainprint – an estimate of the intellectual contribution of research**
27 **institutions to reducing greenhouse gas emissions**

28

29 **Abstract**

30 Research and innovation have considerable, currently unquantified potential to reduce
31 greenhouse gas emissions by, for example, increasing energy efficiency. Furthermore, the
32 process of knowledge transfer in itself can have a significant impact on reducing emissions,
33 by promoting awareness and behavioural change. The concept of the ‘carbon brainprint’ was
34 proposed to convey the intellectual contribution of higher education institutions to the
35 reduction of greenhouse gas emissions by other parties through research and teaching/training
36 activities. This paper describes an investigation of the feasibility of quantifying the carbon
37 brainprint, through six case studies. The potential brainprint of higher education institutes is
38 shown to be significant: up to 500 kt CO₂e/year for one project. The most difficult aspect is
39 attributing the brainprint among multiple participants in joint projects.

40

41 **Keywords:** carbon brainprint, carbon footprint, universities, research, higher education,
42 greenhouse gas.

43

44 **1 Introduction**

45 The need to reduce greenhouse gas (GHG) emissions is widely, though not universally,
46 accepted. In the Climate Change Act 2008, the UK Government committed the country to
47 reducing its GHG emissions by 34% by 2020 and 80% by 2050. These targets require action
48 to reduce GHG emissions from all sections of the economy, including universities, which are
49 expected to cut their own carbon footprints in line with these national targets (HEFCE, 2010).
50 These emissions vary widely with the size and nature of the institutions: annual GHG
51 emissions by universities from fuel and energy consumption in 2005 were 1–
52 90 kt CO₂e/institution (SQW, 2010). This concern is part of a wider trend for universities,
53 like other business, to study and improve their environmental performance (Baboulet and
54 Lenzen, 2010).

55 The process of quantifying their own emissions has led universities to consider the possibility
56 of measuring the contribution of research to reducing the emissions of other organisations.
57 Universities could have an impact through research leading to new technologies, the transfer
58 of the results of past research into practice, developing novel ways to promote behavioural
59 change, and training and education to provide the necessary knowledge and skills to effect
60 change. The carbon footprint is a commonly-used measure of the total set of GHG emissions
61 caused directly and indirectly by an individual, organisation, event or product, although the
62 definition and the boundaries used vary between studies according to their context and
63 purpose (Pandey et al., 2011). The phrase ‘carbon brainprint’ was first proposed as an
64 analogue of the carbon footprint to describe the wider impact of universities on GHG
65 emissions emissions by the Deputy Chief Executive of the Higher Education Funding
66 Council for England (HEFCE) during consultation on its GHG emissions reduction targets.

67 The objectives of the Carbon Brainprint project were to test whether it was possible to
68 quantify the carbon brainprints of university activities, explore the difficulties in doing so,
69 propose procedures and estimate the potential brainprints of several examples. This paper
70 will summarise the general approach, briefly describe the case studies used to develop the
71 concept, discuss what was learned from the case studies and identify some of the remaining
72 problems in developing a general method for all types of university activities.

73

74 **2 Methods**

75 **2.1 Case-study approach**

76 As the objectives required development and testing of a method to quantify a previously
77 conceptual measure, a multiple case study approach was adopted, in which the method
78 evolved during the case studies. This approach was selected in preference to defining a
79 method in advance, so that it could respond to the insights gained and test the underlying
80 concept not the implementation.

81 The case studies were selected in advance to provide a diverse set of examples, encompassing
82 technological interventions, training courses, detailed modelling and influencing behaviour
83 (Table 1). All the cases were expected to have some impact on carbon footprint reduction, but
84 only one (training for landfill gas inspectors) had quantified it. In addition to the technical
85 differences between the cases, the type of engagement of the universities with the users
86 varied, including implementation within the university campuses, long term research and
87 development contracts with single customers, ‘pure’ research that had yet to be put into
88 practice, and public sector consultancy relying on uptake by commerce to implement it. Each
89 case was expected to provide different challenges to the methods being developed.

90 After completion, the case studies were reviewed individually and collectively to assess the
91 need for revisions to the methods, areas of difficulty and conclusions related to the overall
92 aims.

93 **Table 1. Initial case studies**

Project	University
Ceramic coatings for jet engine turbine blades to improve engine efficiency	Cranfield
Improved delivery vehicle logistics to save fuel	Cranfield
Training for landfill gas inspectors to improve methane capture	Cranfield
Novel offshore vertical axis wind turbines compared to conventional turbines	Cranfield
Intelligent buildings for energy management	Reading
Optimising defouling of oil-refinery preheat trains to reduce fuel consumption	Cambridge

94

95 **2.2 Guidelines**

96 A set of initial principles or guidelines for the case studies was drawn up by members of the
97 project team, guided by the project steering committee and revised following the case studies.
98 These principles were based on established approaches to carbon footprinting, including PAS
99 2050:2008 (BSI, 2008) and the Carbon Trust good practice guide (Carbon Trust, 2009),
100 which are underpinned by guidance from the Intergovernmental Panel on Climate Change
101 (Eggleston et al., 2006) and the methods of life cycle assessment (LCA) (e.g. Pennington et
102 al., 2004; Rebitzer et al., 2004). However, as the intention was to obtain an estimate of a
103 change in total emissions, it was anticipated that the level of detail would be coarser than that
104 needed for an LCA of a specific functional unit, and that parts of the footprint unaffected by
105 the change could be neglected. Indeed, it has been noted that, while footprints generally
106 should be based on LCA, they have different characteristics, because they “have a primary
107 orientation toward non-LCA experts and society in general”, whereas LCA is designed for
108 technical experts using indicators that “are not necessarily the lens through which society
109 views environmental protection” (Ridoutt et al., 2015).

110 The guidelines divided the process of conducting a study into five main stages: system
111 definition, boundary definition, data gathering, assessment and uncertainty analysis.

112 *System definition* should begin with an interview with the main academics who carried out
113 the work, from which a general qualitative summary would be written describing the case, its
114 application and expected impact. The *boundary definition* should follow from this, specifying
115 the process, spatial, temporal and conceptual boundaries of the system being considered. It
116 was anticipated that the boundaries would need to be drawn widely: in principle they would
117 include all upstream and downstream emissions over a long time period. As the estimate was
118 likely to contain significant uncertainty, a cut-off precision of 1% was suggested to avoid
119 spurious precision.

120 *Data gathering* should include both the activity and emissions. The activity data would
121 necessarily be specific to each case. Some emissions data would also be case-specific, but
122 much could be found in standard sources such as the European Life Cycle Database (ELCD,
123 2010) and the UK guidelines (AEA, 2010).

124 The *assessment* of the change in emissions was the core of the methods being developed. As
125 the aim was to assess the change in emissions, it could be achieved by several approaches
126 depending on the data available, including directly evaluating baseline and changed
127 emissions, evaluating baseline emissions and applying a proportional change to a component
128 of the activity, or evaluating the change alone. The units to be used were mass of carbon
129 dioxide equivalent, using the global warming potential (GWP) with a 100 year time horizon
130 (GWP100). Depending on the context it might be appropriate to give a lifetime total, and
131 annual quantity, or both. For an intervention or development in the past, data about its uptake
132 or rate of use should enable assessment of its impact to date, referred to as the ‘retrospective
133 brainprint’ with reasonable confidence. More recent developments would rely for their

134 impact on future uptake, implying much greater degree of uncertainty in their potential
135 results, known as the ‘prospective brainprint’.

136 *Uncertainty analysis* is required as part of national GHG inventories (Eggleston et al., 2006),
137 and the carbon brainprint contained additional sources of uncertainty, particularly in the
138 prospective brainprint, so the same approach should be followed as far as possible. The usual
139 method is to define distributions for the main variables and parameters from data or expert
140 judgement, then use Monte Carlo simulation to derive output distributions and present the
141 results as the mean and 95% confidence interval.

142 One issue that was identified in the guidelines, but not fully resolved, was the attribution of
143 the brainprint between multiple participants. When there were multiple university
144 participants, it was proposed that this could be based on the share of the research income, or
145 their documented roles. Indeed, if the aim was to estimate the impact of the university sector,
146 there would be no need for finer attribution. Dealing with other participants whose roles went
147 beyond implementation and uptake was anticipated to raise further difficulties.

148

149 **3 Case studies**

150 The case studies will be summarised, with emphasis on their contribution to the development
151 of the method. Full details can be found in the project report (Parsons et al., 2011).

152 **3.1 Ceramic coatings for jet engine turbine blades**

153 The aviation industry is estimated to contribute about 2–2.5% of GHG emissions, and the
154 number of aircraft in service is projected to double between 2011 and 2031 (Grote et al.,
155 2014). Reducing emissions from aircraft through both operational changes and improvements

156 in efficiency is, therefore, an important part of overall GHG emissions reduction. The Surface
157 Science and Engineering Group at Cranfield University has been working with Rolls-Royce
158 plc for over 17 years to improve the insulating performance of ceramic thermal barrier
159 coatings (TBCs), which are applied to jet turbine blades to protect them from the high
160 temperature gases leaving the combustion chamber and to increase the efficiency of the
161 engine. As a result, the TBCs used in the current generation of aircraft turbofan jet engines
162 permit operation at a temperature drop about 80 °C greater than prior to the research, with an
163 estimated fuel saving of about 1% (inferred indirectly from other information). This case
164 study considered two engine types: the Trent 700, used on about half of the Airbus A330
165 aircraft currently in service, and the Trent 500, used on all Airbus A340-500 and A340-600
166 aircraft.

167 Good data on the numbers of aircraft delivered and in service was available from (Airfleets,
168 2011) and full data on existing orders came from (Airbus, 2010). The activity data was
169 statistical summaries of the number and distance of flight legs derived from the Association
170 of European Airlines (AEA) via another university project (C. Miyoshi, personal
171 communication). In the absence of other data, these were assumed to be typical of all
172 operators.

173 No fuel consumption data was available from the operators, so it was modelled using publicly
174 available estimates (EMEP/EEA, 2009) for the cruise phase standard engine tests for take-off
175 and landing (CAA, 2010). The emissions during extraction and refining of the fuel were
176 taken from (ELCD, 2010). Estimates of the emissions associated with fuel transport and
177 manufacture of the blades showed they were negligible in comparison with the direct
178 emissions.

179 The estimates of the current emissions reductions for individual aircraft were 1016–
180 1646 t CO₂e/year depending on the model, giving a total retrospective GHG emissions
181 reduction of 568 kt CO₂e/year (95%: 429–721) for the aircraft in service. Including all the
182 aircraft on order, the mean prospective GHG emissions reduction was 833 kt CO₂e/year
183 (95%: 629–1060). Assuming a service life of 20 years, the total brainprint was approximately
184 16 Mt CO₂e (95%: 12–20). More recent developments by the same team are included in
185 newer engine models and aircraft, so these totals are substantial under-estimates.

186 This case study raised few conceptual challenges, because it concerned an incremental
187 development in a well-studied field. It exemplified the large absolute values (relative to the
188 other case studies) that could be obtained from small changes in energy-intensive processes.
189 There was a residual uncertainty over the estimate of the change in efficiency, which had to
190 be inferred in the absence of experimental data. The assessment required a relatively detailed,
191 process-based model, similar to an IPCC Tier 3 assessment (EMEP/EEA, 2009). Using
192 operational consumption data (Tier 2) would have simplified the study and reduced some of
193 the uncertainties. The research was the work of a single university team, so the full brainprint
194 was attributed to the university. This study raised the question of rebound effects, in which
195 increased efficiency led to lower fares, resulting in more air travel. As there was no way to
196 establish a causal link, and many other factors influence the use of air travel, this was
197 excluded from the assessment.

198 **3.2 Novel offshore vertical axis wind turbines**

199 Researchers within the School of Engineering at Cranfield University were part of a
200 consortium to develop further the concept of Novel Offshore Vertical Axis (NOVA) wind
201 turbines. These turbines have greater potential power capacity than conventional horizontal
202 axis turbines (HAWTs) and have a lower rotation speed and a more accessible hub, which

203 allows for reduced emissions from maintenance over the turbine life cycle. The design has
204 been optimised to a much higher power rating than current models of HAWT, so fewer
205 turbines would be required for the same theoretical power output. It is expected that GHG
206 emissions for an installation of NOVA turbines would be lower than for conventional
207 HAWTs with the same output.

208 This project was still in its development stages, so there were no NOVA turbines in
209 operation, and the brainprint was entirely prospective, based on the results of an LCA that
210 was conducted during the project. The mean estimated total reduction in GHG emissions over
211 a lifetime of 20 years was 102 kt CO₂e for installation of 1 GW rated power, from a baseline
212 for the HAWT installation of 520 kt CO₂e.

213 This case study raised several difficulties with purely prospective assessments. There were
214 large uncertainties in many variables, giving a 95% confidence interval for the lifetime
215 (construction, operation and maintenance and decommissioning) reduction in GHG emissions
216 of -111–315 kt CO₂e. The large uncertainty, including the possibility of an increase in
217 emissions, arises because this is the difference of two random variables that are treated as
218 independent. In practice, common features of the two types of installation mean that there is
219 likely to be a positive correlation, which would reduce the variance of the difference. It
220 should also be noted that the LCA used in this estimate considered a single type of HAWT,
221 whereas an LCA of five types of HAWT found a range of 18–31 g CO₂e/kWh generated
222 (Raadal et al., 2014), which is an additional source of uncertainty. (Direct comparison of the
223 two LCAs is difficult due to differing assumptions and choice of functional unit, but Raadal
224 et al. appear to estimate much higher total emissions.) A fundamental uncertainty not
225 included in this estimate was whether any installations would be built. Although there is
226 value in estimating the potential environmental benefits of current research, it would be

227 unwise to make strong claims on this basis until field trials could provide data to reduce the
228 uncertainties and realistic projections of uptake were possible.

229 As the project had multiple participants, there was a need to consider attribution if the
230 brainprint was to be divided among them. Based on the composition of the team and the
231 division of the budget, Cranfield University's contribution was estimated to be one-third, or
232 34 kt CO₂e. This assumed that the brainprint was attributed entirely to the research
233 institutions. If some of the innovations were contributed by the commercial partners in the
234 consortium, it can be argued that the total university share should be reduced.

235 **3.3 Improved delivery vehicle logistics**

236 A Cranfield University PhD graduate and visiting fellow (Dr Andrew Palmer), contributed to
237 transport recommendations for the food distribution industry (Faber Maunsell, 2007; Fisher et
238 al., 2010), which were taken up by the food and grocery industry body IGD in the Efficient
239 Consumer Response (ECR) initiative and implemented with 40 leading UK brands (IGD,
240 2011a). IGD reported that this initiative had reduced vehicle use by approximately
241 163 million road miles (2.6×10^8 km), or 80 Ml of diesel fuel, in the UK over approximately
242 four years to the date of the report in early 2011. The target was 200 million road miles
243 (3.2×10^8 km) by the end of 2011 (IGD, 2011b), by maintaining the reductions that had been
244 achieved. Using an emission factor of 3.1787 kg CO₂e/l including indirect emissions (AEA,
245 2010), saving 80 Ml of fuel is equivalent to a GHG reduction of 250 kt CO₂e. Applying a
246 standard emission factor to the reduction in distance travelled gave a similar result.

247 The main uncertainty in these estimates was the distance travelled, or fuel use. (Wiltshire et
248 al., 2009) suggest using a coefficient of variation (COV) of 2% for distances and 10% for fuel
249 use per km. As the estimates provided were for the reduction in distance travelled, with

250 additional uncertainties, a normal distribution with mean 250 and COV 15% was used, giving
251 a 95% confidence interval of 177–323 kg CO₂e/kg.

252 In the short term, the best estimate of the future reduction is the average for the period
253 reported: 63 kt CO₂e/year. In the longer term, other changes in transport practice are likely to
254 be introduced, and fuel efficiency is expected to improve (McKinnon, 2009), which would
255 reduce the change in emissions from these measures. Conversely, the success of ECR may
256 lead to similar measure being adopted by other operators both within and outside grocery
257 distribution as part of wider sustainability initiatives, especially as studies show that ‘green
258 logistics’ is neutral (Pazirandeh and Jafari, 2013) or beneficial (Ramanathan et al., 2014) for
259 operational and financial performance. This raised the question of whether indirect reductions
260 of this type should be included. The steering committee agreed to follow the practice of the
261 Carbon Trust and exclude indirect reductions.

262 This case study again highlighted the question of attribution, as the authors of the
263 underpinning report, other than Dr Palmer, were from Faber Maunsell (a consultancy
264 business) and Heriott Watt University. From discussions with Dr Palmer, he was a main
265 contributor to two of the six recommendations and contributed to the other four. An estimate
266 of 30% was therefore used for attribution to him. Although not an employee of Cranfield
267 University, the majority of his contribution was based on his PhD or work at Cranfield, so an
268 estimate of 75% was used. Combining these, the mean estimate of the retrospective brainprint
269 attributable to Cranfield was 56 kt CO₂e, or 14 kt CO₂e/year, with greater uncertainty than
270 the aggregate figure.

271 **3.4 Landfill gas inspector training**

272 This case study considered the impact of a training course, run by academics at Cranfield
273 University in 2008 on behalf of Environment Agency (EA) of England and Wales. The

274 training was a technical course for landfill gas inspectors to improve the recovery of methane
275 at existing landfill sites. Landfill gas is the largest source of methane emissions in the UK: of
276 the estimated UK total methane emissions of 2330 kt in 2008, 966 kt (24 Mt/CO₂e) came
277 from landfill (NAEI, 2011). The course trained 12 EA officers, and drew on the knowledge of
278 a retired EA landfill gas expert in addition to Cranfield staff. At the end of the course, the
279 trainees split undertook 24 site visits, making recommendations for improved methane
280 recovery, such as surface capping, gas well installation or replacement and pipeline
281 maintenance or balancing. A second course was subsequently run for an additional 12
282 officers.

283 The EA assessed the results of the initial set of 24 site visits and estimated that the measures
284 taken had resulted in the collection of an additional 7,600 m³/hr of landfill gas. The EA
285 suggested using a conservative estimate of 40% v/v for the methane content, giving
286 26.63x10⁶ m³ methane/year. Assuming a methane density of 0.68 kg/m³ at 15°C and standard
287 atmospheric pressure yielded 18.1 kt/year of methane, equivalent to 453 kt CO₂e/year using
288 the standard GWP of 25. However, the methane collected would ultimately be burned,
289 emitting carbon dioxide, so the estimated net reduction in GHG emissions was
290 403 kt CO₂e/year.

291 Achieving this reduction required the installation of additional equipment, mainly medium-
292 density polyethylene (MDPE) piping. Combining data on the MDPE used in the largest of
293 nine sites in a separate best-practice study (Raventós Martín and Longhurst, 2011) with an
294 LCA for MDPE (Baldasano Recio et al., 2005), the total emissions for the piping were
295 calculated to be less than 1.5 kt CO₂e. This was less than 1% of the gas captured from each
296 site in one year, so no estimates of equipment life cycle emissions were included in the

297 brainprint calculations. Indirect benefits that could be obtained by using the gas to displace
298 fossil fuels were excluded.

299 There was no data on the work of the first group of trainees after the initial set of visits, or on
300 the second group. The initial interventions would continue to reduce emissions, but the rate of
301 production of methane within the landfill might change over time, and the gas recovery on
302 subsequent sites might be lower due to the selection of the initial set. Assuming the gas yield
303 decreased by 10%/year and that each group made a similar set of visits, but achieved only
304 70% of the reduction obtained in the first year, the total reduction in GHG emissions in year 2
305 compared with the status quo would be 927 kt CO₂e, or a cumulative total of 1,330 kt CO₂e.
306 Extrapolating forward for an additional three years, assuming similar decreases in results, the
307 cumulative emissions reduction over five years would be 5,380 kt CO₂e.

308 In the uncertainty analysis, the change in emissions reported by the EA was treated as certain,
309 but, based on a survey of seven UK landfill sites (Allen et al., 1997), a uniform distribution in
310 the range 36–64% v/v was used for the methane concentration of the gas. This resulted in a
311 95% confidence interval for emissions reduction in the first year of 370–638 kt CO₂e. All of
312 the other variables – the numbers of future visits, their effectiveness and the resulting changes
313 in emissions – were assumptions without supporting data, so were treated as highly uncertain
314 and given independent normal distributions with coefficients of variation of 50%. The
315 resulting 95% confidence intervals were 1,090–1,570 kt CO₂e for the first two years and
316 3,700–7,310 kt CO₂e for the five-year total.

317 The fact that the EA had audited the results of the first training cohort enabled a
318 straightforward and reliable estimate to be made of the total brainprint of this activity. It
319 highlighted the impact that interventions affecting methane could have, due to its high global
320 warming potential. Beyond the first year, the extrapolation entailed large uncertainties. The

321 other main difficulty with this case study was attribution. The course was managed by
322 Cranfield University and taught by its staff, but included knowledge experience from EA
323 staff. The steering committee took the view that the course would not have taken place
324 without the involvement of a university or similar institution, so the brainprint could be
325 attributed solely to the university. However, there is also a case for dividing it between the
326 university and the EA.

327 **3.5 Intelligent buildings**

328 Over the past 20 years many different buildings have been labelled as “intelligent”
329 (Clements-Croome, 2004). Industry has many established intelligent building solutions but
330 finds it difficult to demonstrate and prove their benefits. The ideal system links the building,
331 systems within it and the occupants so they have some degree of personal control. Intelligent
332 controls help to match demand patterns (Noy et al., 2007; Qiao et al., 2006). It has been
333 demonstrated that effective action on GHG emissions requires building users to be involved
334 in both the process and the operation, so that they feel part of carbon management plans
335 (Elmualim et al., 2010).

336 A team consisting of researchers at the University of Reading, the University’s Facilities
337 Management Directorate, Newera Controls Ltd. and Carnego Systems Ltd. conducted two
338 separate investigations to measure and demonstrate the potential for two important and
339 complementary approaches for achieving energy efficiency and GHG emission reductions in
340 buildings. This study was unique within the project in involving new research rather than
341 analysis of the results of previous projects.

342 The first investigation focused on saving electricity used for lighting, office equipment and
343 catering by influencing user behaviour in an office building on the main campus. Electricity
344 consumption was recorded over a 7 month period (October–April) in the trial, with each

345 month divided into occupied days and unoccupied days. The results were compared with the
346 same period in the previous year, having standardised both to an occupancy of
347 20.5 days/month. The reduction in emissions from electricity generation and distribution,
348 using a conversion factor of 0.61707 kg CO₂e/kWh (DECC, 2010), was 7.8 t CO₂e from a
349 baseline of 38.4 t CO₂e, a reduction of about 20%. Although the uncertainty in the measured
350 consumption was low, the comparison with the baseline introduced uncertainty due to the
351 differences in occupancy, weather and other influences on behaviour.

352 The second investigation considered an interventionist approach in an accommodation block
353 at the Henley Business School using intelligent monitoring and control systems. The existing
354 Building Management Systems was enhanced using a Building Energy Management System
355 to control some of the system parameters for occupied rooms and reduce the heating in
356 unoccupied rooms. By comparing the results with another block before and during the trial,
357 energy savings in the form of heating oil were estimated to be about 25%. The reduction in
358 emissions was estimated to be 3.3 kg CO₂e/day, but this was highly variable due to changes
359 in occupancy and weather. The change would be much lower during the summer, but
360 additional savings could be made if the system was extended to other services, such as
361 lighting.

362 Given the uncertainty and variability present in both sets of data and the limited duration, the
363 results were not extrapolated to a carbon brainprint for a whole year or a longer period. On
364 the evidence of these two investigations, measures of this type could reduce non-domestic
365 energy consumption by of the order of 20–25%. A detailed carbon footprint study of one UK
366 university found that building energy use accounted for one-third of its total GHG emissions,
367 of which half were from electricity use in buildings owned by the university (Ozawa-Meida
368 et al., 2013), so the potential reductions within university estates are significant. Many of the

369 same measures could be applicable to other non-domestic buildings, which are responsible
370 for 20% of the UK's GHG emissions (Choudhary, 2012), but the total impact would be
371 highly dependent on uptake.

372 **3.6 Optimising heat exchanger cleaning to reduce fuel consumption in oil** 373 **refineries**

374 Although the largest proportion of GHG emissions from the use of fossil fuels arises from
375 their combustion, the direct and indirect emissions during refining can account for up to 14%
376 of the life-cycle emissions for petrol/gasoline (Elgowainy et al., 2014). Heating the crude oil
377 from ambient temperature to its bubble point (360–380 °C) prior to fractional distillation is
378 the major energy consumer amongst all distillation processes in the chemical and petroleum
379 industries (Humphrey et al., 1991). About 60–70% of the heat (Panchal and Huang-Fu, 2000)
380 is recovered from the hot product streams of the crude oil distillation unit in a series of heat
381 exchangers, known as the preheat train, prior to entering the furnace. Without the preheat
382 train, 2–3% of the crude oil throughput would be used for heating the furnace. To maintain
383 their efficiency, the heat exchangers need to be cleaned periodically, during which the
384 performance of the preheat train is reduced.

385 Research in the Department of Chemical Engineering and Biotechnology at the University of
386 Cambridge funded by the Engineering and Physical Sciences Research Council used a model
387 of the preheat train to optimise the cleaning schedule, subject to constraints on the
388 temperature at several points (Ishiyama et al., 2010, 2009).

389 Two refineries for which the necessary data were available were considered in the study: a
390 Repsol YPF refinery in Argentina and the Esso Fawley Refinery in the UK. Simulation
391 studies were conducted with and without optimised cleaning schedules to estimate the
392 difference in fuel use for heating. The only emissions considered were those arising from

393 direct combustion of oil products to heat the crude oil prior to distillation, calculated using a
394 stoichiometric method based on the fuel composition. The predicted changes were small
395 fractions of the total throughput of the refinery, so the resulting change in total output was
396 neglected.

397 The analyses simulated a three year period for the Repsol YPF case and two years for Esso
398 Fawley. Compared with current practice, systematic cleaning at the Repsol YPF refinery was
399 predicted to result in an average GHG emissions reduction of 1.0 kt CO₂e/year. If the desalter
400 inlet temperature was constrained, the emissions reduction was 0.77 kt CO₂/year. For the
401 Esso Fawley refinery, the predicted average reduction in emissions with systematic cleaning
402 was 1.4 kt CO₂/year.

403 The differences between the two refineries studied in terms of throughput and configuration
404 show that it is not possible to extrapolate directly from these results to other installations,
405 however, from the results obtained, a realistic estimate of the likely GHG emissions reduction
406 for each refinery is of the order of 1 kt CO₂/year. There were no implementations in practice
407 that could demonstrate this, but the university was working with the company IHS-ESDU to
408 include the algorithm in a commercial software product.

409 The estimation in this case was simple, as the existing model included most of the necessary
410 calculations. Within the model, the furnace efficiency was the main source of uncertainty.
411 Both results assumed a furnace efficiency of 90%; if the efficiency was lower, greater
412 reductions in emissions would be obtained.

413

414 **4 Discussion**

415 The Carbon Brainprint project aimed to develop and make available robust methods to
416 calculate both retrospective and potential estimates of the contributions that universities make
417 to reducing GHG emissions. Six contrasting case studies were used to develop and test the
418 methods, and to provide an indication of the benefits that might be obtained. The magnitude
419 of the retrospective brainprints varied widely between case studies, from about
420 12 t CO₂e/year to over 500 kt CO₂e/year (Table 2). The large absolute values were often the
421 result of small changes in efficiency in processes with high emissions. Although larger
422 proportional reductions in emissions were found in other studies, these were pilot studies, so
423 the absolute values were small, though the future potential if they were adopted is very large.
424 It was clear from the landfill gas case study that interventions to reduce GHGs other than
425 carbon dioxide can have very large impacts due to the high GWP of the gases considered.

426 Case studies in which changes in emissions or activity had already been measured provided
427 the clearest demonstration of the benefits of innovation or knowledge transfer to GHG
428 emission reduction. These cases were also simplest and least uncertain to evaluate, as they
429 allowed a direct calculation. Where such results had not been recorded, even for an existing
430 innovation, such as turbine blade coatings, it was necessary to use a model-based (Tier 3)
431 approach, which was considerably more time-consuming and contained many sources of
432 uncertainty. Inevitably, extrapolation to future impacts required a model, however simple,
433 and introduced many new uncertainties. If universities wish to provide a clear demonstration
434 of the impact of their work, some engagement with the users after implementation to collect
435 operational data would greatly simplify the process and provide the most reliable evidence.

436 In most cases, the change in emissions during operation far outweighed emissions involved in
437 the application of the innovation. The exception was the NOVA turbine study, in which the

438 bulk of expected emissions would occur during construction and installation. It therefore
439 required a full LCA, but fortunately an existing LCA model was available.

440 The most contentious issue in several studies was attribution of the brainprint among
441 different parties. Although it was recognised that the development and implementation are
442 vital, the steering committee concluded that the brainprint attributed to the research or
443 training team should include the full reduction in emissions, as it provided the foundation for
444 all that followed. Where the research involved collaboration between several higher
445 education or research sector parties, simple methods, such as considering the proportions of
446 the research budget or documented project roles could be used. Indeed, to assess the overall
447 benefits of universities, it is not necessary to attribute the brainprints to individual
448 institutions, though the institutions might have their own interest in doing so. Furthermore, if
449 the contribution of the non-university parties was similar in nature to that of the universities
450 (e.g. the transport logistics case study), the same method could be applied. The most difficult
451 cases were where there was a distinct contribution from non- university participants that went
452 beyond providing funding or implementing the results of research, for example the training
453 for landfill gas inspectors. One point of view was that if the benefits could not have been
454 realised without the university (or an equivalent) then the full brainprint could be attributed to
455 the university, and the results shown reflect this. If the intention was to make a comparison
456 between different universities, this might be adequate. However, this view may fail to
457 recognise the intellectual contribution from other parties and overestimate the role of
458 universities in total. Further work is needed to develop a more rigorous method of attribution.

459 All of the case studies were initially proposed because they were expected to result in a
460 reduction in GHG emissions, which left open the question of whether other activities might
461 result in increases. In general, energy efficiency meets both business and environmental

462 objectives, and public policy supports reductions in GHG emissions and improved
 463 sustainability in general, so these are well-funded areas of research. Nevertheless, it is
 464 possible that research and development with other objectives, or even in pursuit of these
 465 aims, could have side effects that increased GHG emissions. The same methods could be
 466 applied to quantify these. As with the GHG emissions reductions, only a few activities with
 467 large impacts are likely to be significant, so the scope of a complete review could be limited
 468 by identifying any projects likely to result in large increases in energy consumption or
 469 emissions of methane and other potent GHGs.

470 **Table 2. Summary of case study total annual emissions reductions (without attribution**
 471 **to specific universities)**

Project	Emissions reduction, kt CO₂e/year	Period
Ceramic coatings for jet engine turbine blades to improve engine efficiency	570	Retrospective
Improved delivery vehicle logistics to save fuel	63	Retrospective
Training for landfill gas inspectors to improve methane capture	400	Retrospective
Intelligent buildings for energy management	<< 1	Retrospective
	Potential 20% reduction in CO ₂ e	Prospective
Novel offshore vertical axis wind turbines compared with conventional turbines	1.7 for 1 GW installed	Prospective
Optimising defouling of oil-refinery preheat trains to reduce fuel consumption	~1 per refinery	Prospective

472

473 **5 Conclusions**

474 The results of the project met the original objectives by using case studies to develop
 475 procedures, which could be applied more widely, to quantify the external benefits of some
 476 university activities in reducing GHG emissions, termed the carbon brainprint. The estimated
 477 emissions reductions already achieved from single projects were up to 570 kt CO₂e/year. The

478 six projects were selected for study because they were expected to produce reductions in
479 GHG emissions, so the large reductions seen in three cases are probably relatively rare
480 compared with the more modest results found in the others. Whilst the carbon brainprint
481 should not be used to offset an institution's carbon footprint (up to 90 kt CO₂e/year), it
482 provides an additional method for universities to evaluate and demonstrate their wider
483 impact.

484 The main difficulty identified in the case studies was the method of attribution amongst
485 multiple parties, especially when some were from outside the university and research sector.
486 This still needs further development. The case studies only included research, consultancy
487 and training with fairly direct links to outcomes. The benefits of general educational activities
488 were not addressed and would be difficult to quantify.

489 The project highlights the significant contribution of universities to reducing the GHG
490 emissions of others, and should encourage further institutions to attempt to evaluate the
491 brainprints of other activities.

492

493 **6 Acknowledgements**

494 The Carbon Brainprint project was supported by the Higher Education Funding Council for
495 England (HEFCE) under its Leading Sustainable Development in Higher Education
496 programme, with support for case studies from Santander Universities. HEFCE, Research
497 Councils UK and the Carbon Trust were members of the steering committee, which provided
498 guidance, but did not direct the research. The Carbon Trust also advised on best practice in
499 carbon footprinting.

500 We are grateful to the many university staff at Cranfield, Cambridge and Reading
501 Universities who shared their work with us so enthusiastically.

502 We also thank the external partners and clients for the projects on which these case studies
503 are based: Rolls-Royce plc, the ETI NOVA consortium, IGD, the Environment Agency,
504 Esso, Repsol YPF, Carnego Systems Ltd and Newera Controls Ltd.

505

506 **7 References**

- 507 AEA, 2010. 2010 Guidelines to Defra / DECC's GHG Conversion Factors for Company
508 Reporting. Version 1.2.1 FINAL, Updated: 06/10/2010. Produced by AEA for the
509 Department of Energy and Climate Change (DECC) and and the Department for
510 Environment, Food and Rural Affairs (Defra), London.
- 511 Airbus, 2010. Orders and Deliveries [WWW Document]. URL
512 <http://www.airbus.com/company/market/orders-deliveries/>
- 513 Airfleets, 2011. Production list [WWW Document]. URL <http://www.airfleets.net/>
- 514 Allen, M.R., Braithwaite, A., Hills, C.C., 1997. Trace Organic Compounds in Landfill Gas at
515 Seven U.K. Waste Disposal Sites. *Environ. Sci. Technol.* 31, 1054–1061.
516 doi:10.1021/es9605634
- 517 Baboulet, O., Lenzen, M., 2010. Evaluating the environmental performance of a university. *J.*
518 *Clean. Prod.* 18, 1134–1141. doi:10.1016/j.jclepro.2010.04.006
- 519 Baldasano Recio, J.M., Gonçalves Ageitos, M., Jiménez Guerrero, P., 2005. Estimate of
520 energy consumption and CO2 emission associated with the production, use and final
521 disposal of sheets made of PVC-P, MDPE and bituminous materials. Universtat
522 Politècnica de Catalunya, Barcelona.

523 BSI, 2008. PAS 2050:2008 Specification for the assessment of the life cycle greenhouse gas
524 emissions of goods and services. British Standards Institution, London.

525 CAA, 2010. Civil Aviation Organisation web site [WWW Document]. URL
526 <http://www.caa.co.uk/default.aspx?catid=702&pagetype=68>

527 Carbon Trust, 2009. Code of good practice for product greenhouse gas emissions and
528 reduction claims (CTC 745). The Carbon Trust, London.

529 Choudhary, R., 2012. Energy analysis of the non-domestic building stock of Greater London.
530 *Build. Environ.* 51, 243–254. doi:10.1016/j.buildenv.2011.10.006

531 Clements-Croome, D.J., 2004. *Intelligent Buildings: Design, Management & Operation*.
532 Thomas Telford, London.

533 DECC, 2010. *Guidlines to Defra/DECC’s GHG Conversion Factors for Company Reporting*.
534 London.

535 Eggleston, S., Buendia, L., Kyoko, M., Ngara, T., Tanabe, K. (Eds.), 2006. 2006 IPCC
536 *Guidelines for National Greenhouse Gas Inventories*. Institute for Global
537 *Environmental Strategies*, Kanagawa, Japan.

538 ELCD, 2010. *European Life Cycle Database, ELCD II core data sets* [WWW Document].
539 URL <http://lca.jrc.ec.europa.eu>

540 Elgowainy, A., Han, J., Cai, H., Wang, M., Forman, G.S., DiVita, V.B., 2014. Energy
541 Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S.
542 Refineries. *Environ. Sci. Technol.* 48, 7612–7624. doi:10.1021/es5010347

543 Elmualim, A., Shockley, D., Valle, R., Ludlow, G., Shah, S., 2010. Barriers and commitment
544 of facilities management profession to the sustainability agenda. *Build. Environ.* 45,
545 58–64. doi:10.1016/j.buildenv.2009.05.002

546 EMEP/EEA, 2009. EMEP/EEA air pollutant emission inventory guidebook — 2009.
547 Technical guidance to prepare national emission inventories. EEA Technical report
548 No 9. European Environment Agency.

549 Faber Maunsell, 2007. Reducing the external costs of the domestic transportation of food by
550 the food industry. Department for Environment, Food and Rural Affairs.

551 Fisher, D., McKinnon, A., Palmer, A., 2010. Reducing the external costs of food distribution
552 in the UK, in: *Delivering Performance in Food Supply Chains*. pp. 459–477.

553 Grote, M., Williams, I., Preston, J., 2014. Direct carbon dioxide emissions from civil aircraft.
554 *Atmos. Environ.* 95, 214–224. doi:10.1016/j.atmosenv.2014.06.042

555 HEFCE, 2010. Carbon reduction target and strategy for higher education in England.
556 HEFCE, Bristol.

557 Humphrey, J.L., Seibert, A.F., Koort, R.A., 1991. *Separation Technologies Advances and*
558 *Priorities*, DOE/ID/12920-1. USDA, Washington, D.C.

559 IGD, 2011a. ECR UK - Sustainable Distribution [WWW Document]. URL
560 <http://www.igd.com/index.asp?id=1&fid=5&sid=43&tid=59>

561 IGD, 2011b. Sustainable distribution: miles better [WWW Document]. URL
562 <http://www.igd.com/index.asp?id=1&fid=1&sid=3&tid=41&folid=0&cid=2002>

563 Ishiyama, E.M., Heins, A.V., Paterson, W.R., Spinelli, L., Wilson, D.I., 2010. Scheduling
564 cleaning in a crude oil preheat train subject to fouling: Incorporating desalter control.
565 *Appl. Therm. Eng.* 30, 1852–1862. doi:10.1016/j.applthermaleng.2010.04.027

566 Ishiyama, E.M., Paterson, W.R., Wilson, D.I., 2009. Platform for Techno-economic Analysis
567 of Fouling Mitigation Options in Refinery Preheat Trains. *Energy Fuels* 23, 1323–
568 1337. doi:10.1021/ef8005614

569 McKinnon, A., 2009. Transport challenges and opportunities: briefing paper on the freight
570 transport sector. Prepared for the Commission for Integrated Transport.

571 NAEI, 2011. National Airborne Emissions Inventory [WWW Document]. URL
572 <http://www.naei.org.uk/>

573 Noy, P., Liu, K., Clements-Croome, D.J., Qiao, B., 2007. Design Issues in Personalising
574 Intelligent Buildings, in: Proceedings of 2nd International Conference on Intelligent
575 Environments, Athens, 5-6 July 2007. Institute of Engineering and Technology, pp.
576 143–149.

577 Ozawa-Meida, L., Brockway, P., Letten, K., Davies, J., Fleming, P., 2013. Measuring carbon
578 performance in a UK University through a consumption-based carbon footprint: De
579 Montfort University case study. *J. Clean. Prod., Sustainability management beyond*
580 *corporate boundaries* 56, 185–198. doi:10.1016/j.jclepro.2011.09.028

581 Panchal, C.B., Huang-Fu, E.P., 2000. Effects of mitigating fouling on the energy efficiency
582 of crude-oil distillation. *Heat Transf. Eng.* 21, 3–9. doi:10.1080/014576300270843

583 Pandey, D., Agrawal, M., Pandey, J.S., 2011. Carbon footprint: current methods of
584 estimation. *Environ. Monit. Assess.* 178, 135–60. doi:10.1007/s10661-010-1678-y

585 Parsons, D.J., Chatterton, J., Clements-Croome, D., Elmualim, A., Darby, H., Yearly, T.,
586 Davies, G., Wilson, I., Ishiyama, I., 2011. Carbon Brainprint. Final Report (Summary
587 report, guidance document and six case studies) (Client report No. HEFCE project
588 LSDHE43). Cranfield University, University of Reading and University of
589 Cambridge.

590 Pazirandeh, A., Jafari, H., 2013. Making sense of green logistics. *Int. J. Product. Perform.*
591 *Manag.* 62, 889–904. doi:10.1108/IJPPM-03-2013-0059

592 Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer,
593 G., 2004. Life cycle assessment Part 2: Current impact assessment practice. *Environ.*
594 *Int.* 30, 721–739. doi:10.1016/j.envint.2003.12.009

595 Qiao, B., Liu, K., Guy, C., 2006. A Multi-Agent System for Building Control, in:
596 Proceedings of IEEE/WIC/ACM International Conference on IAT, 18-22 December
597 2006. IEEE Computer Society Washington, DC, Hong Kong, pp. 653–659.

598 Raadal, H.L., Vold, B.I., Myhr, A., Nygaard, T.A., 2014. GHG emissions and energy
599 performance of offshore wind power. *Renew. Energy* 66, 314–324.
600 doi:10.1016/j.renene.2013.11.075

601 Ramanathan, U., Bentley, Y., Pang, G., 2014. The role of collaboration in the UK green
602 supply chains: an exploratory study of the perspectives of suppliers, logistics and
603 retailers. *J. Clean. Prod.* 70, 231–241. doi:10.1016/j.jclepro.2014.02.026

604 Raventós Martín, C., Longhurst, P., 2011. Development of a cost benefit model for a landfill
605 gas infrastructure development. *AWE Int.* March, 17–23.

606 Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt,
607 W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment: Part
608 1: Framework, goal and scope definition, inventory analysis, and applications.
609 *Environ. Int.* 30, 701–720. doi:10.1016/j.envint.2003.11.005

610 Ridoutt, B., Fantke, P., Pfister, S., Bare, J., Boulay, A.-M., Cherubini, F., Frischknecht, R.,
611 Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Levasseur, A., Margni, M.,
612 McKone, T., Michelsen, O., Milà i Canals, L., Page, G., Pant, R., Raugei, M., Sala, S.,
613 Saouter, E., Verones, F., Wiedmann, T., 2015. Making Sense of the Minefield of
614 Footprint Indicators. *Environ. Sci. Technol.* doi:10.1021/acs.est.5b00163

615 SQW, 2010. Carbon baselines for individual Higher Education Institutions in England.
616 HEFCE, Bristol.

617 Wiltshire, J., Wynn, S., Clarke, J., Chambers, B., Cottrill, B., Drakes, D., Gittins, J.,
618 Nicholson, C., Phillips, K., Thorman, R., Tiffin, D., Walker, O., Tucker, G., Thorn,
619 R., Green, A., Fendler, A., Williams, A., Bellamy, P., Audsley, E., Chatterton, J.,

620 Chadwick, D., Foster, C., 2009. Scenario building to test and inform the development
621 of a BSI method for assessing GHG emissions from food. Technical annex to the final
622 report. Report to Defra, Project Reference Number: FO0404.
623