May 2022

Overview Report by Main Panel B and Sub-panels 7 to 12

REF 2021 Research Excellence Framework

Contents

Executive Summary

1. The purpose of this report is to provide key data on submissions, feedback on the process of assessment, and an overview of the research submitted to Main Panel B's sub-panels in REF 2021.
2. Main Panel B saw high quality research across all submissions regardless of the scale of activity at the submitting HEI. The REF 2021 submissions represented a selection of the absolute pinnacle of physical, mathematical, computer, environmental and engineering science across the UK, with some areas notably growing in world-leading quality. Overall, 44 per cent of the research was assessed to be world leading (4*), 46 per cent internationally excellent (3*), 9 per cent internationally recognised (2*) and 1 per cent nationally recognised (1*), where these averages are weighted according to the number of Category A full-time equivalent (FTE) staff included in each submission.
3. In the equivalent report from REF 2014 the main panel compared quality to a previous exercise, however we note caution should be used in comparing the outcomes of REF 2021 to those of REF 2014. These changes are described in the Cross-main panel report. The submission changes have had a significant impact on the shape and quality of submissions. The increased selectivity of outputs combined with the requirement to submit all staff with significant responsibility for research has, on the whole, created profiles with increased levels of world leading and internationally excellent quality. Within engineering, it should also be noted that the combination of four sub-panels in REF 2014 to one single sub-panel in REF 2021 has led to a significant decrease in the number of impact case studies and environment submissions. Further comments are made in the engineering sub-section below.
4. The main panel recognised that some sub-panels in Main Panel B have received a very small sample of the outputs produced by the discipline over the review period, this was the case in REF 2014, but has been exacerbated by the submission changes introduced in REF 2021. There is variation in the size of the sample relative to the discipline, in part relating to the publishing practices within sub-disciplines and the change in submission characteristics.
5. Main Panel B highlighted the difference in scale and variation in Higher Education Institution (HEI) missions of the submissions into Sub-panels 11 and 12 compared to sub-panels 7,8,9 and 10. As a result, caution should be used when reviewing the profiles for sub-panels across Main Panel B.
6. All of the sub-panels in Main Panel B noted an increase in the proportion of outputs with more than 15 co-authors. In REF 2021, 7.0 per cent of outputs submitted to Main Panel B had more than 15 authors compared to 3.4 per cent in REF 2014. This increase is indicative of the collaborative nature of research in Main Panel B. Further consideration is recommended on the role of the author contribution statement in future assessment exercises.
7. Sub-panels noted the increase in outputs tagged as interdisciplinary, notwithstanding the wide variation in how institutions used the interdisciplinary research (IDR) flag. Further large volumes of outputs were recognised as interdisciplinary by the sub-panels. The vast majority of these were nonetheless capable of being assessed within the sub-panels. Irrespective of how they were identified, interdisciplinary outputs were treated equally

and, where necessary, sub-panels made use of cross-referral and joint assessment in order to reach their assessment. On the whole, the definitions of and guidance for interdisciplinary research were helpful, though the inconsistent use of flagging meant that no statistical analysis was possible.

8. There is a general view that the material covered by the sub-panels in Main Panel B is becoming ever more interdisciplinary, making it far easier to recognise quality across multiple disciplinary boundaries.
9. 38 per cent of outputs were judged to be world leading and a further 53 per cent judged as internationally excellent in terms of originality, significance and rigour. However, the importance of research that would meet the criteria for being internationally recognised should not be underestimated, especially in its role in creating impact.
10. Impact in Main Panel B continues to be exceptionally strong. Overall, 50 per cent of impact case studies were assessed to be outstanding and a further 38 per cent provided very considerable impact in terms of their reach and significance. The main panel recommends that further consideration be given to the number of case studies required in each submission and scoring methodology for impact and environment. Main Panel B also highlights the potential benefit of greater overlap between sub-panels and involvement of the main panel in the assessment of these elements.
11. Main Panel B wishes to commend all sub-panel members, output and impact assessors for their devotion to the assessment task that was, of necessity, carried out under unprecedented conditions.
12. Finally Main Panel B would note the extraordinary efforts made by HEIs in making such high-quality submissions, particularly in light of the global pandemic, which disrupted many of the final submission preparations for REF 2021. The Covid mitigations introduced by the Research England REF team were helpful and many institutions made use of these, but we would also recognise the efforts of many hundreds of individuals across the UK.

Overview of submission and results

13. Main Panel B (MPB) received submissions to its six sub-panels as summarised in Table 2. The total number of submissions was 354 compared to 403 in REF 2014. Note the variation in number of submissions and Category A staff FTE across the sub-panels, with Sub-panels 11 and 12 notably larger than 7,8,9 and 10.

Table 1 Submissions to REF2021 and comparison with submissions to REF2014

Panel name		Number of submissions*	Category A staff FTE	% change in Category A staff FTE	Category A staff headcount **	Number of ECRs flagged by HEIs	Number of outputs submitted	Number of outputs attributed to former staff	Number of Impact case studies
Main Panel B	2021	354	18,394.29	37.8%	19,268	3,139	45,153	1,853	1483
	2014	403	13,347		13,930	2,779	49,317	-	1,667
7	2021	39	1,781.77	28.9%	1,900	259	4,385	180	161
	2014	43	1,381		1,489	285	5,250	-	175
8	2021	40	1,502.02	22.2%	1,560	254	3,692	153	139
	2014	34	1,229		1,267	206	4,698	-	152
9	2021	44	2,214.79	29.9%	2,312	330	5,496	234	189
	2014	41	1,705		1,774	302	6,446		203
10	2021	53	2,461.11	27.5%	2,570	408	6,002	317	212
	2014	53	1,931		2,005	418	6,995	-	236
11	2021	90	3,002.21	46.8%	3,176	627	7,296	454	299
	2014	89	2,045		2,159	455	7,665	-	280
12	2021	88	7,432.39	44.8%	7,750	1,261	18,282	515	483
	2014	138	5,062		5,279	1,113	18,263	-	621

***Joint submissions counted as one. ** Category A and C in REF 2014.**

14. The per cent of eligible staff submitted is a reflection of the diversity of institutions, and their missions, submitting to UOAs. Where the percentage of eligible staff submitted is lower, there are more submissions in that UOA where a significant responsibility for research has been defined through the HEIs' Code of Practice and cannot determined by contractual status alone, as reported in HESA staff returns

15. The overall results of the assessment are shown in Table 2. This shows the average overall quality profile for each Unit of Assessment (UOA), and for the main panel as a whole. The average is calculated by weighting each submission in the UOA (or main panel) by the number of Category A staff FTE in each submission. This method is also used to calculate the FTE-weighted average sub-profiles in Tables 4, 7 ,9 and 10.

Table 2 Overall quality profiles (Category A FTE volume - weighted)

Panel name	Average percentage of research activity meeting the standard for: 4*	3*	2*	1*	Unclassified
Main Panel B	44	46	9	1	0
7 – Earth Systems and Environmental Sciences	48	43	8	1	0
8 – Chemistry	49	45	6	0	0
9 – Physics	48	47	5	0	0
10 – Mathematical Sciences	48	48	4	0	0
11 – Computer Science and Informatics	41	43	14	1	1
12 – Engineering	40	49	10	1	0

16. See paragraph 6 of the 'Summary report across the four main panels' for further information on FTE-weighted profiles.

17. It was clear from submissions that the Covid pandemic in the last few months of the REF cycle had impacted research in different ways. Some HEIs had contributed to the national and international response to the pandemic as described in both impact case studies and environment statements. Impact activities and evidence collection in the latter part of the period, especially for case studies involving engagement with the public, had been affected in a number of HEIs.

18. All sub-panels in MPB have seen an increase in the proportion of research considered to be world leading or internationally excellent. In part this indicates that the environment underpinning MPB research is thriving and compared to REF 2014 MPB research has at least maintained if not improved over the period. The increased quality of submissions to MPB also reflects HEIs' ability to better prepare and evidence impact case studies and environment statements. Main Panel B notes that in order to sustain and deepen the UK research base continued investment is vital, especially following the Covid pandemic and its effects on research activity. Further discussion of the output, impact and environment profiles is included in the sections below.

Panel working methods

Main panel working methods

19. The main panel had a key role in ensuring cross sub-panel consistency in assessment standards, employing a range of mechanisms to support this. The main panel confirms that sub-panels applied the working methods consistently.
20. In previous REF exercises and for the early part of REF 2021, the main panel meetings were held in person. From March 2020 through to completion, the meetings were held virtually, in accordance with Covid restrictions. The main panel noted advantages of virtual meetings, including easier participation for international members and reduced travel time. Overall, the main panel were satisfied that the work could be carried out effectively in this manner but note that the lack of more spontaneous discussion and interaction impacted morale and reduced the opportunity for continuous calibration.
21. The main panel undertook equality and diversity training and discussed potential biases prior to key points in the assessment process. Furthermore, a Fairness in REF Intention Plan was drawn up to explore how the main panel as a whole, and individual members, could mitigate biases in the assessment process. The sub-panels also developed Fairness in REF Intention Plans drawing on the Main Panel B plan, but tailored it to their needs and specificities of their disciplines.
22. In line with Annex D of the 'Panel criteria and working methods', the main panel and its sub-panels maintained records of major and minor interests throughout the assessment process, and conflicted panel members were not involved in either the assessment of submitted items or HEIs in which they had declared a disqualifying interest, or in any deliberations about these. Panel members withdrew from any discussion of conflicted individual items or HEI submissions as appropriate. This applied to all members of the sub-panel executives (chairs, deputies, advisers and secretaries). Sub-panel executives reviewed declarations of minor interest to determine what level of action was needed to avoid inappropriate engagement in the assessment process
23. Main panel calibration exercises were undertaken for outputs, impact case studies and environment statements. In all cases, the main panel calibration sample included items from all Main Panel B sub-panels including a selection of interdisciplinary outputs. These items were then also included in sub-panel calibration exercises. Detailed discussion at main panel allowed sub-panel chairs to explore in detail the application of assessment criteria and standards, drawing on the input of international members, particularly in relation to outputs, and user members, particularly in relation to impact items. This experience, together with agreed main panel advice, then supported the sub-panel calibration exercises.
24. Further calibration was undertaken for outputs, impact case studies and environment statements across all four main panels to ensure consistency of interpretation of star levels.
25. Assessments resulting from calibration exercises were disregarded following completion of the calibration exercises and these items subsequently allocated in the normal way to sub-panel members for assessment.

26. Main Panel B had six international members who brought expertise which covered the range of Main Panel B disciplines. A number of them had expertise which spanned several sub-panels. International members contributed fully to the work of the main panel and took a particular role in ensuring the international comparability of assessment standards for outputs, as well as having an oversight of the management and governance of the overall assessment process. They participated in a number of sub-panel meetings dealing with the calibration and assessment of outputs, impact and environment. They also provided input to the handling of grade boundaries for outputs and impact assessment.
27. The international members expressed their confidence in the assessment process. They were impressed by its robustness, credibility and comparability across disciplines and its effectiveness in dealing with disciplinary differences. They noted that the exercise was well managed with effective governance of the process.
28. Main Panel B had three user members who brought expertise in a number of relevant industry, government and public engagement areas. Main panel user members contributed fully to the work of the main panel and took a particular role in the assessment of impact. Each main panel user member participated in the meetings of several sub-panels when dealing with the assessment of impact, and they were therefore able to provide valuable input to the consistency of assessment across sub-panels. They also provided input to the handling of grade boundaries for impact assessment.
29. The main panel user members observed the assessment process to be robust and found that working across a range of sub-panels was effective.
30. The main panel user members and international members noted that the move to virtual meetings diminished the opportunity to over-see multiple panels and liaise across sub-panels.
31. A number of observers from UKRI attended the main panel meetings and some took part in cross-main panel calibration exercises.
32. The main panel was supported by a secretariat consisting of three panel advisers. Each adviser was also responsible for guiding the work of a cluster of two of the six sub-panels, and the sharing of the advisers across sub-panels proved very beneficial in helping to ensure consistency of assessment processes across the sub-panels.
33. The main panel chair also attended a number of sub-panel meetings to observe their work and to seek feedback and check for consistency of approach and assessment standards.
34. The main panel reviewed the assessment outcomes emerging from the sub-panels' work. This was undertaken on an ongoing basis as work was completed by sub-panels to allow consistency of assessment to be monitored. All sub-panels made recommendations to the main panel on sub-profiles and overall profile for each HEI in their submissions, with the main panel collectively approving these results.
35. The main panel confirms that these working methods led to consistent standards being applied across all sub-panels in Main Panel B. The early work undertaken by sub-panel chairs during the criteria-setting phase was particularly advantageous in establishing consistency in the guidance and working methods across sub-panels.
36. The approach to appoint only a sub-set of the full sub-panel at criteria-setting phase has presented some challenges, particularly when inducting and integrating assessment phase members into the agreed criteria and working methods.

Sub-panel working methods

37. Sub-panels undertook calibration exercises for outputs, impact case studies and environment statements, with these exercises following on from the main panel calibrations and including the items from the specific sub-panel which had been considered in the main panel exercise. Output assessors were fully involved in output calibration and impact assessors were fully involved in impact calibration. In addition, some main panel members contributed to output and environment calibration. User members contributed to impact calibration, in all cases working across a number of sub-panels. As noted previously, the assessments resulting from all calibration exercises were disregarded and these items were allocated in the normal way to sub-panel members for assessment. Calibration was an ongoing process with referral back to the main panel at key milestones, for example, at 25 percent and 50 per cent completion of output assessment, to ensure that there was consistency in the interpretation of star levels.
38. As set out in the 'Panel criteria and working methods', sub-panel chairs, consulting with deputy chairs and other panellists as appropriate, allocated work to sub-panel members and assessors with appropriate expertise, taking account of any conflicts of interest. Where sub-panels had requested a taxonomy be applied to submitted outputs, this taxonomy was used to aid the allocation of outputs to reviewers. Where a taxonomy had not been requested, sub-panels executives had additional work in manually allocating each output to a reviewer with appropriate expertise. In some cases, the sub-panel executives were assisted by journal defined taxonomies, but highlighted the challenge of using the largely journal defined taxonomies developed by, e.g., Clarivate, to identify the key science within any given output and match and allocate that output to appropriate readers. The result was a significant amount of additional work by the sub-panel executive to make sure that the outputs were allocated to reviewers with appropriate expertise. The sub-panels within Main Panel B strongly recommend that a taxonomy be required for all sub-panels and used throughout any future REF exercises to support the allocation of outputs to reviewers and to enable the sub-panels to report more effectively on sub-disciplines.
39. Output assessors and impact assessors worked in the same way as panel members in relation to the assessment of outputs and impact respectively, including workload and contribution to the sub-panels' recommendations. All sub-panel memberships also included full panel members identified as user members because they came from industrial, government or similar environments rather than the academic community. While in some cases, depending on expertise, these members had either zero or reduced output workloads, they contributed to the assessment of impact and environment to a good range of the sub-panels, and to the work of the panel overall. Their contribution and commitment were appreciated by all the sub-panels.
40. Table 3 provides a summary of double-weighting requests and outcomes by sub-panel. Only a very small number of outputs for which double-weighting was requested were submitted to Main Panel B sub-panels. These were considered first by the panellists to whom they had been allocated for assessment, who judged the merit of the case made for double-weighting based on the criteria. Only once a decision about double-weighting had been made, was the quality of the output, and if appropriate, the reserve output, assessed. Of the 17 outputs submitted with requests for double-weighting, 16 were judged to meet the criteria.

Table 3 Double weighting requests and outcomes (page 10).

Table 3 Double weighting requests and outcomes

Panel name	Double-weightings requested	Double-weightings accepted
Main Panel B	17	16
7 – Earth Systems and Environmental Sciences	8	7
8 – Chemistry	0	0
9 – Physics	0	0
10 – Mathematical Sciences	4	4
11 – Computer Science and Informatics	0	0
12 – Engineering	5	5

41. Table 4 below provides a summary of the cross-referrals in and out of Main Panel B sub-panels, including a breakdown of activity within the six main panel sub-panels and to/from other main panel sub-panels.

42. Sub-panels in Main Panel B cross-referred a total of 1,055 outputs to other sub-panels, comprising 2 per cent of the total outputs submitted. They accepted 1,139 incoming cross-referral requests from other sub-panels, covering a wide range of outputs falling within their remits. Sub-panels 7, 9 and 10 also made use of joint members or output assessors that reviewed outputs across two UOAs to further support the assessment of research at the UOA boundaries. Two impact case studies were also cross referred.

43. The sub-panels were confident that the expertise of their membership was sufficient to assess the vast majority of the outputs received and outward cross-referrals were only requested when they were on or beyond the boundaries of their subject scope. In making these judgements, sub-panels took note of institutions' requests for sub-panels to consider cross-referral, but the decision on cross-referral rested with the sub-panel irrespective of whether such requests had been made or not.

Table 4 Cross-referral

Panel name	Number of outputs cross-referred out of panel	Number of outputs cross-referred in to panel
Main Panel B	1,055	1,139
7 – Earth Systems and Environmental Sciences	246	201
8 – Chemistry	20	205
9 – Physics	149	201
10 – Mathematical Sciences	184	116
11 – Computer Science and Informatics	14	180
12 – Engineering	442	236

44. Joint consideration of outputs (joint assessment) was requested by sub-panels, especially where advice was needed on applications of the subject matter in other disciplinary fields. This was particularly prevalent where applications were in disciplines covered by other main panels. Joint assessment was a useful mechanism in supporting the assessment of interdisciplinary research. The sub-panels used joint assessment for 178 outputs, representing 0.4 per cent of the outputs submitted to Main Panel B.

45. Main Panel B note that there were challenges in the working practices of cross-referral and joint assessment and further refinement of these would benefit the administration of any future research assessment exercises.

46. More detailed discussion of cross-referral arrangements is included in sub-panel sections of this report, where appropriate.

Scoring schemes

Outputs

47. Each output was assessed against the criteria of originality, significance and rigour and given an integer score on the scale 0-4, corresponding to the starred level descriptors set out in Annex A of the 'Guidance on submissions. Sub-panels' working methods included mechanisms to identify outputs where the quality fell on the borderline between assessment scores, and to enable careful consideration of appropriate scores in these cases. In sub-panels 7, 8, 9, 10 and 12, outputs were scored using a thirteen-point scale and then consolidated to a 0-4 scale. Sub-panel 11 used a bespoke process as described in their sub-panel section.

48. Modelling was carried out to ensure that outputs submitted to REF 2021 were assessed consistently against the criteria.

Impact

49. In developing the impact sub-profiles, all the sub-panels used the same method of assigning a star level to each case study. Each case study was graded on a nine-point scale consisting of integer and half-integer scores from 0-4, with the integer scores corresponding to the starred level descriptors for the impact sub-profile. Half-integer scores of 0.5, 1.5, 2.5 or 3.5 were assigned to case studies that were judged to be between two of the starred levels and included elements of both the upper and lower star-levels. Impact case studies were reviewed by multiple members and assessors, who then came together to agree a score on the nine-point scale.

50. An impact case study with a half-integer score contributed to the impact sub-profile by assigning half of its grade to each of the two integer star levels that the half-integer score fell between. For example, if there were four case studies in the submission, each case study contributed 25 per cent to the impact sub-profile. If one of the case studies was graded as 3.5, it contributed 12.5 per cent at 4* and 12.5 per cent at 3* to the impact sub-profile.

Environment

51. In developing the environment sub-profiles, all the sub-panels used the same method of assigning star levels to the submitted material. Each section of the environment template was graded on a nine-point scale consisting of integer and half-integer scores from 0-4, with the integer scores corresponding to the starred level descriptors for the environment sub-profile. Half-integer scores of 0.5, 1.5, 2.5, or 3.5 were assigned to sections of the environment template that were judged to be midway between two integer star levels.

52. A section of the environment template with a half-integer score contributed to the environment sub-profile by assigning half of its grade to each of the two starred levels that the borderline grade fell between.

53. Main Panel B recommends further consideration be given to the scoring methodology for Environment and Impact allowing sub-panels to better represent the variations in quality.

Overview of research outputs

54. Table 5 gives the overall FTE volume weighted output sub-profiles for the main panel and each of its sub-panels. For an explanation of FTE volume weighting please see paragraph 16.

55. Sub-panels and the main panel consider that the increase in world-leading quality of the submitted outputs reflects both the change in REF 2021 submission rules but also indicates a thriving research base from which to select some exceptionally strong outputs. Several sub-panels noted a change to the HEIs submitting into the UOA, many entering a UOA for the first time, but in all cases pockets of world-leading or internationally excellent research outputs were found.

Table 5 Outputs sub-profiles for main panel and sub-panels (Category A FTE volume - weighted)

Panel name	Average percentage of outputs judged to meet the standard for: 4*	3*	2*	1*	Unclassified
Main Panel B	38.7	53.1	7.4	0.7	0.1
7 – Earth Systems and Environmental Sciences	44.8	45.9	8.6	0.5	0.2
8 – Chemistry	44.9	50.8	4.1	0	0.2
9 – Physics	44.9	50.3	4.5	0.1	0.2
10 – Mathematical Sciences	43.4	53.5	2.9	0.1	0.1
11 – Computer Science and Informatics	37.6	49.2	12.6	0.5	0.1
12 – Engineering	33.1	57.5	8.0	1.3	0.1

56. Main Panel B and the sub-panels recognise interdisciplinarity is inherent in the physical and environmental sciences and engineering and the UOA descriptors recognised this. Interdisciplinary work now represents a significant proportion of the outputs submitted to Main Panel B and sub-panels received many examples of excellent interdisciplinary research. The sub-panels had appropriate membership and processes to enable them to robustly assess most of the interdisciplinary work within the sub-panel to which it had been submitted. Joint assessment was, however, used when necessary.

57. MPB and sub-panels noted that the interdisciplinary flag was used inconsistently by HEIs of all types. Many HEIs did not use it at all whereas others flagged selected outputs. A few HEIs flagged a high proportion of their outputs as interdisciplinary.

58. Citation data, provided by Clarivate, were used by sub-panels 7, 8, 9 and 11. For sub-panels 7, 8, 9 and 11 it was noted that there could be variability in the quality and usefulness of the data at sub-discipline level. As set out in the criteria document, for these sub-panels, panellists used their academic judgement to evaluate the outputs and only used citation data when appropriate to inform the assessment of the academic significance of outputs. Further comment on the use of citation data is included in sub-panel sections of this report, where appropriate.

59. Sub-panels 11, and 12 made use of the information (100 words) that institutions were invited to submit about the significance of outputs, not evident from the output itself. Where used appropriately, this provided useful information that was very helpful in assessing the significance of outputs. However, these sub-panels were disappointed that not all institutions made effective use of this part of the submission and a small number of HEIs actually used it in ways that were explicitly disallowed in the Main Panel B published guidance.

60. Sub-panel 9 collected information about author contribution for outputs with more than 15 co-authors. No additional information was required about the author's contribution when the staff member to whom the output was attributed was identified as either lead or corresponding author (regardless of the number of authors). For each submitted

co-authored output where there were more than 15 authors and where the submitted member of staff was not identified as the lead or corresponding author, institutions were required to affirm the substantial contribution to the research by the submitted member of staff in a statement using up to 100 words.

61. Sub-panels 9 and 10 note the increase in hyper-authored papers and provide further comment in their respective sub-panel reports

62. For review articles and some other output types, the main panel's criteria document invited the submission of textual commentary identifying the original research or new insights reported. This information was not provided for some review articles submitted. As noted in REF 2014, the main panel continues to recommend that consideration be given to this requirement being mandatory for future exercises.

63. Table 6 shows a breakdown of outputs types within each UOA, and for the main panel as a whole.

Table 6 Breakdown of output types

Type Code	Output type	Main Panel B	7 – Earth Systems and Environmental Science	8 – Chemistry	9 – Physics	10 – Mathematical Sciences	11 – Computer Science and Informatics	12 – Engineering
A, B, C	Books and parts of books	118	26	0	2	26	37	41
D	Journal article	42,999	4,357	3,688	5,483	5,823	5,573	18,075
E	Conference contribution	1,859	1	1	1	35	1,672	149
U	Working paper	131	0	0	9	118	3	1
F	Patent/ published patent application	15	0	3	1	0	2	9
N,O	Research reports	9	1	0	0	0	2	6
G,H,Q,S	Software, website content, research datasets	3	0	0	0	0	3	0
I,J,K,L, M,P,R,T	Other types	5	0	0	0	0	4	1
	Total	**45,139**	**4,385**	**3,692**	**5,496**	**6,002**	**7,296**	**18,282**

64. In relation to the future assessment of outputs, the main panel has the following observations:

    a. Where sub-panels elect to use a taxonomy, Main Panel B recommends applying this taxonomy consistently across all stages of the assessment including the survey of submission intentions, descriptors, and submission system.

    b. Main Panel B welcomed the open access requirements for outputs, recognising that all forms of open access should be supported, for example the continued use of repositories such as ArXiv.

Overview of impact

65. Table 7 gives the overall FTE volume weighted impact sub-profiles for the main panel and each of its sub-panels. All sub-panels received examples of outstanding impact from a wide range of HEIs.

66. Sub-panels were pleased by the wide range of types of impact received and the quality of the research and outputs that underpinned case studies. The sub-panels were impressed by the exceptional reach and significance of many of the examples of impact submitted. Further comments on the range and types of impact are given in the sub-panel sections of this report.

67. Across all sub-panels a relatively small number of case studies were submitted based on public engagement activity. It was recognised that this may in part be due to the underuse of quantitative and qualitative approaches to evaluating public engagement activities in the engineering and physical sciences. Main Panel B benefited greatly from the membership of an expert who worked across the sub-panels to support the assessment of public engagement impact case studies.

Table 7 Impact sub-profiles for the main panel and sub-panels (Category A FTE volume - weighted)

Panel name	Average percentage of impact judged to meet the standard for: 4*	3*	2*	1*	Unclassified
Main Panel B	51.0	38.4	8.9	1.3	0.4
7 – Earth Systems and Environmental Sciences	53.8	41.0	5.2	0.0	0.0
8 – Chemistry	53.1	39.0	7.1	0.8	0.0
9 – Physics	46.9	46.5	6.4	0.2	0.0
10 – Mathematical Sciences	55.4	37.7	5.7	0.8	0.4
11 – Computer Science and Informatics	50.4	34.4	10.3	2.7	2.2
12 – Engineering	49.9	37.0	11.6	1.5	0.0

68. The panel recognises that many HEIs are actively developing strong environments in which to support and promote impact but considers that it is also important to continue to recognise that research can lead to unanticipated impacts. Furthermore, it was noted that as we continue to report on impact, the fundamental underpinning research is not necessarily referenced in the case study. It should not be presumed that the impact is only as a result of the research stated, but potentially a much more extensive series of research over many decades

69. Sub-panels welcomed the easier access to the corroborating evidence for impact case studies, where it had been possible for HEIs to submit this as part of their submission. They considered that the case study format remains an effective way of assessing impact, and that the volume of case studies relative to submitted FTEs was appropriate. However, they noted that very large submissions were able to make highly selective decisions around impact case studies, compared to small submissions where a minimum of two cases was required. Similarly in some cases, the panel noted particular challenges in submitting cases for newer units, where the research base had not reached maturity.

70. They also considered that the 2* threshold for the quality of the underpinning research was appropriate, and it was notable that only a very small proportion of case studies were assessed as not meeting this threshold. However, there still appears to be misunderstanding in some HEIs on what constitutes eligible underpinning research for impact.

71. The same criteria and processes were applied to all impact case studies, irrespective of if they had been flagged as continued or not.

72. In terms of the submitted case studies, sub-panels observed that the best case studies made a clear case for the links between the underpinning research and the impact claimed and provided quantitative evidence of the reach and significance of the impact in the assessment period. Some case studies were submitted where the impact was at a very early stage and was yet to develop more fully. A small number of case studies included a description of anticipated future impact, which was not eligible for assessment.

73. Many case studies contained in-depth evidence of the impact achieved but in other cases the evidence provided to corroborate claims of impact was insufficient. The sub-panels recognise the difficulty of obtaining corroborating evidence from some industrial and government sources. An alternative measurable might be, for example, evidence of sustained and enduring third party support for a given research activity. Similar caveats might apply to case studies that can only be viewed by assessors with an appropriate level of security clearance; the sub-panels found it challenging to assess the small number of such submitted impacts in a timely and even-handed way.

74. The panel noted that the submitted case studies were on the whole, of very high quality with over 88 per cent demonstrating outstanding or very considerable reach and significance. The panel reflected that this is a strong indication of the impact of UK research. The panel notes that there are some types of impact that are harder to evidence and that these may not have featured in the case studies submitted to REF 2021.

75. In relation to the future assessment of impact, the main panel has the following observations:

    a. Strengthening the guidance around the importance of linking the research to the impact, in some impact case studies this was not sufficiently clear rendering them unclassified.

b. Main Panel B recommends that further consideration should be given to the impact case study requirements for HEIs submitting to a UOA for the first time. In the current exercise HEIs were required to submit a minimum of two impact case studies, this may disadvantage new submissions which cannot make use of the underpinning research period. The main panel suggests that, in any future REF exercises, some allowance is made for emerging submissions.

c. Main Panel B recommends further scrutiny be given to the number of case studies required where there is disparity between small units potentially submitting an impact case for every five FTE and larger units submitting an impact case for, on average, every 20 FTE.

Overview of research environment

76. Table 10 gives the overall FTE volume weighted environment sub-profiles for the main panel and each of its sub-panels. Overall, the quality of the environment submissions presented was exceptionally high, with evidence that many units have sustainable environments conducive to producing research of world-leading and internationally excellent quality.

77. All sub-panels have seen an increase in world leading and internationally excellent research environments, compared to REF 2014. In part, this is as a result of efforts across the disciplines in Main Panel B to address staff development needs at all career stages, progress equality and diversity agendas, diversify and increase research income and to maximise collaboration opportunities. The sub-panels welcomed the increased use of data to substantiate successes.

78. The sub-panels recognised the challenges facing small submissions and submissions from recently established departments. In compiling environment statements, it was (relatively) easier for HEIs submitting large numbers of FTEs to fill the requisite number of pages with impressive narrative and records of achievement. For example, smaller submissions can be limited in what they can achieve within the unit and may sit within a larger, multidisciplinary school and they rely on HEI-level or school-level policies and activity. Where these activities were included in the institutional statements and the two statements were not cross referenced, it was not clear how units related to their institutional context. Smaller units could be more explicit on how they interact with these wider activities. Examples of wider influence in the academic community will inevitably increase in proportion to the size of the unit and this was taken in to account during the assessment.

79. The incorporation of support for impact into the environment statement also allowed many excellent examples of impact and engagement strategies and evidence of their success to be highlighted. The strongest statements illustrated the synergies across their research and impact strategies and how these supported people, income generation and collaborations and vice versa.

Table 8 Environment sub-profiles for the main panel and sub- panels (Category A FTE volume - weighted)

Panel name	Average percentage of environment judged to meet the standard for: 4*	3*	2*	1*	Unclassified
Main Panel B	51.0	35.5	11.9	1.6	0.0
7 – Earth Systems and Environmental Sciences	50.1	35.5	13.3	1.1	0.0
8 – Chemistry	55.3	36.5	7.7	0.5	0.0
9 – Physics	61.9	37.1	1.0	0.0	0.0
10 – Mathematical Sciences	53.7	40.4	5.6	0.3	0.0
11 – Computer Science and Informatics	36.1	33.9	25.7	4.3	0.0
12 – Engineering	52.2	33.7	12.3	1.8	0.0

80. Many submissions detailed excellent achievements over the period, with the majority delivering on well-articulated plans and strategies. The best submissions also articulated goals for the future, but the panels remained cognisant of the impact of Covid and were understanding of submissions that were more guarded in their future aspirations.

81. Several HEIs outlined future strategies that include a major, and important, role in helping drive local regional industries and the local economy. The main panel considers this a legitimate and worthwhile ambition that can be rewarded by the REF assessment where the principles and processes adopted by HEIs clearly demonstrate best practice and are conducive to supporting research and impact at the highest levels.

82. There was good evidence of progress and greater understanding of the challenges in equality and diversity, with initiatives like Athena SWAN and the Race Equality Charter supporting such change. Some EDI plans still lacked details and data, and Main Panel B would encourage greater transparency in providing data on all protected characteristics. There were some examples of best practice in family friendly policies, promotion processes and EDI training. Across the vast majority of submissions to Main Panel B there was heightened awareness of issues and plans in place, particularly around recruiting, supporting, and promoting women. However, the sub-panels note that there is still a lot that could be done to encourage a more diverse research community.

83. There was strong evidence provided in collaboration and contributions to the research base, with global reach in many statements. The sub-panels noted that in many submissions noted a thriving impact culture and some excellent examples of working with industry, business and building regional, national and international partnerships.

84. The sub-panels noted that in the very best statements, an embedded approach to impact was evident across all four sections.

85. Where institutions chose to append a Covid statement, on the whole they articulated the practices engaged across the UK and shared a great deal in common.

86. Institutional statements provided context but were generally considered unhelpful by sub-panel members. In a small number of instances, the contextual elements included in the institutional statement were perceived to be useful, but this was certainly not universally the case.

87. Table 9 gives a summary of the data submitted in the REF 4a, 4b and 4c that was used to inform the assessment of the "people" and "income, infrastructure and facilities" sections of the environment template.

Table 9 Summary of environment data for Main Panel B

Panel name	Category A staff head count	Category A Staff FTE	Total Doctoral Degrees Awarded in REF period	Total research income for REF period (£000)*
Main Panel B	19,268	18,394.62	53,285	14,589,290
7 – Earth Systems and Environmental Sciences	1,900	1,781.77	4,085	1,273,713
8 – Chemistry	1,560	1,502.02	7,356	1,650,091
9 – Physics	2,312	2,214.79	6,442	2,513,251
10 – Mathematical Sciences	2,570	2,461.11	4,501	686,387
11 – Computer Science and Informatics	3,176	3,002.21	6,658	1,372,331
12 – Engineering	7750	7,432.39	24,243	7,093,517

88. Table 10 shows the doctoral degrees awarded annually by sub-panel.

89. In REF 2014 a total of 31,027 doctoral degrees were awarded over a five-year period, equating to 6,205 per annum.

90. In REF 2021 a total of 53,290 doctoral degrees were awarded over a seven-year period, equating to 7,612 per annum.

91. This marked increase in doctoral degrees awarded signals the vitality of the sub-disciplines and success of doctoral training partnerships during the REF 2021 period. Main Panel B also notes the strong trajectory during the REF 2021 period with year on year increases in degrees awarded (with the exception of a drop in 2019-20, potentially as a consequence of the Covid pandemic).

Table 10 Doctoral degrees awarded by Sub-panel (page 20).

Table 10 Doctoral degrees awarded by Sub-panel

Panel name	2013 -14	2014 -15	2015 -16	2016 -17	2017 -18	2018 -19	2019 -20	Total
Main Panel B	6606.1	7,146.9	7,401.8	7,689.5	8,143.7	8,272.7	8,024.0	53,284.6
7 – Earth Systems and Environmental Sciences	544.0	569.5	580.1	543.2	606.3	621.4	620.0	4,084.6
8 – Chemistry	962.5	1,025.5	1,026.2	1,064.7	1,129.9	1,064.7	1,082.9	7,356.2
9 – Physics	835.5	870.1	829.4	947.0	956.2	1,004.5	999.2	6,441.8
10 – Mathematical Sciences	515.5	613.1	613.7	650.1	681.2	715.6	711.6	4,500.9
11 – Computer Science and Informatics	808.9	925.9	959.0	918.9	1,065.8	1,025.6	953.9	6,658.0
12 – Engineering	2939.6	3,142.8	3,393.5	3,565.6	3,704.2	3,840.9	3,656.4	24,243.1

92. Table 11 shows the income per sub-panel over the period and Table 12 shows research income by source.

93. In REF 2014 a total of £7,233,562 (£000) external income was reported over a five-year period, equating to £1,446,712 (£000) per annum.

94. In REF 2021 a total of £14,589,290 (£000) external income was reported over a even-year period, equating to £2,084,184 (£000) per annum. The figures are not adjusted for inflation,

Table 11:Total nominal external research income (£000)

Panel name	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2 019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
Main Panel B	1,666,118	2,009,810	2,182,672	2,084,184	14,589,290
7 – Earth Systems and Environmental Sciences	165,772	180,867	185,415	181,959	1,273,713
8 – Chemistry	206,783	247,662	239,129	235,727	1,650,091
9 – Physics	274,828	347,117	378,261	359,036	2,513,251
10 – Mathematical Sciences	86,914	97,359	100,423	98,055	686,387
11 – Computer Science and Informatics	168,534	185,162	203,727	196,047	1,372,331
12 – Engineering	763,288	951,644	1,075,717	1,013,360	7,093,517

Table 12 Total nominal external income broken down by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	776,556	860,080	1,013,308	957,596	6,703,175
UK-based charities (open competitive process)	56,535	61,943	83,655	76,679	536,753
UK-based charities (other)	8,947	9,192	13,910	12,527	87,690
UK central government bodies/local authorities, health and hospital authorities	173,932	213,784	306,861	274,575	1,922,022
UK central government tax credits for research and development expenditure	0	180,538	12,634	34,815	243,705
UK industry, commerce and public corporations	167,600	183,155	184,732	182,059	1,274,415
UK other sources	12,866	14,558	15,365	14,892	104,247
EU government bodies	334,766	351,028	368,976	361,525	2,530,672
EU-based charities (open competitive process)	878	572	406	497	3,481
EU industry, commerce and public corporations	20,517	25,917	32,978	30,189	211,324
EU (excluding UK) other	12,248	12,087	12,252	12,228	85,594
Non-EU-based charities (open competitive process)	6,841	6,378	7,773	7,440	52,082
Non-EU industry commerce and public corporations	60,935	56,563	72,164	68,331	478,320
Non-EU other	33,496	34,019	57,659	50,830	355,809

95. Table 13 shows research income in kind by sub-panel. For REF this is defined as the estimated value of Research Council facility time allocated through peer review and used by researchers at submitted units. For some UOAs the data does not reflect the full amounts received due to complications in attributing the data to single submissions.

Table 13 Nominal research income in kind broken down by sub-panel (£000)

Panel name	Income for AY 2013-14	Income for AY 2014-15	Income for AY 2015-16	Income for AY 2016-17	Income for AY 2017-18	Income for AY 2018-19	Income for AY 2019-20	Total income-in-kind
Main panel B	226,464	257,805	276,300	261,536	268,507	252,987	302,277	1,845,875
7 – Earth Systems and Environmental Sciences	7,212	8,930	9,463	8,489	8,795	8,055	7,313	58,258
8 – Chemistry	23,579	23,370	25,406	27,488	22,497	26,067	23,845	172,252
9 – Physics	163,201	179,472	185,447	178,531	184,989	160,288	213,393	1,265,320
10 – Mathematical Sciences	595	621	2,833	970	1,054	1,553	5,778	13,403
11 – Computer Science and Informatics	0	8	62	234	221	101	429	1,055
12 – Engineering	31,877	45,405	53,089	45,824	50,951	56,923	51,519	335,587

96. These data demonstrate that BEIS remains a critical source of funding for UK research in Main Panel B. EU funding is also noted as a significant contributor to the external income secured across Main Panel B during the REF 2021 period.

97. Sub-panels reported an increase in interdisciplinary working and more collaborative research, both within academia and with external partners. UK science and engineering continues to benefit from major international collaborations and access to national and international facilities.

98. Main Panel B observed that the strongest environment statements demonstrated synergies across their strategy, collaboration, income, use of facilities and investment in further infrastructure.

99. In relation to the future assessment of environment, the main panel has the following observations:

- Research-income-in-kind information lacked robustness. Opportunities to standardise collection of such data would be welcomed by Main Panel B.
- Further consideration of a more granular scoring scale for environment statements.
- The institutional statement was generally considered unhelpful, the sub-panel suggests its burden and value require further assessment.

Sub-panel reports

100. Detailed subject-specific comments from the six sub-panels of Main Panel B follow.

UOA 7: Earth Systems and Environmental Sciences

Summary of Submissions

	2021	2014	% difference
Number of submissions*	39	45	-13.3%
Category A staff FTE	1,781.77	1,381	+29.1%
Category A staff headcount**	1,900	1,489	+27.7%
Number of outputs†	4,385	5,250	-16.5%
Outputs per Category A staff headcount**	2.31	3.53	-34.6%
Impact case studies†	161	175	-8.0%

***Joint submissions counted as one. **Category A and C in REF 2014. † change in methodology since REF 2014**

Overall Profile for the Sub-panel

	Average percentage of impact judged to meet the standard for:				
	4*	3*	2*	1*	Unclassified
Overall	48	43	8	1	0
Output	44.8	45.9	8.6	0.5	0.2
Impact	53.8	41.0	5.2	0.0	0.0
Environment	50.1	35.5	13.3	1.1	0.0

1. The sub-panel received 39 submissions, comprising 1,900 Category A researchers and an FTE total of 1,781.77. The sub-panel received six submissions from HEIs that had not previously returned submissions to this UOA, contributing 7% of the overall FTE within the UOA. There is a slight decrease in the number of submissions made to this UOA, which may be a reflection of the multidisciplinary nature of many Earth Systems and Environmental Science research units. Comparisons between the 2014 and 2021 submissions and associated outcomes should be made cautiously, due to the significant changes in submission rules of the two exercises.
2. As noted in REF2014 and previous research assessment exercises, the scientific understanding of the Earth and the environment is fundamental to addressing global grand challenges. Research in this subject area generates applications of immense value

to a very wide variety of economically and socially vital industries, as well as providing essential information to guide governments and policy formers, but it also gives insights into our planet that are deeply fascinating to the public and the media. The relevance of the research in this discipline to policy is emphasised by recent declarations of climate and biodiversity loss emergencies by governments and public bodies around the world; in addition, research into the Earth and environment also engages with high profile emerging issues of public concern relating to environmental pollution such as both microplastics and urban air quality and health.

3. The submissions to this sub-panel reflected the inherent multidisciplinary nature of Earth Systems and Environmental Science research units; sub-panel (SP) 7 was involved with many out-going cross-referrals with most going to the Geography and Environmental Studies sub-panel. 201 outputs submitted to other cognate sub-panels were cross-referred into SP 7 from a wide range of sub-panels including Geography and Environmental Studies, Agriculture, Food and Veterinary Sciences and Biological Sciences.
4. It is the sub-panel's impression that the quality of the submissions to REF 2021 was exceptionally high. A significant majority of submitted outputs were considered world-leading or internationally excellent. The sub-panel reviewed a wide range of impact types and found excellence in all areas. Similarly, in the vast majority of submissions, there were aspects of environments conducive to supporting world-leading or internationally excellent research.

Outputs

5. Earth Systems and Environmental Sciences continues to produce outputs of the highest international standard across its full range of disciplines and the outputs submitted showed continued excellence and sustainability in the discipline. The vast majority of outputs were judged to be of high international calibre (91 per cent four star or three star) with 45 per cent assessed as world-leading (four star). A large majority of institutions presented evidence that they are carrying out world-leading science, with clusters of internationally competitive groups. World-leading and internationally excellent research was identified across all sub-disciplines within the sub-panel, with notable strengths for each highlighted below.
6. The sub-panel received interdisciplinary outputs across all sub-disciplines and identified a significant additional number that had not been flagged by the HEI as interdisciplinary research (IDR). This provides good evidence that IDR approaches are now mainstream, and that there is strong appreciation that an interdisciplinary approach enhances critical thinking, both within Earth and environmental sciences and across the broader boundaries of social science, economics, arts and humanities. In totality, this is proving useful in addressing global problems/challenges. The sub-panel would encourage this continued integration of the sciences, social science, economics, arts and humanities to address these challenges. The sub-panel notes that the increased interdisciplinarity required for tackling actual and potential global challenges presents increasing opportunities and necessities for Earth Systems and Environmental Sciences researchers to be trained in recognising and working with research methodologies of the social sciences and humanities.

7. As in REF 2014, the sub-panel boundaries continue to be fluid with outputs spanning the range of disciplines present in Main Panel B and other panels. The sub-panel's perception is that the range of outputs was wider than in REF 2014, particularly in terms of an increased presence of more social science- and environmental economics-facing outputs. The use of computational modelling and machine learning continues to grow and proliferate into new areas and applications. Since REF2014, the vastly increased quantities of earth orbiting satellite data have transformed research into the earth and its environment, including data processing algorithms, validation, novel observations, models and their interpretation. They have been used in studies from the core through to the crust, the oceans, biosphere, cryosphere and atmosphere, and there are examples of world-leading outputs in all these areas.
8. The sub-panel received cross-referral requests accounting for 8 per cent of the outputs submitted; a small number of HEIs made particular use of these requests. Where appropriate these outputs were cross-referred, and advice sought from other sub-panels across all main panels. Where the sub-panel felt they had the competence, these outputs were reviewed within the sub-panel.
9. World-leading and internationally excellent research was found in all output types. The sub-panel was consistent in applying the criteria of originality, significance and rigour to all outputs and particularly welcomed the increasing number of conceptual papers and longer form outputs.
10. The sub-panel received a number of systematic reviews, syntheses and meta-analyses which developed new hypotheses or insights, which were well received. In a small number of cases, reviews submitted for output assessment were found to contain little or no new research content; in a very small number of cases submitted review articles were therefore graded unclassified as they failed to meet the REF definition of research.
11. The sub-panel took no account of the journal of publication when assessing articles and were not influenced by journal rankings in the scoring of outputs. The sub-panel noted that world-leading journal articles were found in the full range of journals from the "high-profile" through to the highly technical.
12. Citation information was provided to the sub-panel but was not core to the assessment of outputs, rather it was used to support assessments where appropriate. Whilst the most highly cited outputs were frequently rated world-leading or internationally excellent, some outputs with low or zero citations were judged to be of the highest quality, in particular when outputs had been recently published or were highly specialised. Conversely, some highly cited outputs were rated at internationally recognised or below.
13. Within the wide spectrum of Earth Systems and Environmental Sciences, there are a number of sub-discipline themes to comment upon.

Geosciences

14. Within the broad area of geoscience, the sub-panel noted that there was a strong and active research base over many HEIs across the UK.
15. All round significant strengths across a broad range of topics indicates that, as a whole, the discipline is in very good health. Although there was evidence of international excellence across all sub-disciplines, the sub-panel noted particular strengths in

a. Global seismology and studies of earth core, mantle and crustal processes

b. Geohazards, particularly earthquakes, volcanic hazards and tsunamis

c. Palaeontology, particularly through integration with earth system modelling, molecular evolution and the development of conservation palaeobiology

d. Global and planetary change, particularly palaeoceanography and palaeoclimatology especially with respect to our understanding of global elemental cycles.

16. The Geosciences continues to draw strongly on access to technology, collaborative data and international exploration teams. Combined with very strong outputs on fundamental geoscience, especially in sedimentology, structural geology and igneous petrology, the discipline demonstrated a consistent, high profile and sophisticated growth in understanding of geological processes in deep time, and the origin and evolution of the Earth as a planetary body.

17. A strong, emerging area is at the intersection between biology, geology and soil science particularly the interaction between plants, minerals and microbiology and application to areas such as land use, climate change and carbon budgets. There was excellent evidence throughout the sub-discipline of integration of new technologies in remote sensing, imaging and micro-analytical techniques, the former being applied to societal issues and the latter providing strength in low temperature geochemistry and mineralogy. Overall, geochemical analysis was strong and widely applied.

18. The sub-panel noted that outputs related to the exploitation of natural resources were notably strong and made use of innovative methods. This research provides a good base for a transition to clean energy and Net Zero. Some excellent outputs deepened our understanding of critical metal mineralisation, demonstrating capacity to show international leadership in the supply of the raw materials needed for a Net Zero world. There was evidence of good emerging research into anthropogenic impacts on our natural environment, particularly in the area of microplastics and coastal processes. Some outputs used automated methods and machine learning to exploit big datasets, although this area is still emergent.

19. Compared to REF 2014, there appeared to be a decline in the number of outputs submitted on the topics of metamorphic petrology and deep crustal processes, though much of this remains world-leading. The sub-panel also noted the relatively small number of outputs submitted concerning marine geoscience and exploration geophysics.

Atmosphere, Ocean and Cryosphere Sciences

20. The sub-panel received an impressive set of outputs in atmosphere, ocean and cryosphere sciences from a range of HEIs. Much of the international excellence in these disciplines has been driven by the international and intergovernmental drivers such as the Montreal Protocol, the Convention on Long-Range Transboundary Air Pollution, and the Intergovernmental Panel on Climate Change. In addition to papers addressing the fundamental science of climate change, the sub-panel received a number of impressive cross-disciplinary outputs applying physical insights to topics such as ecosystems and climate policy, and to engaging directly with international treaties.

21. World-leading outputs focused on modelling or experimental work were identified and welcomed by the sub-panel. That said, there has been a marked tendency towards large multi-author outputs detailing the results of high-profile international programmes, combining in situ and remotely sensed observations with numerical modelling. Several

of these outputs described significant advances in understanding. This trend of integrating modelling with observations is highly desirable for increased understanding of complex atmospheric composition, dynamics, and climate processes, and for increased confidence in model predictions.

22. There has been a decline, relative to REF 2014, in the number of submitted outputs in areas such as atmospheric and ocean dynamics and gas-phase chemical kinetics. However, many of these outputs were rated highly by the sub-panel. The sub-panel recognises that a significant fraction of outputs in these areas may have been submitted to other sub-panels such as Chemistry or Physics.
23. Outputs investigating atmospheric aerosol — its fundamental properties, behaviour in pristine and polluted environments, and direct and indirect forcing of climate — comprise a distinctive element of world-leading Earth Systems and Environmental Sciences. Novel use of national and international facilities from cognate fields such as high-energy physics and materials science has emerged strongly since the last assessment.
24. Regional and global-scale assessments of air quality affecting human and plant health integrated fundamental atmospheric chemistry and dynamics to produce outstanding outputs. These outputs will inform policies to improve life expectancy and food security.
25. There has been a growth in the number of outputs addressing interactions between the different components of the climate system, for example ocean-ice and land-atmosphere interactions, and chemistry-climate Earth system modelling.
26. The sub-panel received some outstanding outputs in palaeoclimate, setting out and testing hypotheses; these studies were most impressive when fully integrating proxy data and numerical models in a rigorous manner, and accompanied by detailed methodologies.
27. A significant number of outputs were received in planetary atmospheres, where UK investigators are embedded in, and regularly lead, large international efforts. Particularly noteworthy has been the role of robotics in transforming this sub-discipline, expertise which could usefully be transferred into other parts of the discipline.
28. Outputs responding directly to climate policy (i.e., assessing intended and unintended consequences of policy choices) were a welcome and distinctive component of outputs in this area. Such outputs often included significant interdisciplinary research along with judicious model development or coupling to pass information from the physical climate to the societal domain.

Ecology and evolution

29. Ecology in the context of Environmental Sciences has grown tremendously in academic and societal significance since REF2014. This is reflected in the number of internationally excellent and-world-leading papers in both basic understanding and in applied research, and is to be welcomed at a time when there are demands for evidence-based decision making at both local and global levels.
30. In addition to contributing high quality research in the subject areas mentioned in the preceding sections, the sub-panel was particularly impressed with the increasing and innovative collaboration between ecology, physiology and genetics, and between ecology, genetics and archaeology. The growing use of big data analysis is also positively noted. These developments focus on basic ecology and on globally significant questions, such as the potential impact of climate change on biodiversity worldwide.

31. The sub-panel notes and welcomes that many key global challenge ecological fields, such as conservation biology, have joined forces with social sciences and economics as well as the arts and humanities to enhance both basic understanding and uptake of solutions to central global environmental challenges.
32. The increase in outputs tackling the development of new and pragmatic indicators tracking ecological and social change following specific natural resource management interventions is welcomed as a particularly challenging and rewarding area.
33. As well as basic and applied research questions, the sub-panel was also pleased to see the increase in meta-analyses and other rigorous synthesis approaches being submitted. These papers aid not only the increased effectiveness of approach to further investigations but provide an increasingly accessible resource of international and world-leading papers for future decision making.

Impact

34. The sub-panel was particularly impressed by the quality and diversity of the impact case studies presented, 95 per cent of which were judged to be outstanding or very considerable, with 54 per cent outstanding. The vast majority of case studies showed very significant contributions to environmental protection, understanding climate change, public policy development, as well as to the UK and global economy. There were also excellent examples of public engagement. Notably all submitted case studies were judged to present at least considerable impacts in terms of their reach and significance, with many very considerable and outstanding impacts.
35. Sub-panel members were joined by five impact assessors for the assessment of impact case studies. Between them, the impact assessors read all submitted impact cases, concluding that the sector is generating exceptional impact that is responsive, xciting, and evident in all the HEIs. The sub-panel thanks them for their expertise and enthusiasm.
36. Many of the strongest case studies were underpinned by excellent research, and the sub-panel noted, that although not always referenced, many cases could be traced to original 'blue skies' research, which had also played an instrumental role in generating the impact.
37. Case studies were well presented and well evidenced, and the sub-panel was impressed by the overall quality of submitted case studies, noting that only rarely did a case lack coherence, clear pathways, or had weak evidence.
38. In atmosphere ocean and cryosphere sciences, notably strong impact case studies described impacts on global policy, around climate change, communicating the effects of ocean and atmospheric pollution to mass audiences. The reach of the impacts from this research area was outstanding, not only impacting international policy, but also benefitting the global south.
39. Geosciences saw exceptionally strong cases on carbon capture and storage, water contamination, resilience to natural hazards and mineral exploration relevant to Net Zero, with impacts of outstanding significance and global reach.
40. Major strengths in ecology and evolution included habitat conservation, biodiversity and ecosystem management, noting also that there were outstanding impact case studies which demonstrated impacts beyond those on the environment and including impacts on public policy and services, agriculture, health and wellbeing.

Environment

41. The size of the submissions to UOA 7 varied considerably. The units with over 80 per cent of their environment submission graded as being internationally excellent or world-leading generally ranged in size from 20 to over 100 FTE, but it was not axiomatic that the research of a large unit would be of the highest quality. A coherent strategy and associated support for staff, investment and infrastructure were important factors in research quality. Many moderate and medium-sized units performed just as highly as much larger units. Similarly, units split across sites were commended for their supportive environments, despite the inherent challenges this brings.

42. Across all submissions there was evidence of increased awareness of and plans to support equality, diversity and inclusion; the strongest submissions were able to evidence progress in addressing gender balance within their units. Engagement with the Athena SWAN framework was high, but support for other protected characteristics still remains patchy.

43. The sub-panel observed sustained investment in people and facilities in a great number of submissions, and good diversity of research funding streams. Support and training for doctoral students and early career researchers has strengthened since REF 2014.

44. The sub-panel was pleased to note that Early Career Researchers (ECRs) represented 14 per cent of the overall headcount submitted. This compared to 12 per cent of the submitted outputs being attributed to ECRs. Support for staff progression and development was evident in most submissions, with some excellent examples of utilising workload models to protect research time. However, the sub-panel noted that there are opportunities for some units to do more to recruit, nurture and develop ECRs.

45. All submissions demonstrated support for training and progressing PGR students, and the sub-panel is pleased to note a 19 per cent increase in the average number of PhD degrees awarded per annum during this REF period compared to REF 2014. In REF 2014 a total of 2,472 degrees were awarded over a five-year period, averaging to 494 per year. In REF 2021 this has increased to 4,102 over a seven-year period, averaging to 586 per year.

46. Research income during the period is dominated by research council funding, contributing 50 per cent of the average annual income. EU funding contributed a further 20 per cent, and 7 per cent was obtained from UK industry. The sub-panel was pleased to see submissions that had developed strong strategies and support mechanisms for generating income at all career stages, particularly where income during this REF period was modest.

47. All submissions described an impressive suite of engagement and collaborative activities over the period and all units have played a role in advancing the discipline at regional, national and international level, including through roles in publishing, learned societies, and/or committees. The strongest submissions described how these activities then shaped the direction and development of staff within the unit and how they supported delivery of the unit's strategy.

48. The sub-panel was impressed by the breadth and depth of public engagement activity outlined by many of the units and was pleased to note increased support and recognition for such activity. Many submissions also demonstrated excellent examples of a local or regional focus, with connections to local communities; the very best had complemented this with international collaboration and influence.

49. There has been continued growth in international collaboration and overall, the sub-panel was of the view that the UK Earth Systems and Environmental Sciences research base continues to have many world-leading qualities and be internationally competitive.

Research income by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	79,214	78,602	94,887	90,322	632,252
UK-based charities (open competitive process)	3,736	4,431	6,176	5,578	39,048
UK-based charities (other)	915	677	1,052	979	6,851
UK central government bodies/local authorities, health and hospital authorities	13,971	13,964	14,621	14,434	101,039
UK central government tax credits for research and development expenditure	0	13,919	1,120	2,788	19,517
UK industry, commerce and public corporations	13,240	13,707	12,427	12,726	89,083
UK other sources	3,033	3,417	2,301	2,565	17,955
EU government bodies	36,512	36,833	37,428	37,212	260,486
EU-based charities (open competitive process)	350	258	195	226	1,581
EU industry, commerce and public corporations	3,349	2,871	2,360	2,575	18,022
EU (excluding UK) other	2,505	2,421	3,349	3,095	21,668
Non-EU-based charities (open competitive process)	1,110	824	1,065	1,037	7,261
Non-EU industry commerce and public corporations	5,459	6,217	5,008	5,245	36,715
Non-EU other	2,378	2,727	3,426	3,176	22,235

UOA 8: Chemistry

Summary of Submissions

Name	2021	2014	% difference
Number of submissions*	40	34	+8.1
Category A staff FTE	1,502.02	1,229	+22.2
Category A staff headcount**	1,560	1,267	+23.1
Number of outputs†	3,692	4,698	-21.4
Outputs per Category A staff headcount**	2.4	3.71	-35.3
Number of outputs attributed to former staff†	153	-	-
Impact case studies†	139	152	-8.55

***Joint submissions counted as one. **Category A and C in REF 2014. †Change in methodology since REF 2014. There was one joint submission in REF2021.**

Overall Profile for the Sub-panel

	Average percentage (Category A FTE volume weighted) judged to meet the standard for:				
	4*	3*	2*	1*	Unclassified
Overall	49	45	6	0	0
Output	44.9	50.8	4.1	0	0.2
Impact	53.1	39.0	7.1	0.8	0
Environment	55.3	36.5	7.7	0.5	0

Summary and Overview

1. The submissions to UOA 8 clearly showed the continued vibrancy and strength in UK chemistry during the seven-year assessment period. The output, impact case study and environment assessments all show substantial uplifts from REF 2014. While some of this can be attributed to changes to the submission criteria for REF 2021, it is also very clear that this uplift reflects the continued excellence and sustainability of chemistry research. The submitted outputs contained numerous examples of world-leading and internationally excellent research and the impact case studies demonstrated a wide variety of impact types with extensive and wide-ranging reach and significance for the economy and for society.

2. The submissions showed the extraordinary range and impact of Chemistry in the UK, including numerous interdisciplinary activities spanning boundaries with, for example, medicine and health, biological sciences, physics, materials science and engineering. This breadth is outlined further below, under paragraphs 16 (outputs) and 30 (impact).
3. The environment statements reported continued major investments in UK Chemistry, e.g. in staff, infrastructure, and equipment, continued access to national and international facilities and numerous examples of effective collaborations with academia (national and international) and with industry. The sub-panel was content that most submitted FTEs were working in environments that were conducive to producing research of world-leading and internationally excellent quality and enabled outstanding and very considerable impact. These achievements are all the more impressive given the data in the standard analyses which imply that, although some HEIs have seen a growth in research income, funding across the sector as a whole throughout the assessment period has been relatively flat. Clearly, such a funding environment cannot be a recipe for maintaining excellence and international competitiveness in the longer term.
4. Successful Chemistry PhD completions provide another indicator of the continued vibrancy and growth of activity within the discipline; the total number of PhD completions per annum during the REF 2021 assessment period was approximately 10 per cent higher than in the period sampled in REF 2014.
5. UOA 8 received submissions from five HEIs that did not submit to REF 2014. Only one HEI that made a submission to UOA 8 in REF 2014 did not make a submission to REF 2021. Of the two joint submissions in REF 2014, one continued as a joint submission in REF 2021, the other took the form of two separate submissions. The total number of submitted HEIs and FTEs increased by, respectively, 8 per cent and 22 per cent compared to REF 2014.
6. The submissions show that a growing number of chemistry units sit within larger multidisciplinary schools or colleges. The submissions to UOA 8 in such cases necessarily reflect the activities of just a part of these larger groupings and the sub-panel recognises that it can be challenging to unpick such activities to fit the REF sub-panel structure.
7. More detailed observations are presented below but, in a sentence, the sub-panel considered that the submission to UOA 8 provided very clear demonstration of the vitality and the continued success of Chemistry during the assessment period, and emphasised its crucial role in the UK economy and society. HEIs value Chemistry as a discipline and as an enabler of multidisciplinary activity, as demonstrated by the new submissions and by the reported investments in new build and facilities.

Assessment processes

8. Though much of the preparation for the REF assessment process had been completed by spring 2019, covid-restrictions meant that the entire assessment phase took place virtually using the zoom platform.
9. For outputs, independent peer review by two sub-panel members was key to the assessment process. Citation data was also provided and was used as supporting information when assessing the significance of the output.
10. Outputs were allocated algorithmically by matching them against a sub-panel derived taxonomy of research topics (defined in the survey of submission intentions) and member expertise. Assessment of outputs by sub-panel members was sequenced by

use of the randomly allocated REF ID number, Thus, clustering by HEI was avoided and no single reader saw more than a third of the outputs submitted by an HEI. For future exercises, the inclusion of a consistent and fixed taxonomy from the very start of the exercise, in the guidance, submission preparations and IT systems, is strongly recommended.

11. For impact case studies, each submission was allocated to four readers, two of whom were impact assessors and two were full sub-panel members. The initial allocation was made by the sub-panel advisor and panel secretary on the basis of roughly equal loads per impact assessor and per full panel member, ensuring avoidance of all declared conflicts of interest. The allocation was then approved by the sub-panel chair. Assessment of case studies was sequenced by use of the randomly allocated REF ID number. Once all individual scores had been uploaded, the group of four readers for each case study came together to agree a common score.
12. Environment statements were similarly allocated to four sub-panel members and assessed in the same way. REF4 data was used to inform decisions, as outlined in the published guidance, however, the sub-panel noted that some of the data was of limited utility.

Outputs

13. The 3692 outputs submitted to UOA 8 in REF 2021 represent but a few percent of the total number of outputs published by UK Chemistry staff in the qualifying period. The sub-panel is thus acutely aware that it only assessed a very small and selective sub-set of outputs, that are not necessarily representative of the entire body of work from the sector in the assessment period. This same cautionary note must apply to any conclusions that might be drawn from the fraction of the work submitted to UOA 8 flagged as having relevance to specific sub-disciplines, for example, forensic science.
14. The sub-panel observed a very high quality of outputs across the UOA, with 94 per cent of submitted outputs being assessed as world leading or internationally excellent. Overall, there was a 21.4 per cent decrease in the number of submitted outputs (due to the changes in submission criteria). Several HEIs applied for individual and unit circumstances arrangements which reduced the number of submitted outputs by 63 in total. Compared with REF 2014, the percentage of outputs assessed as 4 star roughly doubled (to 44.9 per cent), while the percentage assessed as 2 star halved (to just 4.1 per cent).
15. The submitted outputs spanned all traditional areas of chemistry and illustrated the ever growing 'reach' of the discipline and its application to real world problems. Organic chemistry accounted for 40 per cent of all submissions with excellent outputs spanning the core areas of organic synthesis and medicinal chemistry, as well as interdisciplinary work in biological chemistry and chemical biology. The sub-panel also assessed outstanding core inorganic chemistry and physical/theoretical/computational chemistry outputs and numerous excellent interdisciplinary outputs spanning supramolecular chemistry, catalysis, materials science, energy materials, green (sustainable) chemistry, nanoscience, analytical and atmospheric/environmental science. The overall submission contained numerous outputs from all areas of chemistry that were judged world leading or internationally excellent in terms of originality, significance and rigour.

16. The sub-panel noted many multi-author, multi-institutional submissions featuring international co-authors, often in multidisciplinary journals. Submissions of few-author outputs in more specialist journals, in contrast, were rather rare. Given the previously noted small fraction of all outputs from UK Chemistry units submitted to REF 2021, however, the sub-panel is reluctant to draw any firm conclusions about, for example, areas of relative growth or decline within the discipline based simply on the submitted outputs.
17. The sub-panel had not requested additional information describing the significance of the outputs (which was not considered to be necessary or useful for this UOA). Neither had it sought a description of author role in multi-authored outputs. Of the submitted outputs, 305 (8.3 per cent) had 15 or more co-authors. This represents a significant increase in the fraction of hyper-authored papers submitted to UOA 8 (cf. 75 or 1.6% in REF 2014).
18. The collective expertise meant that the sub-panel felt able to assess the vast majority of outputs submitted to it objectively and fairly.
19. Two sub-panel members were appointed as interdisciplinary advisers and they worked across the sub-panel as required to ensure interdisciplinary research (IDR) was assessed fairly.
20. The sub-panel noted inconsistent use of the IDR flag by HEIs. Some HEIs used the flag liberally, whereas others did not flag any outputs as IDR. In total, 545 outputs were flagged as interdisciplinary by HEIs. The sub-panel decided simply to note when the flag was attached to an output, but not to change the IDR-flag status proposed by the HEI.
21. Post assessment analysis shows no significant difference between the average score awarded to outputs flagged or not flagged as IDR.
22. The panel noted strong interactions between chemistry and other disciplines that were apparent in a large proportion of the outputs. Submitted outputs had been published in journals that spanned essentially all scientific disciplines. More than half of the outputs submitted to UOA 8 appeared in journals classified as 'Chemistry, Multidisciplinary' by Clarivate, and many others fell into either more than one journal category or appeared in journals covering other disciplines. Using this proxy, 2606 of the 3692 submitted outputs were published in multidisciplinary journals.
23. 292 unique titles were submitted to SP8 by more than one HEI, accounting for 666 (or 18 per cent) of the total submissions to the UOA. A total of 619 unique titles were submitted to UOA 8 and at least one other UOA. These two groups of unique titles are not mutually exclusive.
24. The sub-panel received 52 requests from submitting HEIs for cross referral. Of these, 20 were accepted and cross referred to four sub-panels in Main Panels A and B. The collective expertise available within the sub-panel allowed assessment of the remainder without cross-referral.
25. Only one output was identified for joint assessment. Advice was received from Main Panel C.
26. The sub-panel received 205 inward cross referrals from 16 sub-panels that spanned all four main panels, with the largest numbers from Sub-panel 12- Engineering (53), Sub-panel 3 - Allied Health Professions, Dentistry, Nursing and Pharmacy (34) and Sub-panel 5 – Biology (33). This number, which is more than double the number of inward cross-

referrals received in REF 2014, provides further demonstration of the role of Chemistry in underpinning a wide range of research in other fields. Advice was provided on all these outputs.

27. Six outputs were unclassified because the sub-panel judged that they contained no original research. These included review articles and protocols where the originality was not evident in the output nor was it explained as additional information.

Impact

28. The sub-panel received 139 impact case studies for REF 2021 compared to 152 in REF 2014. This 8 per cent decrease is, again, the result of the changes in the published guidance.

29. As in REF 2014, the sub-panel was impressed by the very broad range and quality of the submitted case studies. The underpinning research was similarly broad and interdisciplinary. The submitted case studies spanned economic, health, environmental, policy, social, and some public engagement impacts at international, national and regional levels. Features noted by the sub-panel include:

    a. Economic impact was again exemplified, clearly and strongly. Research in Chemistry is clearly vital for several sectors of UK industry as described below.

    b. The submitted case studies provide many examples where research in HEIs has led to the creation of spin-outs and the development of SMEs, as well as solving problems and delivering opportunities for the biggest corporates.

    c. Synthetic chemistry, physical and physical organic chemistry, and chemical biology all make major contributions to the pharmaceutical and agrochemical sectors, and were fundamental to a number of very highly rated impact case studies, including a series of new cancer treatments, nucleic acid sequencing methods and biocompatible materials for medicine.

    d. Sustainable catalysis and materials chemistry also provided several case studies that directly impacted sustainable manufacturing, circular carbon and clean growth. Processes for recycling plastics, commercial deployment of bio-based materials, benign catalytic manufacturing, low carbon fuels and energy efficient storage devices were all featured in case studies leading to economic and policy impacts.

    e. Several case studies described direct impact on clinical practice and health, including diagnostics, treatments, drug discovery and delivery. Examples addressed impacts relating to topics as diverse as Covid-19, Alzheimer's disease, cancer and anti-doping in sport.

    f. Other case studies addressed areas of environmental science, for example, impacts relating to air quality, drug screening and waste-water monitoring and analysis.

    g. Impacts in public policy included, for example, contributions to the development of measures to control atmospheric ozone depleting substances and in the regulation of chemical hazards and occupational health protection.

    h. Societal impact was also noted in case studies relating to heritage conservation, where fundamental chemical research was playing an essential role.

i. Seven case studies focussed on outreach and public engagement, helping to promote and exemplify the key societal roles of chemistry.

30. The path from fundamental or blue skies underpinning research to transformational, disruptive impact was in many cases fairly linear and relatively easy to describe and to follow. Other case studies drew on a much broader body of underpinning research, and in some cases, chemistry was just one of several key components of interdisciplinary research (along with, for example, biological sciences and medicine).

31. 23 case studies submitted to REF 2014 re-appeared in REF 2021, having realised additional and/or enhanced impact during the current review period. These spanned all areas b. to h. above.

32. As in REF 2014, some submitted case studies described more strategic engagements between individual HEIs and selected industries or partners.

33. Impact assessors who joined the panel for both the present and the immediate past REF exercises were unanimous in the view that the case studies submitted to REF 2021 were of significantly higher overall standard than those submitted in REF 2014 – consistent with the improved impact profile. The REF 2021 submissions were typically more specific, better evidenced and succeeded in capturing more fully the multiple dimensions of the impacts. The sub-panel still saw a few case studies, however, where poor presentation or an inability to provide the necessary level of corroborating information limited the scores that could be given.

34. The case studies submitted to the sub-panel provide many outstanding illustrations of the extensive and wide-ranging reach and significance of the impact of research in Chemistry from the submitting institutions over recent years.

Research environment

35. The sub-panel was very pleased to see that trends noted in REF 2014 regarding an increase in the number of submissions to this UOA and the (re-)opening of some Chemistry units continued in the REF 2021 assessment period.

36. The overall environment sub-profile shows over 55 per cent assessed as four star (i.e. as conducive to producing research of world-leading quality and enabling outstanding impact, in terms of its vitality and sustainability). This represents a significant uplift relative to REF 2014. This sub-profile is sensibly consistent with the output and impact sub-profiles enabled by the environment under assessment, and many of the perceived improvements are highlighted below. Submissions to UOA 8 varied from under 20 FTE to almost 90 FTE and the sub-panel noted that a wider range of activities in all aspects of research environment is possible in the larger units.

37. The sub-panel noted many strong and coherent plans in the submitting units under the **'unit context, research and impact strategy'** section of the statement. Many reported re-structuring and/or re-focussing of research activities to enhance/exploit inherent interdisciplinary strengths, and significant investment (buildings, infrastructure and equipment) in the period since 2014. Many of the stronger submissions also provided clear expositions of achievements against the REF 2014 objectives and of their future strategy and ambitions.

38. Enhanced procedures for recognising, stimulating and achieving yet greater research impact featured strongly in many submissions. Several environment statements outlined a pipeline of recent research activities that were expected to translate into impact of a quality, reach and significance appropriate to support strong future impact case studies.
39. However, there is a rich seam of chemistry impact that is not captured in the current REF structures. These include successful strategic partnerships with companies, creating capabilities that lead to inward investment, sharing R&D facilities or training of PhD students for careers in industry, teaching and higher education, and other professional services.
40. The high level of interdisciplinary and multidisciplinary activity evident in the output submissions was equally evident in the environment statements. Most statements flagged collaborations within the HEI, with cognate and/or complementary groups in industry, and with other research centres within the UK and abroad.
41. The statements relating to open research and research integrity in most submissions reflected a growing emphasis on responsible and ethical innovation, and the now widespread commitment to use of open access publication and 'open science'.
42. Under the **'people'** section, the sub-panel was pleased to note that most submitting HEIs had succeeded in refreshing and strengthening their staff complement in the period since REF 2014. Many submissions reported impressive numbers of early career researchers (ECRs); the standard analyses identified 255 ECRs amongst the 1,560-headcount submitted to this UOA.
43. Most submissions reported appropriate (and, in many cases, impressive) mechanisms for the support and career development of ECRs and for supporting the progression of established staff. Many also reported career development opportunities for research support staff, but few addressed opportunities for core technical (e.g. workshop, stores, etc.) or research-facing administrative staff.
44. All submissions described mechanisms for monitoring the training and encouraging the progress of PhD students, with the strongest demonstrating students and staff being well integrated. The standard analyses report 7356 Chemistry PhD completions in the REF 2021 period (7 years), cf. 4735 in REF 2014 (which sampled a 5-year period). This represents a more than 10 per cent increase in the number of PhD degrees awarded per annum during the review period.
45. All submissions described equality, diversity and inclusion (EDI) procedures and processes in place within the unit/HEI, but the accompanying narratives were of variable quality. Almost all reported external recognition (e.g. Athena SWAN awards) and some of the best submissions offered specific examples of how embracing EDI considerations had materially influenced and improved local behaviour and practice. Future sub-panels should look for tangible demonstrations of how EDI practices put in place for REF 2021 have borne fruit.
46. Under **'income, infrastructure and facilities'**, statements typically expanded on some of the major funding awards noted in the introductory section. Most narratives described new (in the review period) and existing infrastructure and facilities, and strategies for their maintenance, sustainability and periodic upgrade/renewal.
47. Some HEIs reported growth in their research income over the review period, and considerable amounts of institutional investment were apparent in many submissions. The sub-panel identified a clear correlation between the income per FTE ratio and total

FTE numbers and also noted the large variations in income per FTE amongst the various submitting HEIs.

48. The income landscape remains polarised (as noted in REF 2014) and the total income reported in the standard analyses summarised in the table below suggests that, overall, the discipline has (at best) maintained level funding since 2014-5, with relatively little change in relative contributions from the major funding sources during the review period. The sub-panel re-emphasises the challenge of maintaining or growing the excellence of UK Chemistry without significant future uplifts in funding.

49. Many submissions highlighted the extensive and effective use of national and international facilities (experimental and computational) by the UK Chemistry community, both for high-quality core chemistry and for programmes at the boundaries with, for example, biology, medicine, physics and materials science.

50. Most submissions reported extensive and effective networks of collaborations, both national and international, with both academic and industrial partners under **'Collaboration and contributions to the research base, economy and society'.** Many used this section not just to reprise their submitted impact case studies but also to describe other emerging impacts from recent research at the HEI.

51. Rather than seeking covid-related mitigation, many statements devoted space to describing how staff within the HEI had refocussed their activities at very short notice to apply expertise to helping tackle the pandemic. Examples included work on the nucleocapsid protein itself, more general protein structure determination and validation, exploring air quality issues (e.g. air pollution impacts on UK covid-19 mortality) and the quantification of virus transmission in small aerosol particles.

52. All HEIs reported extensive public engagement and outreach activities in this section of the environment statement, detailing a wealth of innovative and influential engagement that in many cases could surely have supported very strong impact case studies. Seven HEIs chose to submit strong public engagement and outreach-centred impact case studies (see bullet 30i).

53. All environment statements also included impressive summaries detailing (i) some of the many contributions made by staff to scientific advisory panels, to learned societies, to UK and international panels and committees and to scientific publishing, and (ii) national and international recognition and awards to staff.

54. Overall, the sub-panel considered that the submissions demonstrated an environment that was conducive to producing research of internationally excellent (and in many cases world leading) quality in terms of its vitality and sustainability and also conducive to enabling very considerable (and in many cases outstanding) impact, in terms of its reach and significance.

UOA 8 Research Income by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	106,423	114,039	117,933	115,732	810,126
UK-based charities (open competitive process)	14,659	14,687	21,625	19,639	137,470
UK-based charities (other)	813	898	1,541	1,346	9,419
UK central government bodies/local authorities, health and hospital authorities	7,930	7,981	9,123	8,790	61,527
UK central government tax credits for research and development expenditure	0	24,070	1,456	4,478	31,348
UK industry, commerce and public corporations	14,018	14,642	14,621	14,538	101,764
UK other sources	393	977	2,285	1,828	12,796
EU government bodies	45,908	52,747	50,506	50,169	351,186
EU-based charities (open competitive process)	178	67	30	57	397
EU industry, commerce and public corporations	2,904	3,254	6,215	5,319	37,236
EU (excluding UK) other	597	1,205	302	473	3,312
Non-EU-based charities (open competitive process)	952	1,502	1,171	1,187	8,308
Non-EU industry commerce and public corporations	7,876	8,016	7,502	7,629	53,402
Non-EU other	4,131	3,574	4,819	4,543	31,800

UOA 9: Physics

Summary of submissions

Name	2021	2014	% difference
Number of submissions*	44	41	+7.3%
Category A staff FTE	2,214.79	1,705	+29.9%
Category A staff headcount**	2,312	1,774	+30.3%
Number of outputs†	5,496	6,446	-14.7%
Outputs per Category A staff headcount**	2.38	3.63	-34.4%
Impact case studies†	189	203	-6.9%

***Joint submissions counted as one. **Category A and C in REF 2014. † change in methodology since REF 2014**

Overall profile

	Average percentage (Category A FTE weighted) judged to meet the standard for:				
	4*	3*	2*	1*	Unclassified
Overall	48	47	5	0	0
Output	44.9	50.3	4.5	0.1	0.2
Impact	46.9	46.5	6.4	0.2	0
Environment	61.9	37.1	1	0	0

1. Within UOA 9 (Physics), the overall standard across all three assessment elements was very high, clearly indicating that UK physics has significant impact both on academia and wider society, which is enabled and supported by vibrant environments in UK institutions.
2. The overall institutional shape of the REF 2021 submission to UOA 9 (Physics) was similar to that reported in REF 2014: the change in number from 41 to 44 submitting institutions came from the addition of three new submissions with FTE < 15, the loss of one submission with 11 FTE and a change from UOA 7 (Earth Systems and Environmental Sciences) to UOA 9 (Physics) for a submission of 42 FTE. Physics remains a discipline in which, predominantly, strong and established units are returned. Already in REF 2014 most Category A staff within the sector were research active and thus the staff cohort

was fully returned to the REF 2014 assessment. Hence the transition, in REF 2021, to a full return for all staff with responsibility for independent research has had little impact on the total headcount. Instead, the increase in the head count returned to UOA 9 (Physics) for REF 2021 reflects a true growth in the UK's research capacity. In contrast, the change in rules from REF 2014 to REF 2021 that reduced the average number of outputs per person from 4 to 2.5, coupled with the flexibility of each individual researcher being associated with between 1 and 5 outputs, has enabled outputs to be chosen with even greater selectivity than in REF 2014. The sub-panel is supportive of the introduction of flexibility in the number of outputs returned per individual which it sees as supporting diversity in the workforce in general, and early-career researchers (ECRs) in particular.

3. The 13-point scoring scale worked well for outputs, where the top three scores all correspond to a 4* grade. Impact and environment were marked on a 9-point scoring scale. This allowed for nuance where elements of different star bands were present, but did not allow strong or weak performance within a star band to be distinguished. The sub-panel recommends that the 9-point scoring scale be reconsidered for future exercises, noting that whichever scoring scale is adopted, the small number of impact case study and environment submissions requires the final grade for these elements to be more nuanced than the integer scale used for outputs.
4. Looking forward to the next REF exercise, the sub-panel believes that the output and impact components are both rigorously assessed and align with what the sector should be trying to achieve, hence should continue to be a central component of any future exercise. The sub-panel also recognises that the environment component is important, capturing the essential contribution to people/culture which underpin the unit's performance and that this aspect is not captured by outputs and impact alone.

Outputs

5. Based on the outputs assessed, physics continues to produce outputs of the highest international standard across its full range of sub-disciplines with no apparent areas of weakness.
6. Each output was independently assessed by at least two members of the sub-panel who were selected according to their expertise match to the output. Once they had scored independently of each other, an agreed score was reached for each output on the 13-point scale (12-10 > 4*, 9-7 > 3*, etc). The outputs were scored in alphabetical order by title, an order hence uncorrelated with any author or institution.
7. In assessing these outputs, the sub-panel was cognisant that the process assesses a very small percentage (estimated to be <5%) of UK physics outputs. Whilst it is probably true that the REF 2021 process assesses many of the mainstream highlights of the sector, the process may not be picking up on the quality of research in, for example, emerging topics that may be seen as high-risk submissions by the submitting institutions.
8. The sub-panel found many examples of excellence within all the various areas of physics that they assessed. The change in submission rules notwithstanding, the overall portfolio of REF 2021 submissions to this unit of assessment has evolved since REF 2014 for several reasons. Examples include: (a) the discovery of gravitational waves and the associated growth in multi-messenger astronomy; (b) the international focus on quantum technology and corresponding increase in activity; (c) the importance of the green economy and focus on, for example, solar cells and (d) an overall rise in the applications of physics

to other subjects e.g., the interfaces with biological and life sciences. The UK is at the international forefront of many of these areas as well as those that formed the bulk of the REF 2014 submissions.

9. Ground-breaking physics research continues to be conducted by large international collaborations exploiting international facilities (including space missions, telescopes, particle accelerators, neutron and light sources etc). UK physicists lead on many of the projects, addressing fundamental questions whose significance is recognised worldwide. The high fraction of internationally outstanding outputs resulting from research undertaken with these facilities demonstrates both the excellent use the community makes of its access to the facilities and the enormous importance of the respective international subscriptions to the quality of our science.
10. At a local level, individual research groups in the UK continue to be highly creative in both establishing new fields and finding innovative solutions to outstanding challenges. This focus on the novel perhaps reflects both our highly competitive funding environment and indeed the REF process itself.
11. The overwhelming majority of outputs are structured to clearly articulate their significance and originality whilst maintaining highest levels of rigour. This clarity of presentation is both welcomed by the sub-panel and importantly promotes the excellence of UK physics on the international stage.
12. Where authorship statements were required, it was evident that some institutions had better processes than others for providing the necessary information. Similarly, responses to authorship audit requests were better handled by some institutions than others. Although ultimately very few outputs were deemed to fall below the level of author contribution that was required, the sub-panel urges the community not to be complacent on this point within any future exercise. The sub-panel recommends that in any future exercise the threshold for contributions be made clearer to allow institutions to interpret it consistently. The sub-panel remains of the opinion that in any future exercise a threshold for author contribution, beyond the author list itself, remains essential for the collaborative physics community. Indeed, the move to high author number papers is not restricted to the physics community and the sub-panel recommends that other sub-panels consider these issues with the hope of agreeing a common policy in any future exercise.
13. Overall, the sub-panel was content that the scoring of outputs was robust; typically, for each output, there was a high degree of agreement between the scores of the respective panellists prior to any discussion. The sub-panel stresses that the assessment of outputs was made without regard to the identity of the authors, journal or the submitting institution(s).
14. The sub-panel was confident that its own range of expertise, combined with the formal processes for joint assessment and cross referral, meant that interdisciplinary research was accurately assessed. However, the sub-panel also noted that the use of the IDR flag varied significantly by institution and hence the flag alone provided little useful information. Ultimately the fraction of outputs assessed at 4* showed no statistically significant difference between core physics and interdisciplinary research as flagged by HEIs. Although the sub-panel felt confident in their assessments, they also felt that the administrative processes of joint assessment and cross referral were unnecessarily complicated and the different detailed working methods adopted by sub-panels were problematic. At a more fundamental level, members of the sub-panel are of the

unanimous opinion that a specific output should be assessed as having a single score no matter to which, or how many, sub-panels it is submitted. World-class research should be recognised as world-class, assessed as a complete piece of work, with all sub-panels to which it is submitted giving the same score. This proposed approach would seem to be fundamental to encouraging and supporting research at the boundary between disciplines.

Impact

15. Each impact case study was independently assessed by four sub-panel members including at least one, and more often two, impact assessors. Once they had scored independently of each other, an agreed score was reached for each case study on the 9-point scale (4*, 3.5*, 3* etc). The impact case studies were scored in alphabetical order by title, hence largely decoupled from institution.

16. In contrast to outputs, the change in submission rules from REF 2014 to REF 2021 has resulted in little change to the portfolio of impact case studies. As with outputs, a concern might also be expressed as to whether the extremely selective nature of the impact assessment, based on only a handful of example case studies, provided the sub-panel with an overview of the impact contributions that the discipline or unit is making overall. Similarly, the fact that the assessment is based upon impact cases that have been many years in the making arguably gives little insight as to the present process or activity currently being undertaken within the units. In REF 2014 the impact template addressed these issues and unfortunately some of this focus has been lost in the amalgamation of the impact agenda within the overall environment statement.

17. The sub-panel believes that the quality and breadth of the impact case studies assessed are excellent examples of the contributions that physics makes to both economic and societal impact. Given that this was the second iteration of consideration of impact in the REF, the sub-panel was a little surprised not to see more examples submitted of continuing impact, for example relating to start-up companies and similar activities that had been submitted in REF 2014 which would now be expected to have grown in scale.

18. Compared to REF 2014, the impact case studies submitted to REF 2021 were better structured and provided greater clarity of the evidence in support of the claimed impact(s). Overall, there was a very large number of outstanding impact cases arising from a variety of areas of the discipline. The impact cases focusing on economic impact were extremely well evidenced and demonstrated how they have fed into a broad range of industry sectors and the wider economy. Similarly for policy, there were cases where evidence was presented of how physics-based advice had not just fed into policy making but had resulted in changes being adopted and implemented downstream. Public engagement cases comprised a significant fraction of the physics return, showing the importance of the subject in capturing the imagination of the public, in particular younger people, and in acting as a vehicle to improve wider scientific understanding. However, the sub-panel felt that some of these cases would have benefitted from designing their evaluation criteria earlier in the process so that the evidence presented was better tied to the impact of that activity on the targeted audience rather than just the level of engagement with that audience. This concern was supported fully by the specialist impact assessors on Main Panel B. Nevertheless, many of the submitted public engagement and outreach cases were outstanding and provide exemplars of how to design and deliver important impact in this sphere.

19. Although supportive of the desire to reduce the administrative burden of REF 2021, the removal of the impact template from the present process has not been fully compensated for fully by the HEIs in the recognition of the need for an impact strategy and description of support structures in the main environment statements. The impact case studies are retrospective whereas it is necessary to recognise, and credit, the present-day steps being taken to support the impact agenda and impact case studies of tomorrow.
20. The sub-panel was appreciative of the contribution made by its impact assessors on whom the scoring of impact relies. However, to ameliorate their workload, it is recommended that the number of impact assessors be increased in any future exercise. It is recognised that whereas outputs require specialist knowledge to assess, impact case studies can be assessed across sub-disciplines. In a future exercise it would be beneficial for the assessment of impact case studies to be made, by both academics and dedicated impact assessors, at the level of the main panel; the sub-panel believes that this would result in better calibration across sub-panels.
21. The sub-panel feels very strongly that impact should continue to be part of any future REF process since it ensures that research and the impact it creates remain part of the same ecosystem within both funder and institutional structures. However, increasing the importance of impact within the overall REF process would require thought as to how it might be assessed so that smaller units do not end up being judged on only a few impact case studies.
22. Overall, in terms of general economic impact, physics makes pivotal contributions to many market sectors to the development of national and international policy making, and to the public appreciation of science. It drives both entrepreneurial spin out and physics-based start-ups as well as making significant contributions to improved products and services provided by both SMEs and UK-based multinationals. Physics is a subject that clearly captures the imagination and physics outreach is having a strong positive influence on public understanding of the discipline and an appreciation of the importance of science more widely.

Research environment

23. Each environment statement was independently assessed by five sub-panel members including at least one member of the sub-panel executive. Once they had scored independently of each other, an agreed score was reached for each of the four environment dimensions on the 9-point scale (4*, 3.5*, 3* etc).
24. The environment in which physics research is conducted remains world class, which, given the overall resourcing challenges, is of great credit to the leadership of UK physics units. Many physics-based units have received significant investment from both national programmes and local institutional funds. Physics as a discipline in the UK has been the basis of a number of national science initiatives, including: the creation of various national research centres in support of the growth of UK-based, high-technology industry.
25. In any future exercise, attention should also be applied to the steps that units are taking in the transition to a greener ecosystem and carbon neutrality, both in terms of the research they conduct and in their operations.

26. Whereas for both outputs and impact cases there was no significant correlation between the percentage of 4* grades with unit size, this was not the case for environment where medium and large institutions tended to score more highly. Of course, the goal of any environment is to produce research and impact of the highest international quality, but environment is more than just outputs and impact; it supports people and careers too. The sub-panel recognises that larger units have an inherent advantage in their ability to evidence the difference they are making to their own environment. Dedicated staff, targeted committees and, to a more variable extent, the flexibility of in-house resources enables environment statements to be written that convey scale and dedication to environment issues. The sub-panel tried to mitigate for these differences in the assessment structure by focussing on the outcomes that such interventions had achieved, irrespective of the mechanism or level of resourcing, or the management structures that were in place. Nevertheless, the correlation between high environment score and unit size remained. For any future exercise, the REF process needs to consider whether these correlations relate to truly desirable outcomes or whether they are driven by the assessment process rules.
27. Within the STEM area, physics has championed many aspects of equality and diversity supported by the Juno project, which was instigated by the subject's professional society, the Institute of Physics. Submissions demonstrated that these initiatives, alongside Athena SWAN and other similar schemes, have been fully embraced by the sector and are improving the diversity of the physics workforce. Physics has made significant progress in sex and gender diversity, evidenced by the increasing number of females in senior roles but, of course, more needs to be done. However, ethnic diversity remains a big issue for the whole of academia and the sub-panel supports initiatives in this domain at both institutional and sector wide level.
28. As was recognised within the impact assessment, physics as a subject lends itself to a high volume of activity related to public engagement. In addition to the impact this has on wider society, the impact that these activities have on practice within units themselves should not be underestimated. Public engagement frequently draws upon many individuals within a unit, including post-graduate research students and ECRs, working in partnership with senior colleagues. Such initiatives build significant team spirit that spills over into the unit's activities more widely.
29. Nearly all units have impressive career support structures in place. These are focussed on both post-graduate and post-doctoral researchers. However, unsurprisingly many of these structures are targeted at careers in academia and further attention needs to be given to how the sector might better support the transition of its researchers into careers beyond academia.
30. Within academia, ECRs with a physics focus continue to be very successful in winning research fellowships from external sources as they progress their own independent research careers. Physics post-graduate researcher numbers continue to grow. This growth in numbers is welcome, but not in itself sufficient to demonstrate a high-quality environment, hence it is important to see the progress that is being made through the structures for doctoral training, including graduate schools, in the formal support of our post-graduate cohort.
31. UK physicists continue to play pivotal leadership roles in nearly all facility-based international collaborations and access to these facilities and networks of researchers thus remains central to the future success of UK physics. The operational mechanisms behind these international collaborations also drive significant income-in-kind to the

benefit of the UK science base. Furthermore, through these collaborations the UK can access internationally leading infrastructure whilst sharing costs with international partners.

32. Physics continues to be a vibrant subject undertaking agenda setting research and impact with the UK hosting many of the world's leading laboratories and research centres which act as career accelerators for students and staff world-wide.

UOA 9 Research income by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	194,801	217,940	249,092	236,885	1,658,198
UK-based charities (open competitive process)	7,130	7,802	8,891	8,484	59,385
UK-based charities (other)	814	1,170	1,292	1,206	8,441
UK central government bodies/local authorities, health and hospital authorities	10,777	12,934	21,956	19,070	133,492
UK central government tax credits for research and development expenditure	0	35,392	2,349	6,734	47,139
UK industry, commerce and public corporations	6,960	7,338	6,253	6,509	45,563
UK other sources	843	1,161	1,098	1,070	7,492
EU government bodies	43,990	53,814	58,768	55,950	391,647
EU-based charities (open competitive process)	21	8	40	33	229
EU industry, commerce and public corporations	780	1,031	1,539	1,358	9,504
EU (excluding UK) other	1,259	1,519	2,539	2,210	15,471
Non-EU-based charities (open competitive process)	938	1,170	1,655	1,484	10,386
Non-EU industry commerce and public corporations	1,898	1,822	5,960	4,788	33,518
Non-EU other	4,617	4,015	16,831	13,255	92,786

UOA 10: Mathematical Sciences

Summary of Submissions

Name	2021	2014	% difference
Number of submissions*	53	53	0.00
Category A staff FTE	2,461.11	1,931	+27.45
Category A staff headcount**	2,570	2,005	+28.18
Number of outputs†	6,002	6,995	-14.17
Outputs per Category A staff headcount**	2.33	3.49	-33.24
Number of outputs attributed to former staff †	317	-	-
Impact case studies†	216	236	-8.47

***Two of these formed a joint submission **Category A and C in REF 2014. † change in methodology since REF**

Overall Profile for the Sub-panel

	Average percentage (Category A FTE volume weighted) judged to meet the standard for:				
	4*	3*	2*	1*	Unclassified
Overall	48	48	4	0	0
Output	43.4	53.5	2.9	0.1	0.1
Impact	55.4	37.7	5.7	0.8	0.4
Environment	53.7	40.4	5.6	0.3	0

1. The submissions to UOA 10 clearly demonstrate the continued strength and dynamism of mathematical sciences in the UK during the seven-year assessment period. The submitted outputs illustrate the breadth and depth of UK mathematical sciences research, while the range of submitted case studies, and evidence presented in the environment templates, are testimony to the extensive impact of the discipline on other disciplines, on society, and on the economy.
2. The results reflect the extremely high quality of the submissions. All three elements of the assessment, outputs, impact case studies, and environment templates, show substantial uplifts from REF2014. Some of this can be attributed to changes to the submission criteria for REF 2021, but it is also clear that these results reflect the continued excellence of UK mathematical sciences units.

3. Sub-panel 10 received 53 submissions, including two new entrants to Mathematical Sciences in this exercise and one joint submission. Two HEIs that made a submission to REF 2014 did not do so for REF 2021. The size difference between the largest and smallest submissions was very marked, ranging from under five FTE to over 170 FTE. A significant number of the smaller units sit within larger multidisciplinary schools or colleges. Evidence of excellence was found in units of all scales.
4. There was evidence that impact and knowledge exchange were embedded into day-to-day activities in HEIs, and that impact is being realised from research from across the breadth of the mathematical sciences. It was notable that, while centred in core mathematical sciences, the majority of output submissions had a strong interdisciplinary component. There was also extensive evidence of international collaboration in both research and training.
5. Environment statements described significant investment in new staff, in new and refurbished buildings, and in provision of access to High Performance Computing both through local investment and through shared facilities. Most submitted FTEs are working in environments judged by the sub-panel to have elements conducive to producing world leading research and outstanding impact.
6. Growth in staff numbers (a 28% increase in headcount, and a just over 27% increase in FTE) was matched by the continued rise in doctoral degree completions in this REF period, the average per year being 643 compared to 503 per year in REF2014. This equates to an average of 0.26 PhD completions per submitted FTE per year in both REF periods. Environment templates demonstrated a clear commitment from HEIs to provide high quality training and support to PGRs, often supplemented through national and international collaborations.
7. HEI submissions show that research income has been relatively flat during the period and, in particular, does not reflect the growth in submitted FTE. Such a constrained funding environment raises concerns for the long-term international competitiveness of the UK.
8. It was noted that several mid-sized units had grown very considerably during the REF period. Some stated explicitly that increasing student numbers was supporting their expansion; others highlighted HEI investment in fellowships, which add to the sustainability of the discipline.
9. The overall submission demonstrated the continued vitality, dynamism and strength of all the sub-disciplines in the mathematical sciences. The sub-panel was extremely impressed by the quality of outputs, the level of HEI investment, and the key contributions made by the mathematical sciences to society and the economy during the period.
10. Though much of the preparation had been completed by spring 2019, owing to Covid restrictions, the vast majority of the assessment process took place virtually using the zoom platform. Extra meetings were scheduled to help meet some of the challenges presented by this adjustment, and the sub-panel is content that it was able to perform its assessments objectively and fairly using this platform.
11. In addition to undertaking tailored training in equality diversity and inclusion, and unconscious bias, the sub-panel used workshop sessions to reflect on the potential for biases in the specific context of assessing Mathematical Sciences submissions and agreed mitigation strategies. These were captured in a Fairness in REF Intention Plan that was revisited at regular intervals during the assessment process. Regular calibration and validation exercises were also invaluable.

12. The 13-point scoring scale worked well for outputs, where the top three scores all correspond to a 4* grade. However, the 9-point scoring scale for impact and environment lacked resolution at the top of the scale with some apparent reluctance to score 4* which was addressed through further sub-panel discussion.

Outputs

13. There were 6,002 outputs submitted to UOA 10 (a 14 per cent decrease since 2014). Allocation of outputs to panellists was based on keywords provided by submitting HEIs (which were mostly taken from the high-level taxonomy used for the Survey of Submission Intentions) and the expertise available within the sub-panel membership. An algorithm assigned each output to two readers based on these criteria, taking account of conflicts of interest with the submitting HEI. Further potential conflicts of interest, for example through co-authors, were identified by the sub-panel executive and outputs were reallocated as necessary. To help ensure that assessments were made without regard to the identity of the authors or the submitting institution(s), the outputs were scored in a numerical order provided by a randomly allocated identifier.
14. The vast majority (97 per cent) of outputs were judged to be of internationally excellent or world leading quality in terms of originality, significance and rigour. World leading research outputs were found throughout the mathematical sciences and in units of all sizes.
15. It was evident from the submission that traditional inter- and intra-disciplinary boundaries are increasingly blurred. Multidisciplinary research, calling upon techniques from right across the mathematical sciences, continues to grow, both in its depth and in its range of applications, the latter naturally including biology, engineering, medicine, physics, parts of computer science and the social sciences. The extent to which rapid developments in the biosciences are meaningfully impacting new mathematical and statistical approaches is particularly noteworthy.
16. Two sub-panel members were appointed as interdisciplinary advisers and worked with other members to ensure that interdisciplinary research was assessed fairly. HEIs were not consistent in their use of the interdisciplinary flag, with several not using it at all. As a result, it is not possible to make any robust estimate of the proportion of IDR in the submission. It was invaluable to have a sub-panel member joint with Sub-panel 9 (Physics) to advise on the large volume of outputs spanning the two disciplines.
17. As in REF 2014, and as set out in the panel criteria and working methods, the sub-panel did not request additional factual information about the significance of outputs, nor did it use citation information. The sub-panel was content that it was fully able to perform its assessment of outputs without these additional inputs. However, a considerable number of outputs were cross-referred or jointly assessed with other sub-panels, in order to ensure well-informed assessment decisions.
18. Sub-panel 10 cross referred 185 outputs to other sub-panels, 106 of which were within Main Panel B, the largest number being 67 to Sub-panel 9 (Physics) (down from 158 in 2014; c.f. paragraph 16). A further 28 outputs were cross-referred to Sub-panel 5 (Biological Sciences). Smaller numbers were referred to 12 other sub-panels spanning all four main panels.

19. Sub-panel 10 received 117 cross-referrals from 16 other sub-panels spanning all four main panels. The largest numbers from outside Main Panel B were 29 from Sub-panel 1 6 (Economics and Econometrics) and 26 (c.f. 50 in REF 2014) from Sub-panel 17 (Business and Management Studies). From within Main Panel B there were 31 cross-referrals in total.
20. Sub-panel 10 requested joint assessment for 34 outputs with 12 other sub-panels. These spanned all main panels. Incoming joint assessment requests were received from five sub-panels in Main Panels A, B and D.
21. A total of 54 outputs submitted had 15 or more authors; 21 (13 from the same HEI) had more than 40 authors. The sub-panel recommends that in any future exercise a statement of author contribution be required for such outputs.
22. Only around 11 per cent of submitted outputs were single author, suggesting that research in the mathematical sciences is an increasingly collaborative endeavour.
23. A total of 398 unique titles were submitted to Sub-panel 10 by more than one HEI, some as many as four times. These accounted for 832 outputs (or 14 per cent) of the total submissions to the UOA. A total of 235 unique titles were submitted to UOA 10 and at least one other UOA. These groups are not mutually exclusive.
24. Amongst the output submissions, a total of 317 outputs (or 5.3 per cent) were attributed to 186 former staff members although HEIs used this approach to varying degrees. Former staff of one HEI accounted for 9 per cent of the total number included in submissions to UOA 10.
25. Only four requests for double-weighting of outputs were received, all of which were judged to meet the criteria.
26. In assessing outputs, the sub-panel observed the following.
    a) The UK remains a major player in the field of combinatorics. Areas of particular strength in this submission included extremal combinatorics, probabilistic combinatorics, matroid theory and combinatorial optimization. The area has been stimulated by problems and challenges from application areas such as networks and data science.
    b) The submission in number theory included internationally leading research, at the very top level, across the length and breadth of the subject, from algebraic aspects of Galois representations, to analytic theory of automorphic functions, including arithmetic geometry and Diophantine approximation. It was enriched by interactions with ideas from logic.
    c) The overall quality of outputs in analysis was extremely high, with impressive agenda setting papers in areas including geometric measure theory, harmonic analysis, geometric analysis, operator theory, and C* algebras. There was substantial world class strength in the broad area of analysis of linear and nonlinear PDEs (with or without stochastic elements), and associated spectral problems, and applications to the modelling of a huge variety of phenomena in the physical world.
    d) The erosion of intra-disciplinary boundaries was evident in the intertwined areas of algebra, geometry, and topology. The submission exhibited excellent activity in representation theory, both in concrete classical forms and versions with categorically sophisticated methods; in geometric group theory; and in homotopy theory. The sub-panel judged the progress in low dimensional topology during this REF period illustrated by the submission to be impressive. Essential geometric input, for example

in the substantial body of work around Floer homology, has been complemented by sophisticated algebraic methods.

e) The REF period has seen top researchers in differential and algebraic geometry moving between these fields, and the submission included collaborative work encompassing not only differential and algebraic geometry, but also geometric analysis and/or integrable systems. It is also notable that since 2014 the power of geometric techniques has spilled ever more into adjacent areas, evidenced by striking geometric proofs of some of the major conjectures in those areas. There was evidence of vibrant and active interfaces between geometry and number theory, representation theory, integrable systems, and mathematical physics. A marked change since 2014 is the amount of work on special metrics in differential geometry, most notably the world-leading progress on G2 geometry, inspired by connections to theoretical physics.

f) Around 12 per cent of outputs in the submission were classified as part of mathematical physics by the submitting unit. Outputs submitted by the UK mathematical physics community provide world-leading contributions to the whole range of international activities. These include major international experiments as well as smaller scale experiments; theoretical and practical work in quantum information; condensed matter simulation and theory; gravity wave and collider physics experiments (through observation, but also developing calculational tools in order to understand complex processes in the fine detail needed to compare with experiment); and theoretical physics from phenomenological work to formal theory and its strong relation to pure mathematics. The outputs highlight the ever-wider range of mathematics being used in mathematical physics including algebra, analysis, combinatorics, geometry, number theory, and probability. Outputs from mathematical physics both draw on and contribute to recent developments in these areas, for example contributing to recent developments within the Langlands programme. Outputs demonstrated mathematical developments giving insight into physics questions, including novel applications of mathematics to quantum field theories, and work on black holes and holography.

g) The submission showed evidence of the increasing connections within mathematical physics itself, with ideas and approaches shared by outputs in gravity, statistical physics, string theory, and quantum information. Growing connections between mathematical physics and topics in informatics/ computer science were evident in some of the string theory outputs, and more especially within the portfolio of statistical physics and quantum information.

h) Research in continuum mechanics in the submission demonstrated the UK's continuing strength in physical applied mathematics, extending from fundamental topics to a wide range of application areas, including astrophysics, biology, geophysics and industry. Similarly, the sub-panel saw world class outputs on all aspects of fluid mechanics, exhibiting a wide range of techniques from the analytic to the experimental. Essentially all papers in these two areas could be described as cross-disciplinary, and the submission displayed exciting advances in the ways that mathematics is being used to uncover and quantify some of the mysteries in the scientific world. This included advances in our understanding of small-scale (micro/ nano) and interfacial phenomena, biomechanics, granular flows, and fundamental understanding of transitions to turbulence.

i) Research in mathematical biology demonstrated that the UK continues to be at the forefront of this discipline internationally. The outputs in mathematics in the life and medical sciences spanned all scales from molecular biology to epidemiology and ecology, with a broad range of mathematical approaches deployed in studying diverse applications. While there was an understandable emphasis on disease (including viral and bacterial infections, heart disease and oncology), outputs covered a vast range of the biosciences, with plant systems biology being one area of growth. The work showcased innovative modelling and the development of novel approaches and techniques, with developments to multiscale methods being particularly noteworthy. Outputs had a noticeable emphasis on connecting the mathematical modelling to real data in an integral and planned manner. This led to many of the interdisciplinary modelling outputs making genuine predictions and providing real insight into the underlying biomedical systems being studied.

j) Research in numerical analysis and computational mathematics at large is strong and varied, with a very healthy mix of important theoretical and algorithmic results. The submission showed that UK computational mathematics is punching above its weight, not only in the more classical areas of computational PDEs, numerical linear algebra, approximation theory, and optimization, but also in emerging areas. In particular, the importance of numerical analysis in the expanding area of machine learning and AI has been picked up and is producing world-leading contributions.

k) The significant increase in activity at the intersection with data science and artificial intelligence has resulted in a notable increase in the number of submitted outputs that took the form of high-quality conference publications.

l) Activity in network science, often in an interdisciplinary context and from a variety of perspectives, is increasing, placing the UK at the forefront of this field.

m) Many of the outputs in areas of applied and computational mathematics incorporated ideas from probability and statistics. This synergy was observed in areas including mathematical modelling, model analysis, algorithm design, algorithm analysis, model calibration, uncertainty quantification, and the generation of test problems.

n) The proportion of outputs classified by submitting units as a topic in statistics (not including probability theory) was comparatively low (around 13 per cent), with approximately a third of these from just five HEIs (and well over half from nine), but this is an underestimate of the proportion of outputs that exploited statistical thinking (c.f. paragraph 26c). There were strong submissions in statistics across a wide range of institutions. Outputs illustrated world-leading applied statistics work impacting numerous other fields (epidemiology, climate, genetics, biochemistry, health, education, business and social sciences, etc) and there was an increase in top quality work at the interface with machine learning submitted to this UOA since 2014. The submission saw a significant growth in methodological research motivated by the challenges arising from new forms of data; in particular the development of efficient computational methods for large and often high-dimensional datasets. Submitted outputs indicate that the UK is maintaining its strengths in areas such as statistical genetics, Bayesian statistics, Monte Carlo methods, time series, but also developing new/strengthening pockets of excellence in areas such as high-dimensional statistics, theoretical statistics, networks and spatial statistics.

o) A substantial proportion of the outputs in operational research were world-leading and helped to shape the international research agenda. In particular, the sub-panel recognised large amounts of excellent work in optimisation and stochastic modelling. It was also pleased to note that many of the operational research outputs described innovative methodology that had been developed for and applied to specific practical problems.

p) The volume of outputs in financial mathematics has declined since 2014, and the focus of submitted outputs has changed, with a significant proportion now attacking problems associated with transaction costs. While the problems considered are technical and mathematically interesting within financial mathematics, there was less evidence in the submission of their applicability in the financial markets. The sub-panel was surprised by how few outputs in data science in the context of finance and financial mathematics were submitted to this UOA.

q) Probability emerges in REF2021 as an extremely vibrant area. There has been significant growth since REF2014, evident in large numbers of world leading outputs on discrete and continuous random structures and their scaling limits, nonlinear (singular) stochastic partial differential equations and universality classes, and much else besides. Probabilistic ideas pervade the submission, with thriving interactions right across the mathematical sciences and in numerous application areas, displaying the signs of an extremely healthy mathematical discipline.

Impact

27. Sub-panel 10 received 212 case studies (compared to 236 in 2014), of which 15 required security clearance. The sub-panel was particularly impressed by the quality and diversity of the impact case studies presented, 93 per cent of which were judged to be outstanding or very considerable in terms of their reach and significance, with 54 per cent outstanding.

28. Sub-panel members were joined by five impact assessors for the assessment of impact case studies, including the calibration exercises. Additional input was sought from two of the user members of Main Panel B.

29. The sub-panel executive allocated each case study to four readers including at least one impact assessor and one academic sub-panel member familiar with the general area of the underpinning research. More readers were allocated where additional expertise and views were required. One case study was cross-referred to Sub-panel 23 (Education) for advice rather than scoring.

30. To avoid clustering by institution, the impact case studies were scored in the numerical order determined by a randomly allocated identifier.

31. For consistency of approach, improving calibration, and efficient use of time, additional virtual sessions to agree scores between groups of readers were held. Non-conflicted members were encouraged to observe discussions which greatly improved calibration. The zoom platform was particularly efficient in supporting this approach.

32. In assessing the case studies, the sub-panel observed that:

a. The breadth of applications of the mathematical sciences displayed by the submission is impressive. Submitted case studies demonstrate the capacity of mathematical sciences to contribute new understanding and tools, nationally and internationally, to areas including the manufacturing and financial sectors, public policy and services, health and wellbeing, the environment, national security, and culture and sport. They also illustrate the multitude of ways in which the community engages with the public, to convey to them the power and beauty of the mathematical sciences.

b. Beneficiaries ranged from individuals, organisations (including, for example, the WHO), communities, industry (from SMEs to large multinationals), to government (local, national, and international). There was demonstrated impact on products, processes, behaviours, policies, practices, and understanding. An important category of impacts was the avoidance of significant harm and waste. The use of advanced mathematical modelling has been used to refine and optimise industrial processes, with very substantial economic benefit

c. Modern statistical and operational research techniques, especially in regard to dealing with uncertainty and quantifying predictions, played a strong role in over half of the submitted case studies, and underpinned all of the cases studies submitted by around 30 per cent of HEIs. However, the research underpinning cases was drawn from right across the mathematical sciences. A number of case studies demonstrated the important role of the mathematical sciences in generating impact of outstanding reach and significance from multidisciplinary research projects. State of the art algorithms in numerical analysis and data science were also seen to form the basis of many impressive cases. Probabilistic methods played a prominent role, for example in quantifying uncertainty and in algorithms in numerical analysis and data science. Much of the impact is embedded in scientific and computing software, making it naturally scalable and long-lasting.

d. Impact was seen across topics that are currently at the forefront of public consciousness, including public health policy in response to Covid-19 (which formed at least part of the impact for 16 case studies), efficient and reliable energy distribution, decision making for insurance and pension services, weather forecasting, and ecology and conservation. For example, cases documented the role of mathematical sciences in influencing large scale, international public health initiatives with the potential of saving many lives, helping monitor and manage wildlife, and reducing the number of animal deaths from animal testing.

e. Highly confidential case studies mainly described significant developments in capability or assurance in the field of national security. Many of these case studies were based on mathematical research that was in itself of the very highest calibre.

f. The sub-panel received fourteen impact case studies that were based wholly, or in part, on public engagement. The majority of HEIs confined description of public engagement activity to the environment template, in which a direct link to a specific body of underpinning research is not required.

33. The sub-panel observed that in the mathematical sciences the time between research being conducted and impact being created can be very long, pathways may not be linear, and auditing the pathway to impact may be challenging.

34. In the best case studies the link between the underpinning research and impact claimed was articulated clearly and the reach and significance of the impact was supported by explicit evidence. Where the underpinning research undertaken by the submitting unit

was part of a large collaboration which generated very substantial impact, it was helpful that the submitting unit's contribution to the impact was explained. Good case studies made this clear.

35. The sub-panel expressed a general concern that the requirement to have two or more impact case studies drives smaller departments to grow or shift away from the core of the discipline to topics that can deliver immediate impact. Thus, a challenge for the mathematical sciences community is to maintain and grow its strong world-leading role in mathematical topics without immediate and foreseeable impact. This is the heart of the subject and a decline here would undermine the strength and sustainability of the entire subject, and indeed reduce its potential for impact in the longer term.
36. There were 25 case studies submitted to REF 2021 flagged as continuations of cases submitted to REF2014, having realised additional and/or enhanced impact during the current review period. Equally, for many case studies the impacts achieved were quite recent, with a high potential for even greater impact arising in the coming years.
37. The fact that mathematics has impact in the past, present and future should be celebrated publicly and highly visibly to encourage future collaborations and association of success with mathematics for current and aspiring researchers, the public, industry, and government collaborators alike. The submission provides a wealth of excellent examples of the profound impact of the mathematical sciences.

Research environment

38. The overall environment sub-profile shows a significant uplift in the percentage assessed as world leading (four star) relative to 2014, although a direct comparison is difficult to make as, unlike REF 2014, this exercise did not require HEIs to produce a separate impact template. The scores are consistent with the output and impact sub-profiles enabled by the environment being assessed, and reflect, amongst other improvements highlighted below, substantial progress on embedding EDI and impact into day-to-day activities of units, coupled with significant HEI investment.
39. The sub-panel executive allocated each environment statement to four readers, and more readers were allocated where additional views were required. To improve calibration and make the best use of time, an additional virtual session was arranged to agree scores. Non-conflicted members were encouraged to observe discussions which improved calibration.
40. The sub-panel based its grading of environment statements on the written content, recognising that the context mainly represented the pre-Covid years.
41. The standard data analyses provided context, but were not used in a formulaic way in the assessment.
42. In assessing environment, the sub-panel observed the following:
    a. There was a good deal of variability in the explicit linkage between UOA environment statements with their institutional-level statements, even in areas where policies and initiatives would be expected to apply across disciplinary boundaries.
    b. Many units reported strong and coherent strategies. Stronger submissions clearly articulated progress against the aims that they had laid out in REF 2014.

c. The sub-panel was impressed by the strategies for embedding and promoting interdisciplinary and impactful research, and for reaching out to diverse communities demonstrated by the submissions. There were myriad examples of researchers using multiple media to convey the excitement and influence of the mathematical sciences to audiences of all ages.

d. The sub-panel noted that EDI is becoming increasingly embedded in the activities of most units, although staffing profiles still show imbalances across the sector. Most progress had been made on addressing gender equality, with actions to improve equity of opportunity and experience for other protected groups less mature. Almost all templates reported external recognition (e.g. Bronze or Silver Athena SWAN awards at unit and/or institutional level). The best submissions offered specific examples of how embracing EDI policies had led to material improvements.

e. There was a significant rise in the average number of PhD completions per year between the REF 2014 and REF 2021 assessments. The total number in the five-years up to REF 2014 was 2515. For the current seven-year REF period, the submissions show that this has risen to 4501. This reflects the increase in submitted FTE due to planned growth in some HEIs (c.f. paragraph 6). The sub-panel was pleased to note comprehensive training and support available to research students in the majority of units, and the extent to which PGRs are being prepared for a variety of future careers. The benefits of (national and international) collaborative PGR training between HEIs were particularly notable.

f. The sub-panel welcomed the increasing levels of support and mentorship provided to early career researchers across the majority of units. Many units also had fellowships for early career researchers and/or a policy of proleptic appointments for holders of prestigious research council fellowships. According to HEI submissions, the number of ECRs in the submission fell from 418 in REF 2014, to 408 in this submission, representing a drop from around 21 per cent of submitted staff to around 16 per cent. However, this does not seem to be consistent with the narrative reports and strongly suggests changes in reporting practice.

g. The sub-panel noted widespread good practice in supporting career development and progression of established staff.

h. The sub-panel noted the challenges faced by smaller units, which do not always benefit from the economies of scale, diversity of activities, and the associated networking and impact opportunities of larger units. Nevertheless, the sub-panel judged those aspects of the research environments presented by units at all scales, and in HEIs that are distributed across the UK, are conducive to internationally excellent or world-leading research.

i. The submission demonstrated healthy recruitment into the UK of mathematical scientists from all over the world. In contrast to REF 2014, the most significant growth in FTE was not in the largest units, but in medium size units.

j. In many cases, the sub-panel would have welcomed more detail of the ways in which units encourage and facilitate exchange of staff with business, industry, and third sector bodies.

k. HEI submissions show that research income for the UK mathematical sciences has remained broadly flat during the period and, in particular, this does not reflect the growth in submitted FTE. Many units reported very significant benefits-in-kind, including access to facilities and data and contributions to training, from

industrial collaborators. The UKRI research councils remain a significant funder for mathematical sciences, as illustrated in the table below, but the risk posed by losing access to European funding is a concern in an uncertain funding landscape.

l. The mathematical sciences community is international and the vitality of UK involvement in the mathematical sciences worldwide was reflected in an impressive range of international collaborations; fellowships and research grants from international bodies; prizes, awards and distinguished lecture invitations.

m. Environment statements detailed extensive impact activities not captured by the REF impact case studies. These included wide-ranging public engagement and outreach activities. Collectively they also document the remarkable way in which the UK mathematical sciences community pivoted its activities to support efforts to tackle the pandemic, from modelling the disease and accelerating drug discovery, to predicting demand at food banks.

n. Evidence of the impressive level of commitment of UK researchers to the mathematical sciences profession internationally included extensive service with learned societies, numerous advisory roles, service on editorial boards, conference organisation, and service for national and international grant-awarding bodies. Contributions to graduate training spanned the globe, with a particularly notable increase in activities in support of mathematical sciences in developing countries.

43. All submissions have been judged to have demonstrated a research environment with elements conducive to producing research of internationally excellent quality and enabling very considerable impact in terms of vitality and sustainability. Two large submissions have been judged to have had 100% world leading environments. It was notable that in 28 of the 53 submissions all aspects of the mathematical sciences unit's environment were judged to be conducive to producing research at internationally excellent and world leading levels.

UOA 10: Research Income by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	51,375	50,679	53,812	53,016	371,114
UK-based charities (open competitive process)	3,361	4,286	6,631	5,829	40,804
UK-based charities (other)	270	303	1,502	1,154	8,081
UK central government bodies/local authorities, health and hospital authorities	4,654	6,333	6,812	6,436	45,050
UK central government tax credits for research and development expenditure	0	9,124	498	1,659	11,615
UK industry, commerce and public corporations	4,873	4,480	3,435	3,790	26,527
UK other sources	604	395	928	806	5,639
EU government bodies	14,804	16,429	19,115	18,115	126,806
EU-based charities (open competitive process)	0	0	6	4	28
EU industry, commerce and public corporations	500	642	874	788	5,513
EU (excluding UK) other	188	321	227	235	1,645
Non-EU-based charities (open competitive process)	1,161	1,018	1,283	1,227	8,592
Non-EU industry commerce and public corporations	860	911	1,965	1,657	11,596
Non-EU other	4,265	2,438	3,335	3,339	23,376

UOA 11: Computer Science and Informatics

Summary of Submissions

Name	2021	2014	% difference	2008
Number of submissions*	90	89	+1.1%	81
Category A staff FTE	3,002.21	2,045	+46.8%	1,839
Category A staff headcount**	3,176	2,159	+47.1%	1,910
Number of outputs†	7,296	7,665	-4.8%	7,491
Outputs per Category A staff headcount**	2.30	3.55	-35.2%	3.92
Impact case studies†	299	280	+6.8%	-

***Joint submissions counted as one. **Category A and C in REF 2014. † change in methodology since REF 2014**

Overall profiles

	Average percentage (Category A FTE weighted) judged to meet the standard for:				
	4*	3*	2*	1*	Unclassified
Overall	41	43	14	1	1
Output	37.6	49.2	12.6	0.5	0.1
Impact	50.4	34.4	10.3	2.7	2.2
Environment	36.1	33.9	25.7	4.3	0

1. The submissions to UOA 11 (Computer Science and Informatics) reflected a vibrant and diverse research community delivering considerable impact. There has been a significant increase in the number of staff returned to this unit of assessment since the REF 2014. This growth reflects the significant investment and expansion in the area with most submitting units growing and some doubling in size. This growth also reflects the overall vibrancy of UK research in this area and the strength of impact it continues to deliver.

Working methods

2. The sub-panel of 25 members read and assessed 7,303 research outputs, 90 environment statements and were joined by eight impact assessors in reading and assessing 299 impact case studies. All meetings during the assessment phase were undertaken virtually with final assessment decisions made in plenary sub-panel sessions. Sub-panel members were removed from plenary sessions during discussion of items where they were conflicted. The assessment placed a considerable burden on sub-panel members and impact assessors, who undertook this work with impressive dedication and care, alongside substantial roles and pressures in their home organisations.
3. All sub-panel members undertook tailored training in equality, diversity, inclusion and unconscious bias. This was augmented by workshop sessions where the sub-panel reflected on the potential for biases in the specific context of assessing Computer Science and Informatics research, and agreed mitigation strategies. These were captured in a Fairness in REF Intention Plan that was revisited at regular intervals during the assessment process.

Allocation to Reviewers and Scoring

4. Outputs, impact case studies (ICS) and environment statements (ES) were allocated to sub-panel members and impact assessors (collectively reviewers) using an automated approach that aimed to ensure that each reviewer received the same workload, whilst avoiding conflicts of interest. The system also aimed to ensure that each pair of reviewers shared roughly the same number of assessments, avoiding cliques and facilitating cross-calibration.
5. For outputs, the research area labels provided by submitting institutions (Table 3) were used to assign each output to three reviewers: an expert in the area, a reviewer familiar with the area, and a generalist. Each ICS was assigned to four reviewers: two sub-panel members and two research-user impact assessors. Each ES was assigned to six sub-panel members.
6. Assessment proceeded in three phases, dealing with outputs, ICSs and ESs in turn. In each phase, each reviewer independently assigned a score to each item allocated to them to be assessed based on the published scoring critera. For outputs, a 13-point scale was used (4*+, 4*, 4*-, 3*+, 3*, 3*-, 2*+, 2*, 2*-, 1*+, 1*, 1*-, 0), whilst for each ICS and ES and a 9-point scale was used (4, 3.5, 3, 2.5, 2, 1.5, 1, 0.5, 0). For ESs, each section (i.e., strategy, people, income, collaboration) was scored separately using a 9-point scale. Agreed panel scores were mapped to the five point scale.

Using Reviewers' Scores to Agree REF Grades

7. The sub-panel undertook a calibration exercise prior to each assessment phase to ensure a criteria-based approach to scoring was adopted by all reviewers.
8. The sub-panel used bespoke normalisation software to ensure consistent calibration, and to support moderation. For each of the elements of the assessment (outputs, impact and environment) the software used reviewers' raw scores to produce a ranked list of items, together with a disagreement score for each item.
9. Agreeing a final score for each item followed a similar approach for each element of the assessment, with a moderation session and a grade assignment session.
10. In the moderation session, the whole sub-panel worked through the list of items, sorted by decreasing disagreement score, discussing reviewers' rationale for their scores, and agreeing changes where necessary. This continued until a point was reached where it was clear no more score changes would be necessary.

11. In the grade assignment session, the sub-panel worked with the ranked list produced by the software, following moderation, and collectively agreed where to place grade boundaries. For outputs, grades were assigned directly on the 5-point scale. For impact case studies and each of the four environment statement sections, grades were assigned on the 9-point scale, with non-integer scores counting 50% to each of the bracketing integer scores when constructing the grade sub-profile.

Handling Interdisciplinary Research

12. The sub-panel appointed four members as Interdisciplinary Research (IDR) advisers. During output assessment, all sub-panel members were asked to flag any outputs assigned to them that they thought might need specialist handling, paying particular attention to those marked as interdisciplinary by the submitting institution. The IDR advisers of the sub-panel, the sub-panel chair and deputy chair met to determine the best course of action for dealing with each flagged output.

13. In calibration exercises and sub-panel meetings, it was consistently emphasised that the assessment was of the excellence (originality, significance and rigour) of the research in the round, not just of the Computer Science and Informatics aspects of it, and that any added value of interdisciplinarity should be reflected in the score allocated.

14. The sub-panel observed that the use of the interdisciplinary flag varied considerably across submitting institutions. The sub-panel does not feel that the flagged interdisciplinary outputs are an accurate reflection of the interdisciplinary work submitted, with the proportion of interdisciplinary outputs significantly higher than would be indicated by the interdisciplinary flag. In practice, Computer Science and Informatics is inherently interdisciplinary, working closely with both related disciplines (engineering, psychology, mathematics, etc.) with whom the boundaries have always been porous, and application areas (health, education, etc.) that enable researchers to validate the practical applications of research advances by applying them to realistic, complex problems.

Software

15. All software used is open source, and is available at: https://gitlab.com/REF2021_SP11

Outputs

16. Outputs were assessed independently by three sub-panel members, and grades were agreed following the process set out in paragraphs 4-13.

17. Outputs returned to the sub-panel reflected the enormous diversity of the subject domain, with a heterogeneity of approaches and traditions and a strong culture of interdisciplinary research that engages in real-world problems. This was reflected in a high proportion of outputs demonstrating close work with associated disciplines and a broad set of application domains. Foundational work that engages with real-world problems continues to be a strength of UK academic computing research, including work on intelligent systems, computer vision, human-centred computing and in ‘big data’ and data analytics. There is also much evidence of contributions to the underpinning innovation base in the UK (e.g. health and life sciences, manufacturing, finance etc.), with a growing emphasis on cyber-security, privacy and ethics around digital technologies.

18. Submitting institutions were asked to code outputs against a topic list provided by the sub-panel. The numbers of outputs submitted in each category are provided in

Table 3. Quality profiles did not vary much with topic area with over 85% of outputs demonstrating work at a 4* or 3* level. The largest single topic area was Machine learning (612 outputs) which alongside work in Knowledge representation and reasoning (253), and Planning search, control and distributed AI (229) show that UK research in intelligent systems is vibrant. There were also significant numbers of outputs in Computer vision (536), Security and privacy (522), Human computer interaction and interaction design (475) and Networks (362). It is noteworthy that, spread over several topic areas, there were over 1,250 outputs in foundations of computing, making an important contribution to the future health of the discipline. Fewer outputs were coded against Hardware, Software organisation and properties, and Computer systems organisation than in the REF 2014 although the topic list used has changed since then, reflecting the dynamic nature of the discipline. Outputs returned to the sub-panel across all topics also reflected work across a broad set of computing application areas including life sciences, medicine, psychology, education, geoscience, and physics.

19. Multi-author outputs dominated the submission reflecting a broad collegial approach to research, with author lists reflecting both international collaboration and interdisciplinary work. Approximately 15% of the outputs submitted were returned by more than one institution reflecting the strength of collaboration in the discipline across the UK. In such cases the sub-panel ensured the same grade was awarded to a given output, irrespective of submitting institution.

20. As anticipated, given the nature of the discipline, the sub-panel received a very broad range of interdisciplinary outputs, not all of which were flagged as such. The assessment of interdisciplinary outputs was overseen by the IDR advisers (see paragraph 11, above). In the vast majority of cases, it was judged that the sub-panel was competent to undertake the assessment, drawing, where necessary, on input from sub-panel members with specialist IDR experience. Such outputs were assessed on their broad contribution, not simply on their Computer Science and Informatics content. In cases where the major contribution was to another discipline, outputs were cross-referred to the appropriate sub-panel. This included Medicine (cross-referred to UOA 1: Clinical Medicine), Art, Design and the Performing Arts (cross-referred to UOA 32: Art and Design: History, Practice and Theory and UOA 33: Music, Drama, Dance, Performing Arts, Film and Screen Studies), Physics (cross-referred to UOA 9: Physics) and Maths (cross-referred to UOA 10: Mathematical Sciences).

21. The sub-panel received incoming cross-referral requests from many other sub-panels (181 from 19 sub-panels), the great majority of which were handled by sub-panel members on the same basis as outputs submitted directly to this sub-panel. The few such cross-referral requests not accepted by the sub-panel were declined on the grounds that they fell outside the sub-panel's sphere of competence.

22. As set out in the REF 2021 'Panel criteria and working methods', institutions were able to provide 100 words of factual information about significance, if this was not fully evident in the output. The sub-panel noted that the 100-word statements were provided for nearly all outputs and many did not follow the guidelines provided in the REF 2021 'Panel criteria and working methods' (para. 256-257). Examples of good practice included information on best paper prizes, editorial endorsement and real-world impact, but too often statements were submitted that provided no additional evidence of significance, some simply repeating the abstract, others commenting on originality and/or rigour. Sub-panel members took care to ignore content in statements that did not follow the guidelines.

23. The REF 2021 'Panel criteria and working methods' also allowed for additional statements to be provided for non-text outputs, outputs with material in common with outputs submitted to REF 2014, and reviews. The sub-panel noted that submitting institutions rarely took advantage of the opportunity to provide such statements.
24. As set out in the REF 2021 'Panel criteria and working methods', sub-panel members made limited use of citation data to contribute to their judgement of the academic significance of outputs. The sub-panel recognised, in advance, the limitations of such data, with poor indexing of outputs for some areas of Computer Science and Informatics, and highly variable citation practices across different sub-fields. As a result, a high citation rate was taken as positive evidence of significance, but absence of citations was not interpreted as lack of academic impact. In practice, the format in which citation data was provided made it very difficult to compare citations across different sub-disciplines within Computer Science and Informatics. As a result, citation data was even less useful than anticipated.

Number of outputs submitted in each topic area (page 62).

Number of outputs submitted in each topic area

Topic#	Topic	Number of Outputs Submitted
1	Accessibility	11
2	Applied computing - arts, humanities and other	63
3	Applied computing - business and enterprise	38
4	Applied computing - document management and text processing	11
5	Applied computing - education	56
6	Applied computing - law, forensics, social and behavioural sciences	98
7	Applied computing - life and medical sciences	585
8	Applied computing - operations research	49
9	Applied computing - physical sciences and engineering	218
10	Collaborative and social computing	56
11	Computational complexity and cryptography	92
12	Computer graphics	138
13	Computer systems organisation	98
14	Computer vision	536
15	Continuous mathematics, analysis and software	65
16	Cryptography	77
17	Data management systems	68
18	Design and analysis of algorithms	293
19	Discrete mathematics	76
20	Distributed and concurrent computing	89
21	Embedded, real-time and dependable systems	133
22	Hardware	41
23	Human computer interaction and interaction design	475
24	Information Retrieval	80
25	Information storage systems	5
26	Information systems applications	73
27	Knowledge representation and reasoning	253
28	Logic	243
29	Machine learning	612
30	Modelling and simulation	91
31	Models of computation and formal languages	151
32	Natural language processing	196
33	Networks	362
35	Parallel computing methodologies	49
36	Planning, search, control and distributed AI	229

Topic#	Topic	Number of Outputs Submitted
37	Probability and statistics	68
38	Security and privacy	522
39	Semantics and reasoning	157
40	Software creation and management	147
41	Software notation and tools	90
42	Software organisation and properties	87
43	Symbolic and algebraic manipulation	30
44	Theory and algorithms for application domains	240
45	Ubiquitous and mobile computing	81
46	Visualisation	99
47	World Wide Web	72

Impact

25. Impact case studies were assessed independently by two sub-panel members and two research user impact assessors, and grades were agreed following the process set out in paragraphs 4-10.

26. The sub-panel noted the high quality of many of the ICSs submitted. Many institutions are deriving high-value intellectual property from their research and have been successful in translating it into practice. The best of the ICSs submitted provided clear quantifiable evidence of both the reach and significance of the impact achieved, and provided clear statements on the link to underlying research of at least 2* quality. However, the sub-panel saw some ICSs where the impacts were outstanding, but the direct link to underpinning research that was judged to be of at least 2* quality was not established.

27. Much of the research submitted to the sub-panel addresses real-world problems, leading to direct impact at a global, international, national and regional scale, and this was reflected in the impact case studies submitted. The sub-panel recognised substantial impacts across a very broad range of business, public service and community activities, touching most aspects of human endeavour. As well as direct impacts in the technology sector, major impacts in safety & security, health & wellbeing, creative & media and infrastructure & logistics were noteworthy. The reach of some of the most significant impacts was phenomenal, affecting the lives of billions of citizens across the globe. The sub-panel also acknowledged the importance of the local partnerships reported in many ICSs, and recognised significant impacts on their communities and regional economies.

28. Taken together these ICSs demonstrate very impressive and substantial impact from Computer Science and Informatics research, which is perhaps unsurprising as computer systems now underpin almost all human activity, from research in other disciplines,

through business, education, entertainment, and into the heart of government. The growth in the use of large-scale data and AI systems since the last exercise has further amplified the ubiquitous nature of computer systems. The breadth of impact of computer science is reflected in the wide range of impact types submitted. These included: economic impact through start-up companies and collaborations with industry; contributions to commercial and public domain software infrastructure; work with the health services and influencing policy and standards. All impact types were welcomed and were assessed on an equal footing. The impact from the discipline as a whole is likely to be greater than that reflected in the impact case studies submitted.

29. The sub-panel was appreciative of the contribution made by its research user impact assessors on whom the scoring of impact relies, alongside the work of the sub-panel members. Assessment of ICSs placed a considerable burden on our impact assessors who are outside the higher education sector. It is important that future exercises can continue to recruit experienced impact assessors given these demands and the importance of understanding impact from the perspective of research users.

Research environment

30. Environment statements were assessed independently by six sub-panel members, and grades were agreed following the process set out in paragraphs 4-10, using the detailed criteria set out in the REF 2021 'Panel criteria and working methods' (paras 345-358).

31. The sub-panel noted inconsistent use of institutional and unit ESs. In the best submissions the institutional ES provided general context, whilst the unit ES addressed all of the assessment criteria as they applied to the unit. In other submissions, information that was key to the assessment was only present in the institutional ES, with no attempt in the unit ES to cross-reference or discuss the application of institutional policies and practices at the unit level. This made assessment more difficult, but sub-panel members took care to credit relevant information wherever it was presented in the unit ESs drawing upon the institutional ES for context.

32. A diverse set of units was submitted to UOA 11 (Computer Science and Informatics), with unit size ranging from less than 10 to over 100 FTE, and host institutions covering the full range of institutional missions. Units adopted different strategies reflecting their different strengths. The best of the ESs submitted addressed the detailed criteria systematically, providing the information requested and with clear strategic statements that were evidentially linked to outcomes. Many ESs described research organisations with a coherent vision and a clear articulation of the structure and processes in the submitted units. In some cases, the sub-panel would have welcomed more details of the impact of these processes in practice and evidence of their success.

33. Computer Science and Informatics is in rude health. Overall funding has been stable (Table 4). There has been considerable investment in staff across the sector with most institutions increasing the number of researchers returned to the REF 2021 and some units doubling in size.

34. The sub-panel noted that there have been dramatic changes in the Computer Science and Informatics landscape over the assessment period, with huge advances in the quality and scale of research across both the developed and the developing world. The UK research community has embraced the opportunities this has presented, as

evidenced by increasing internationalisation of co-authored outputs and of academic appointments in the UK. This has enriched the research culture, but is not without risk. Over the coming period it will be important to ensure the UK remains an attractive environment for talented Computer Science and Informatics researchers, maintaining the capacity to contribute on the global stage.

35. An impressive community of high-quality ECRs has been developed, and growth in the number of doctoral degrees awarded in Computer Science and Informatics, noted in the last assessment, has continued over the REF 2021 period. It will be important to ensure that research funding is in place to sustain the future growth that this implies.

36. Computer Science and Informatics continues to face particular challenges in ensuring the representation of women. Virtually all submissions recognised this and reflected it in their EDI strategies. Many had applied for, or achieved, Athena SWAN awards. Similarly, many were engaged with national initiatives. Support for female doctoral students was commendable with a number of institutions putting in place specific support mechanisms, although the sub-panel would welcome broader adoption of best practice. Institutions have started to broaden their EDI strategies to address a wider range of protected characteristics and ensure equal access and opportunity, though the sub-panel would have valued more information about access strategies and outcomes for all under-represented communities. The sub-panel welcomes the ways in which EDI is becoming central to environment strategies and encourages the growing emphasis on a holistic approach to EDI.

37. The impact strategies demonstrated that the culture toward impact has matured since the previous exercise, with an increasing emphasis on delivering impact reflected in the institutional policies and support mechanisms embedded in units of assessment. The research impact delivered by most institutions goes well beyond the work reported in the impact case studies, with significant contributions to the vibrancy of their local regions and some excellent examples of public engagement. Sub-panel members noted a growing recognition of impact contributions and the use of mechanisms such as proportional appointments (less than 1 FTE) to allow staff to drive impact activities including spin-out companies and holding part-time industry positions.

38. The statements on research integrity reflected a growing emphasis on responsible innovation and the inspection of the ethics of research as part of everyday practice. The sub-panel welcomed the current commitment to the use of open access publication and would encourage the widespread shift to open science, including the publication of data sets, software and research protocols already demonstrated by some institutions.

39. Collaborative research and larger grants are a strong trend reflecting the funding bodies' strategies in the projects they resource. Significant EU funding into Computer Science and Informatics gives a strong international flavour to much of the collaborative research reported during this period, highlighting concerns around the impact of any removal or reduction of this form of funding. Collaborations often include industry as well as academic partners. Many institutions actively encourage multi-disciplinary research, and departments often lead or are involved in multi-disciplinary institutes and centres. The sub-panel noted the particular contribution that Computer Science and Informatics makes in support of the excellence of research in other disciplines across the spectrum, with many units involved in pan-institutional research centres.

UOA 11 Research Income by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	76,155	76,668	84,335	82,071	574,498
UK-based charities (open competitive process)	3,159	3,416	6,083	5,284	36,990
UK-based charities (other)	989	863	1,143	1,081	7,569
UK central government bodies/local authorities, health and hospital authorities	15,142	15,854	29,982	25,843	180,904
UK central government tax credits for research and development expenditure	0	15,933	1,201	3,134	21,939
UK industry, commerce and public corporations	8,637	9,470	12,865	11,776	82,429
UK other sources	1,204	1,302	1,786	1,634	11,436
EU government bodies	55,053	52,245	51,862	52,373	366,609
EU-based charities (open competitive process)	0	20	19	17	117
EU industry, commerce and public corporations	605	614	1,543	1,277	8,936
EU (excluding UK) other	728	1,163	1,285	1,188	8,318
Non-EU-based charities (open competitive process)	600	767	759	737	5,162
Non-EU industry commerce and public corporations	3,517	3,819	5,582	5,035	35,246
Non-EU other	2,745	3,027	5,281	4,597	32,180

UOA 12: Engineering

Summary of Submissions

In REF 2014 Engineering research was submitted to four sub-panels: 12 (Aeronautical, Mechanical, Chemical and Manufacturing Engineering); 13 (Electrical and Electronic Engineering, Metallurgy and Materials); 14 (Civil and Construction Engineering); and 15 (General Engineering). REF 2021 saw these sub-panels merged to form a single sub-panel, 12 (Engineering). The sub-panel felt there were some advantages to the single sub-panel approach in terms of equity of assessment and opportunity to see a much broader spectrum of impact and environment. However, there were challenges in operating at such scale, for example, in managing large plenary discussions and in observing subtle changes in sub-disciplines within Engineering. Further feedback on the advantages and operational challenges will be provided to the REF Director to support future decision making.

Name	2021	2014*	% difference
Number of submissions**	88	138	-35.5%
Category A staff FTE	7,432.39	5,062	+46.8%
Category A staff headcount***	7,750	5,279	+46.8%
Number of outputs†	18,282	18,263	+0.1%
Outputs per Category A staff headcount**	2.36	3.46	-31.8%
Impact case studies†	483	621	-22.2%

***Total of four sub-panels. **Joint submissions counted as one. ***Category A and C in REF 2014. †Change in methodology since REF 2014.**

Overall Profile for the Sub-panel

	Average percentage (Category A FTE weighted) judged to meet the standard for:				
	4*	3*	2*	1*	Unclassified
Overall	40	49	10	1	0
Output	33.1	57.5	8.0	1.3	0.1
Impact	49.9	37.0	11.6	1.5	0.0
Environment	52.2	33.7	12.3	1.8	0.0

1. The submissions to Sub-panel 12 showed real strength and diversity in UK engineering during the seven-year assessment period. The overall quality of research was found to be very high with 91 per cent of outputs assessed in terms of originality, significance and rigour as being of at least internationally excellent quality. The impact of research was found to be high with over 87 per cent of the volume weighted impact results judged to have very considerable or outstanding reach and significance. Environment submissions were similarly found to be of a high standard with over 85 per cent of the volume weighted environment results judged to demonstrate vitality and sustainability conducive to producing research of internationally excellent or world-leading quality.
2. Unit of Assessment (UOA) 12 (Engineering) received submissions from 89 HEIs, including one joint submission, comprising 7,432.39 full time equivalent (FTE) Category A staff and a total of 7,750 Category A individuals. The submissions were from departments and schools of widely varying size that ranged from entire departments in long-established universities to much smaller submissions from newer universities and from specialised research units. Comparisons between the 2014 and 2021 submissions and associated outcomes should be made cautiously, due to the significant changes in submission rules between the two exercises and the amalgamation of four REF 2014 sub-panels into the single REF 2021 sub-panel.
3. The range of research disciplines was very wide and there was extensive evidence of interdisciplinary and internationally collaborative research.
4. The overall quality of the research outputs submitted affirmed the academic and scientific health of the themes within engineering disciplines. There was evidence of investment and growth across the institutions submitted and the landscape now features a number of larger institutions where the scale of the environment appears particularly conducive to the production of relatively high impact. The increase in numbers of early career researchers and PhD completions, the increasing activity across discipline boundaries and the investment in many institutions also evidenced vitality and sustainability and was not restricted to the larger submissions, with some smaller submissions either newly entering or making significant improvement.
5. The sub-panel agreed that the administrative support and process mechanisms had been excellent and that the calibration and validation exercises had been invaluable. There was remarkable coherence and consistency of grading.
6. The sub-panel operated as a single unit, ensuring equitable assessment across all disciplines.
7. The 13-point scoring scale worked well for outputs, where the top three scores all correspond to a 4* grade. However, the 9-point scoring scale for impact and environment lacked resolution at the top end of the scale with some apparent reluctance to score 4 which was addressed through further sub-panel discussion.

Outputs

8. In total 18,282 outputs were submitted across the full range of engineering disciplines, with the vast majority comprising journal publications. In addition, some conference papers, a small number of books, book chapters, reports and patents were submitted.
9. Outputs submitted were within, but not limited to the following broad categories: biomedical engineering, bioengineering; chemical engineering; civil engineering; communications and signal processing; computational modelling; dynamics and control; electrical engineering; electronics; energy; environmental engineering; human factors; manufacturing and design; materials; mathematics; mechanics and structures; mining engineering; nuclear; optics and photonics; systems and sensors; thermofluids; and transportation.
10. 324 outputs were cross-referred to other subpanels in response to a direct request from the submitting HEI. A further 120 outputs were cross-referred to provide additional guidance for assessment of inter-disciplinary research. In addition, 236 were cross-referred to the sub-panel from other sub-panels, the highest proportion of these being from Sub-panel 13 (Architecture, Built Environment and Planning). Outputs were also cross-referred from Sub-panel 3 (Allied Health Professions, Dentistry, Nursing and Pharmacy), Sub-panel 32 (Art and Design: History, Practice and Theory) and Sub-panel 33 (Music, Drama, Dance, Performing Arts, Film and Screen Studies), with smaller volumes from 16 other sub-panels. A small number of HEIs made particular use of cross-referral.
11. The panel noted that a high number of submitted outputs were highly interdisciplinary and internationally collaborative. The sub-panel was pleased to note a high proportion of outputs which showed demonstrable significance in terms of the commercial, translational and/or industrial potential to lead to impacts for the benefit of the UK and beyond. The sub-panel welcomed the increase in interdisciplinary outputs, but noted inconsistent use of the IDR flag by HEIs. Some HEIs used the flag liberally, whereas others did not flag any outputs as IDR. Nonetheless, the use of up to three topic tags for each output provided good evidence that IDR has become mainstreamed.
12. Sub-panel members were joined by 20 output assessors for the assessment of outputs. These assessors were fully integrated into the sub-panel for this element of assessment and provided valuable support and expertise. The sub-panel believes the use of assessors was vital in ensuring the robust assessment of the large volume of outputs submitted and would recommend the practice is continued in future exercises.
13. Independent peer review by two sub-panel members or output assessors was key to the assessment process. The initial allocation was undertaken algorithmically, using the taxonomy of research topics, on the basis of roughly equal loads per assessor and sub-panel member, and ensuring avoidance of all declared conflicts of interest. The allocation was then approved by the sub-panel chair. The taxonomy proved useful in the allocation process and in enabling submissions to highlight interdisciplinary research. Nonetheless, there is scope to improve and simplify the taxonomy ahead of any subsequent assessment exercise.
14. As stated in the published working methods, the sub-panel members and assessors did not use citations in their assessment of outputs.
15. The additional factual information on significance, the '100 words', continue to be of value to this sub-panel. However, a number of HEIs did not use them effectively, many simply summarising the paper rather than providing the additional information requested by the Main Panel B criteria. 823 duplicate outputs were submitted to Sub-

panel 12 by two institutions, with a very small number being submitted by three or four institutions. In a small number of cases, the difference in the '100 words' resulted in minor differences to the assessment score.

16. The changes to the rules for HEI selection of outputs and nature of the allocation of outputs to assessors has presented some challenges in reporting on trends within Engineering. Overall, the sub-panel received outputs spanning the full breadth of engineering ranging from highly theoretical to applied but observed a high proportion of theoretical outputs.

17. The following observations are offered based on sub-panel member's perceptions of the submitted outputs and are by no means exhaustive. The observations are offered particularly where any known growth or decline across the discipline, within the REF period, is substantiated by what has been observed in the submitted outputs. The sub-panel observed;

    - An increase in outputs in fields such as; biomedical engineering, bioengineering, device design, device materials, computer engineering, cyber physical systems, electrical machines and drives, electrical distribution networks and topologies, advanced nanoscale engineering, membrane technologies and autonomous systems.
    - An increase in outputs examining topics such as energy efficiency, security aspects of communications systems and incremental theoretical modifications to existing wireless communications concepts, without experimental verification.
    - An increase in the application of machine learning techniques to multiple topics where, for example, data-driven analytic research enabled by machine learning and capabilities to acquire real world data at scale was evident in interesting applications of computer vision in engineering research and showed that this field is maturing.
    - Strong representation from fields relating to energy capture, storage and energy materials.
    - Strong representation from geotechnical engineering with good applications across a number of sectors including renewable energy and rail transport, with developments in both traditional (e.g. constitutive modelling) and developing (e.g. bio-inspired) areas. There was a range from micromechanical studies to some large scale and/or globally significant field studies in collaboration with industry.
    - Good representation of manufacturing research within the contributing science bases, such as the materials science, chemistry and physics underpinning manufacturing processes and technologies and an increasing body of strong research in bio-manufacturing. Conversely, there was comparatively little evidence of manufacturing-related automation and robotics research or progress in topics relating to the organisation of manufacturing, and only more recent evidence of work arising from circular economy research.
    - Strong representation in the tribology field covering molecular modelling, novel substrates, coatings and surface texturing for reduced friction in mechanical and biomechanical systems.
    - An increase in aerospace engineering outputs covering composite structures, propulsion systems and computational and experimental aerodynamic optimisation for net-zero concepts.
    - Relatively few submitted outputs covering mechatronic systems and robotics for manufacturing systems.

- Pockets of strength in fields such as additive manufacturing, water and environmental engineering, thermodynamics, engineering design, fundamental chemical engineering, but overall numbers of outputs submitted were low.
- Relatively few submitted outputs in fields such as green economy, construction management and nuclear energy.
- Strong pockets of high-fidelity modelling and experimental validation studies for aerospace, including turbomachinery.
- Relatively few submissions relating to the design of environmentally friendly aircraft and urban air mobility, and the technologies that will facilitate such new platforms, be it from an airframe or operational viewpoint.
- Strong representation of papers connected to sustainability, but few appeared to be driving the agenda forward, and few had quantitative assessments, such as life cycle assessments and costings.
- Outputs from the materials science community demonstrated a vibrant activity across a wide range of topic areas and applications, with many outputs at the interface of at least two disciplines, including; biomaterials, chemical synthesis, surface chemistry, electronic devices, computational modelling and materials physics. There was also evidence of excellence in the field of materials characterisation using advanced techniques.
- Very good representation from polymers, composites and aerospace, reflecting the UK's strong position in these areas, along with strong growth in papers on graphene with encouraging indicators of future impact.

18. All areas exhibited some world-leading output. The panel noted established and emerging pockets of excellence, even in quite small institutions and from those submitting to this UOA for the first time.

Impact

19. The sub-panel received many examples of outstanding impact and noted many impacts which would be likely to continue to develop in the future. The sub-panel determined that there was a very high proportion (87 per cent) of impact case studies demonstrating very considerable to outstanding significance and reach, with many examples of major contributions to society and the economy in the UK and internationally.
20. Sub-panel members were joined by 20 impact assessors for the assessment of impact case studies. Each case study was allocated to four readers, two of whom were impact assessors and two were academic sub-panel members. The initial allocation was made by the sub-panel adviser and panel secretary on the basis of appropriate expertise and roughly equal loads per impact assessor and per academic panel member, ensuring avoidance of all declared conflicts of interest. The allocation was then approved by the sub-panel chair. Members and assessors worked in small groups to arrive at scores, with membership of these groups rotating to allow cross calibration. Despite the broad range of disciplines in engineering, there was a very good level of consistency in the individual views of the assessors and members and full agreement of the final scores.
21. The sub-panel noted that a large number of case studies related to business, economic impact, and that this may not necessarily reflect the breadth and depth of impact activity

taking place across engineering disciplines. The sub-panel noted very few case studies related to societal or cultural impact and would have welcomed such case studies.

22. The sub-panel saw impressive contributions made to the aerospace, construction, transport, marine, energy, defence, healthcare and manufacturing industries, as well as in many other areas. In addition, there were excellent contributions to policy and sustainability. It was notable that the companies and organisations involved included major nationally and internationally known, well-established brands, as well as less well-known organisations. There were also a significant number of spin-out companies, formed as a direct consequence of the academic research.
23. The sub-panel was pleased to see a high proportion of traceable and realistic claims made in impact case studies, with well-articulated pathways and strong evidence. In a minority of case studies more evidence of the impact in the assessment period would have been helpful, and in some cases the impact appeared to be at an early stage. On the whole the sub-panel found case studies which focussed on one or two key impacts rather than diffuse, multiple small impacts, more convincing.
24. Panel members who served on the present and the immediate past REF exercises were unanimous in the view that the case studies submitted to REF 2021 were of significantly higher overall standard than those submitted in REF 2014 – consistent with the improved impact profile. The REF 2021 submissions were typically more specific, better evidenced and succeeded in capturing more fully the multiple dimensions of the impacts.

Environment

25. The size of the submissions to UOA 12 varied very considerably. In the majority of cases where a single submission to REF 2021 replaced multiple submissions to REF 2014, a clear description was provided of the structure of the composite submission. Some HEIs had used the opportunity of a single submission to integrate their organisational units while others, for good reason, had not. Units adopted different strategies for presenting their environment reflecting the different strengths of the units.
26. Each submission was allocated to five readers who were sub-panel members. The initial allocation was made by the sub-panel advisor and panel secretary on the basis of roughly equal loads per academic panel member, ensuring avoidance of all declared conflicts of interest. The allocation was then approved by the sub-panel chair. Once all individual scores had been uploaded, the group of five readers for each statement came together to agree common scores. Members worked in small groups to arrive at scores, with membership of these groups rotating to allow cross calibration.
27. Many institutions provided forward-looking, exciting, dynamic and effective strategies, showing a clear and coherent vision for their future research activities and demonstrated evidence of achieving strategic aims and objectives since REF 2014. The majority of environment statements described managed research organisations where research is focused on specific societal challenges. Although there was some evidence of curiosity-driven research activity, the sub-panel would have welcomed more detail on mechanisms used to support new, curiosity-driven, research which will be essential to the long-term health and international competitiveness of the discipline.

28. The sub-panel noted extensive evidence of investment in people, including training, promotion, equality of opportunity and postgraduate development across the majority of submissions. With regard equality, diversity and inclusion (EDI), the sub-panel noted that there is improved awareness and some improvements in representation and descriptions of the mechanisms in place, but there is room for further improvement across the discipline. Some approaches to EDI felt driven by compliance rather than describing a strategy to improve. Furthermore, there was variability in the evidence provided of their efficacy. The sub-panel would have valued EDI data across PGRs and staff at all career stages.
29. The sub-panel was pleased to note that ECRs represented 16 per cent of the overall headcount submitted to the sub-panel and observed some excellent models of support and development across a broad range of HEI submissions.
30. The sub-panel noted significant variation in levels of funding and numbers of PhDs per FTE across the submissions. There were multiple causes for such variation and care was taken to only use such information, in conjunction with the wider narrative, to inform the assessment of environment. All submissions demonstrated processes were in place to monitor, train and progress PhD students, with the strongest describing well integrated communities of students and staff.
31. Overall, the submissions to this sub-panel, awarded 24,243 research doctoral degrees over the seven-year period, averaging to 3.13 per submitted staff headcount and 3,463 per year. In REF 2014 the total degrees awarded across the four Engineering sub-panels was 13,553 over a five-year period, with an average of 2,711 per year. This represents over 27 per cent increase in degrees awarded per year during the review period.
32. The submissions also show a strong diversity of income sources, with close to 63 per cent of average annual research income non-BEIS Research Councils based, including industry, EU and other sources. Notable contributions to average annual research income during the period include; EU funding at 15 per cent, UK Central Government bodies/local authorities, health and hospital authorities at 20 per cent and UK industry at 13 per cent.
33. There has also been significant investment in major capital equipment and facilities in key centres and institutes. Associated with investment in infrastructure, experienced high level technical specialists in the operation and use of equipment were complementary members of research teams.
34. The submissions show that these disciplines benefit from a strong ethos of collaborating nationally and internationally, both with academe and with industry. Some submissions showed a priority for regional/local interaction and support, while others were more international in their outlook. There was also clear description of support for impact in the majority of submissions.
35. All environment statements also included details of the many contributions staff had made to advisory panels, to learned societies, to international panels and committees and to scientific publishing. There were similarly impressive details provided of national and international recognition and awards.

UOA 12 Research Income by source (£000)

Income source	Income in AY 2013-14	Income in AY 2014-15	Average income for AY 2015-16 to AY 2019-20	Average income for AY 2013-14 to AY 2019-20	Total income for AY 2013-14 to AY 2019-20
BEIS Research Councils, The Royal Society, British Academy and The Royal Society of Edinburgh	268,589	322,151	413,249	379,570	2,656,988
UK-based charities (open competitive process)	24,490	27,321	34,249	31,865	223,054
UK-based charities (other)	5,146	5,280	7,381	6,761	47,329
UK central government bodies/local authorities, health and hospital authorities	121,459	156,717	224,367	200,001	1,400,009
UK central government tax credits for research and development expenditure	0	82,101	6,009	16,021	112,147
UK industry, commerce and public corporations	119,872	133,518	135,132	132,721	929,048
UK other sources	6,790	7,306	6,967	6,990	48,930
EU government bodies	138,498	138,959	151,296	147,705	1,033,938
EU-based charities (open competitive process)	329	218	117	161	1,130
EU industry, commerce and public corporations	12,379	17,504	20,446	18,873	132,114
EU (excluding UK) other	6,971	5,458	4,550	5,026	35,180
Non-EU-based charities (open competitive process)	2,080	1,097	1,839	1,768	12,374
Non-EU industry commerce and public corporations	41,325	35,777	46,148	43,978	307,844
Non-EU other	15,360	18,238	23,967	21,919	153,433

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