The dynamics of global public research funding on climate change, energy, transport, and industrial decarbonisation

AbdulRafiu, Abbas, Sovacool, Benjamin K and Daniels, Chux (2022) The dynamics of global public research funding on climate change, energy, transport, and industrial decarbonisation. Renewable and Sustainable Energy Reviews, 162. a112420 1-17. ISSN 1364-0321

This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/105292/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher’s version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.
The dynamics of global public research funding on climate change, energy, transport, and industrial decarbonisation

Abbas AbdulRafiu *, Benjamin K. Sovacool, Chux Daniels

Science Policy Research Unit (SPRU), University of Sussex Business School, Falmer, United Kingdom

ARTICLE INFO

Keywords:
Public research funding
Climate change adaptation
Energy transitions
Technology innovation
Carbon emission
Interdisciplinary

ABSTRACT

This paper explores the funding trends, topical themes, and notable gaps in global public research funding across the areas of energy, climate change, transport, and industrial decarbonisation from 1990 to 2020. The paper organizes its analysis along the themes of financial and spatial patterns of funding, patterns of disciplinary funding, and the temporality (and shifting research priorities) within funding patterns. It finds that funding for energy and climate research remains concentrated within the European Commission, United Kingdom and United States. Climate change adaptation research is the most funded general area, and the specific topics of energy efficiency, climate resilience, and climate information systems, managing climate risks, energy storage, carbon dioxide removal and solar energy are the most funded technologies. There is significant diversity in the disciplines funded, with the social sciences supported almost as much as the engineering and physical sciences and meaningful amounts of funding disbursed to the arts and humanities and the life sciences. A large majority of projects identify themselves as transdisciplinary. The paper, lastly, discusses research gaps and future research questions.

1. Introduction

Averting the consequence of climate change will require new technological innovation and behavioural changes. There are arguments around the possibility of a profoundly altered climate and challenges its posed to everyday life, thus; the world needs transitions to more clean energy technologies and sustainable economy that can only be driven by research and development (R&D). In this regard the fossil fuel dependent sectors are particularly focused on to achieve the transitions [1–3]. The process of generating knowledge and innovation over time has led to the discovery of new technological advancements and industrial revolutions, whose impact today is a disproportionate amount of carbon emissions [4].

Public research funding is a critically important element of knowledge generation, aimed at serving societal needs. Shifts in policies and research priorities offer an important clue, revealing which technological innovations are capable of accelerating sustainability or driving more equitable and responsive patterns of technology adoption. Therefore, exploring the extent of funding and categories of funded research can itself lead to more effective, mission driven research [5]. Meanwhile, the debate around climate change and finance remains focused on ‘climate action’ with the proportion on climate adaptation and mitigation funds, but fails to make a more definitive contribution to R&D needed in addressing the social problems created and compounded by energy systems [6].

Recent studies suggest that the emergence, diffusion, and the impact of radical low-carbon innovations over the years are effective, given that each argument support the use of linear model of innovation studies that address the demand side in various phases of the transition processes [7–9]. In contribution to the debate on climate change and energy transitions studies, this paper examines the public research funding across the domains of climate change, energy, transport and industrial decarbonisation. It analyses how funded research projects are shaping and evoking consciousness in achieving just-transitions and generating new technological innovations [10,11]. To be clear, our paper covers not only “basic” research, but also research funding over the more applied categories of demonstration, development, and commercialization.

Climate change mitigation options, including electrification of transportation, wind and solar, fuel efficiency, and reforestation, are now widely researched across various programmes as a form of low-cost, low-carbon development. In addition, while the cost of production for these solutions is declining rapidly the behavioural changes is equally
### Table 1
General areas and disciplines examined in this paper.

| General area                  | Discipline                                                                 |
|-------------------------------|----------------------------------------------------------------------------|
| Arts and humanities           | 1. Archaeology                                                            |
|                               | 2. American Studies                                                       |
|                               | 3. Architecture                                                           |
|                               | 4. Area Studies                                                           |
|                               | 5. Art and Design                                                         |
|                               | 6. Classics                                                              |
|                               | 7. Communication Studies                                                 |
|                               | 8. Dance and Performing Arts                                              |
|                               | 9. Divinity and Religious Studies                                         |
|                               | 10. English and Literature                                               |
|                               | 11. History                                                              |
|                               | 12. Language and Linguistics                                              |
| Social sciences and economics | 13. Music                                                                 |
|                               | 14. Philosophy                                                           |
|                               | 15. Theology                                                             |
|                               | 16. Accounting and Finance                                               |
|                               | 17. Anthropology                                                         |
|                               | 18. Behavioural sciences and social psychology                           |
|                               | 19. Business and Management Studies, Cultural and Media Studies           |
|                               | 20. Development Studies                                                   |
|                               | 21. Economics and Econometrics                                           |
|                               | 23. Education Studies                                                    |
|                               | 25. Energy Studies                                                       |
|                               | 26. Geography, Regional Studies, and Urban Studies                       |
|                               | 27. Law and Legal Studies                                                |
|                               | 28. Library and Information Management                                    |
|                               | 29. Politics and International Studies                                    |
|                               | 30. Public Policy and Administration                                      |
|                               | 31. Sociology                                                            |
|                               | 32. Social Work                                                          |
|                               | 33. Sports Studies                                                       |
|                               | 34. Town and Country Planning                                             |
| Engineering and technology     | 35. Chemical Engineering                                                  |
|                               | 36. Civil engineering                                                    |
|                               | 37. Computer Sciences                                                    |
|                               | 38. Data Sciences                                                        |
|                               | 39. Electrical and Electronic Engineering                                 |
|                               | 40. General Engineering                                                  |
|                               | 41. Mechanical, Aeronautical and Manufacturing Engineering                |
| Life sciences and medicine    | 42. Mineral and Mining Engineering                                        |
|                               | 43. Nanotechnology                                                       |
| Natural and physical sciences | 44. Agriculture                                                          |
|                               | 45. Biological Sciences                                                  |
|                               | 46. Clinical Psychology                                                  |
|                               | 47. Dentistry                                                            |
|                               | 48. Food Science & Technology                                            |
|                               | 49. Health Sciences                                                      |
|                               | 50. Medicine and Medical Sciences                                         |
|                               | 51. Neuroscience                                                         |
|                               | 52. Nursing                                                              |
|                               | 53. Pharmacology                                                         |
|                               | 54. Psychiatry                                                           |
|                               | 55. Public Health                                                        |
|                               | 56. Veterinary Science                                                   |
|                               | 57. Applied Mathematics                                                  |
|                               | 58. Astronomy and Cosmology                                              |
|                               | 59. Chemistry                                                            |
|                               | 60. Earth Sciences                                                       |
|                               | 61. Environmental Sciences and Ecology                                    |
|                               | 62. Geology                                                              |
|                               | 63. Metallurgy and Materials                                              |
|                               | 64. Physics                                                              |
|                               | 65. Pure Mathematics                                                     |

Source: Authors, based on the classification scheme of academic disciplines from the QS World University Rankings.

### Table 2
Topical areas and low-carbon technologies examined in this paper.

| Topical area                          | Technology                                                                                       |
|---------------------------------------|-------------------------------------------------------------------------------------------------|
| Climate change adaptation             | 1. Adaptation and adaptive capacity                                                            |
|                                      | 2. Researching drought resistant crops                                                          |
|                                      | 3. Coastal afforestation                                                                       |
|                                      | 4. Drought                                                                                      |
|                                      | 5. Erosion prevention                                                                          |
|                                      | 6. Managing climate risks                                                                      |
|                                      | 7. Economic resilience                                                                         |
| Energy systems                        | 8. Mangrove regeneration and plantation management                                              |
|                                      | 9. Deployment of coastal sediment barriers to reduce climate-vulnerabilities                    |
|                                      | 10. Glacial flood control                                                                       |
| Geo/climate engineering               | 11. Early warning systems                                                                      |
|                                      | 12. Hurricanes and tsunamis                                                                    |
|                                      | 13. Earthquakes                                                                                |
|                                      | 14. Coastal protection                                                                         |
|                                      | 15. Climate information system                                                                  |
|                                      | 16. Climate-resilient irrigation design                                                         |
|                                      | 17. Carbon dioxide removal                                                                     |
|                                      | 18. Bio-energy with carbon capture and sequestration (BECCS)                                     |
|                                      | 19. Direct air capture with carbon capture and storage (DACS)                                    |
|                                      | 20. Enhanced Weathering                                                                        |
|                                      | 21. Ocean Alkalinity Enhancement                                                                |
|                                      | 22. Ocean Fertilisation                                                                       |
|                                      | 23. Afforestation                                                                             |
|                                      | 24. Biochar                                                                                  |
|                                      | 25. Solar radiation management                                                                  |
|                                      | 26. Aerosol injection                                                                         |
|                                      | 27. Marine cloud brightening                                                                   |
|                                      | 28. High-albedo crops and buildings                                                             |
|                                      | 29. Ocean mirror                                                                             |
|                                      | 30. Cloud thinning                                                                           |
|                                      | 31. Space sunshades                                                                          |
|                                      | 32. Biofuels (generally in the form of biodiesel and ethanol)                                   |
|                                      | 33. Biomass and Biogas (generally meant to include the combustion or use of wood, agricultural residues, cellulosic energy crops, and/or waste as well as biogas) |
|                                      | 34. Coal (including coke, coal-to-liquids, and clean coal)                                      |
|                                      | 35. Energy efficiency, demand response, load management, demand side management                |
|                                      | 36. Energy storage, distributed storage and batteries                                           |
|                                      | 37. Fusion energy                                                                            |
|                                      | 38. Geothermal energy (including heat pumps)                                                    |
|                                      | 39. Heating and cooling (including district heating, combined heat and power)                   |
|                                      | 40. Hydroelectricity                                                                          |
|                                      | 41. Hydrogen (generally meant to encompass fuel cells using renewable fuels and at times natural gas) |
|                                      | 42. Natural gas (including conventional and unconventional gas as well as liquefied natural gas and shale gas) |
|                                      | 43. Nuclear power plants                                                                       |
|                                      | 44. Oil and LPG (including conventional and unconventional resources as well as refined gasoline and diesel) |
|                                      | 45. Solar energy (including solar PV as well as solar thermal or Concentrated Solar Power)       |
|                                      | 46. Wind energy (including onshore and offshore turbines)                                       |
|                                      | 47. Electricity Transmission & Distribution                                                    |
|                                      | 48. Pipelines                                                                                |
| Transportation and mobility           | 49. Petroleum fuels (oil, gasoline, diesel, petrol)                                             |
|                                      | 50. Alternative fuels (biofuel, sunfuel, ethanol, biodiesel, hydrogen fuel cells)               |
|                                      | 51. Passenger vehicles (internal combustion engines, scooters, motorcycles)                     |
|                                      | 52. Electric vehicles (including PHEVs, BEVs, e-bikes and scooters)                             |
|                                      | 53. Ridesharing and carpooling                                                                  |
|                                      | 54. Automated vehicles                                                                        |

(continued on next page)
widening, with expansion in technological improvement creating an economies of scale [12–14]. Yet hydrogen diplomacy is also becoming centre of discussion by countries and industrial stakeholders [15]. As a result of emergence of new technologies, renewable energy production increased general capacity in 2017 by nearly 9% above 2016. In 2017 the global electricity capacity increased to about 70%. This is due to incremental strengthening of innovative technologies in the manufacturing of cost-effective generation of wind electricity and solar PV [4]. Sovacool (2014) argues that altering dependable technologies and human behaviour to consumptions is critical to achieve a reliable, safe and low-carbon future, which also suggest, that investment in R&D will play a major role in defining the sustainable future technologies [16]. However, Hamborg (2020) asserts that despite the importance of realignment of human behaviour for low-carbon future, other studies revealed how the social sciences, the arts and humanities are ignored in deepening research in sustainable energy. Large statistical data institutions do not generally collect qualitative information on energy consumption, which is essential to sociotechnical change [17]. Against this backdrop, innovation-driven development strategies are needed to usher in an era of inclusive sustainability that requires a more comprehensive approach to both innovation systems and behavioural approach that would enhance economic growth [18].

To help deepen our knowledge and understanding on these issues, this paper explores the funding trends, topical themes, and notable gaps in global public research funding across the areas of energy, climate change, transport, and industrial decarbonisation. The paper critically catalogues and examines public research programmes across some of the largest funders and countries in the world, including the most substantial funders of public research or countries responsible for high carbon emissions. The study is drawn from a unique dataset on funding trends, amounts, technologies and topics on climate change, energy systems, transport, and industrial decarbonisation (such as industrial feedstocks, or negative emissions technologies) over a 30-years period, from 1990 to 2020. This includes an evaluation of the sectors receiving the most funding, top-awarded universities, top-awarded disciplines, and extent of interdisciplinary funding.

The paper then examine the extent to which public research funding influence or shape the dynamics on knowledge and innovation in relation to climate change, energy, transport, and industrial decarbonisation. In addition, we assessed which research councils and disciplines had the highest percentage of social science or interdisciplinary funding. Our findings reveal critically emergent gaps in research topics and data quality, which can lead to greater accountability in the future. The gaps in research topics could themselves motivate future research teams towards deeper investigation of the issues raised [19]. The findings enable the identification of not just “hot topics”, going along with the crowd or groupthink, but also under-researched topics that, perhaps, are even more worthy of exploration.

The remainder of the paper is structured as follows. Section 2 reviews the literature on recent trends in innovation and patterns of R&D. Section 3 explains our research design and analytical protocol. Sections 4–6 present our results organised by financial and spatial patterns (Section 4), disciplinary patterns (Section 5), and research gaps (Section 6). Section 7 concludes.
2. Examining trends in innovation, research and development (R&D)

Schumpeter’s work (1934) on “innovation” the word which is derived from the Latin noun innovates, wherein the modern innovation originate from. He expalicates “innovation” as “new combinations” of existing skills and knowledge, or a new embodiment of equipment and resources that could form a better solution. In this sense, when we use institutional framework to brings together for the development of products, goods, and services [20]. Shayegh et al., (2017) traces innovation back to late 1950s as a scientific discipline, and thousands of researchers and scientific community now sees the discipline as a

Fig. 2. Top countries or regional actors receiving public funding for energy and climate research, 1990 to 2020 (N = 17).
Source: Authors. Top panel shows country recipients of funding as a percentage of the total, bottom graph displays these on a world map with the darker shading indicating more funding.
component of research [21].

While it can be argued that there is essential role innovation must play in sustainability transition, but we are constrained to how policy can provide clear models for mobilising innovation [22]. The concepts of ecosystem-innovation policy is currently giving insights into how innovation studies can help reshape and make a difference [23], an example is in the innovation for transformative change [24]; see also [25] and transformative innovation policy (TIP) [26,27].

Based on a the concept of directionality [28-30]; see also [31], scholars in this group of academic thought argue that the direction of innovation is important, alongside the rate and pace of innovation; and that increasing R&D funding or strengthening national system of innovation (NSI)/actors is inadequate in addressing e.g., the growing inequality and achieving significant reductions in climate change or decarbonisation. Directionality concerns the highlights of implications and arguments over technological development, institutional framework that will drives social behaviour. In addition, the debates provide an insight into understanding how the societal acceptance could drive the trajectories in development, through knowledge and innovation [31] or policy targeted at particular developmental goals [32].

Schot and Steinmueller (2018) make a deeper argument about the current theorising of knowledge within the field of innovation studies, that focus simply on increasing funding for R&D (Frame 1) or strengthening the NSI (Frame 2) is inadequate for achieving transformative change at systems level (Frame 3, TIP) and addressing pressing societal challenges as articulated in the SDGs, and adopt TIP or transformative change as a new approach. However, in Schot and Steinmueller’s consideration, the role of firms in transformative innovation is mostly excluded in the existing knowledge based on innovation, even though the business organisations are mostly the primary source of innovation in modern societies and that without their active involvement in the well-intended process, transformative innovation can rarely make impacts. Possibly, this recent research findings within innovation studies can provide some answers. Nevertheless, Schot and Steinmueller described sustainability transitions by policymakers which supported their first framing where government sponsors mission-oriented research, especially military activities where technologies were developed for defence – Jet aircraft, ballistic, missiles, radar, atomic weapons, and computers and as well adapted to civilian application [24].

Foxon (2015) examines the role of innovation on sustainability transition and emphasizes about expectations of future technology market, and policy development, political and regulatory shifts, and the institutional framework which can affect incentives and barriers that are critical to knowledge flows among various actors [33]. Other scholars of sustainability transitions suggest that sustainability show varying features that evince the interdisciplinarity needed to stimulate transitions; arguably, this could pose more challenges than in other areas. This is not only due to interconnected principles but also due the needed speed and the extraordinary scale required to make complex changes [34].

First, it is important to stress that governing innovation can be influence partly by governing framework and largely through policy instruments [35]. However, in order to achieving substantial progress in sustainability transition, it is evident that policy’s impact is most important and not its procedure. It is also critical to consider and apply various range of policies – that are crucial for sustainability transitions innovation, that are being used and which are working in other areas [36]. Second, achieving more ambitious transformative policies that contemporary challenges require speed, scale and complexity of required changes and it raise important questions concerning the directionality of policy and policy instruments, coordination, and governance. Which have been central to innovation studies over time, but that has probably become increasingly greater relevance. Third, the main focus of Schot & Steinmüller, (2018) is to understand and essentially to differentiate between theories – or frames – used to understand, develop and justify innovation policy, on the one hand, and innovation policy practice on the other hand [24].

Therefore, funding R&D can potentially increase opportunity of swift transitions to low-carbon in different ways [37]. Some R&D could generate knowledge that would have been gained through investment in technology deployment and learning. This type learning process (curve) of R&D reduces cost by following a path dependant. However, firms tend to reduce starting cost due somewhere down the learning curve from the original starting point. For instance, when business sector research into incremental improvements in manufacturing processes might generate information during the technology deployment. The ‘curve-following’

Fig. 3. The general technological areas or systems funded by energy and climate research, 1990 to 2020 (N = 1000 projects).
Table 3

| No. | Technology or topic | General area | Number of projects supporting technology or topic |
|-----|---------------------|--------------|--------------------------------------------------|
| 1   | Energy efficiency, demand response, load management, demand side management | Energy systems | 183 9.3% |
| 2   | Adaptation, resilience and adaptive capacity | Climate adaptation | 157 7.9% |
| 3   | Climate information systems | Climate adaptation | 102 5.2% |
| 4   | Managing climate risks | Climate adaptation | 94 4.8% |
| 5   | Energy storage, distributed storage and batteries | Energy systems | 73 3.7% |
| 6   | Carbon dioxide removal | Geo/climate engineering | 69 3.5% |
| 7   | Solar energy (including solar PV as well as solar thermal or Concentrated Solar Power) | Energy systems | 65 3.3% |
| 8   | Economic resilience | Climate adaptation | 59 3.0% |
| 9   | Energy storage | Energy systems | 57 2.9% |
| 10  | Electric vehicles (including PHEVs, BEVs, e-bikes and scooters) | Transport and mobility | 54 2.7% |
| 11  | Electricity Transmission & Distribution | Energy systems | 50 2.5% |
| 12  | Biomass and Biogas (generally meant to include the combustion or use of wood, agricultural residues, cellulosic energy crops, and/or waste as well as biogas) | Energy systems | 46 2.3% |
| 13  | Alternative fuels (biofuel, synfuel, ethanol, biodiesel, hydrogen fuel cells) | Transport and mobility | 42 2.1% |
| 14  | Process emissions | Industrial decarbonisation | 41 2.1% |
| 15  | Heating and cooling (including district heating, combined heat and power) | Energy systems | 40 2.0% |
| 16  | Wind energy (including onshore and offshore turbines) | Energy systems | 37 1.9% |
| 17  | Heating and cooling (including district heating, combined heat and power) | Energy systems | 35 1.8% |
| 18  | Distributed generation/co-generation | Energy systems | 34 1.7% |
| 19  | Drought | Climate adaptation | 33 1.7% |
| 20  | Bio-energy with carbon capture and sequestration (BECCS) | Geo/climate engineering | 32 1.6% |

Source: Authors

R&D is a type that firms try to maximize profit through modification of an existing products or services, and this kind of R&D is usually, though not exclusively, undertaken by the corporate sector, this type of R&D is called incremental R&D. For example, Liu et al. (2018) describes this in the improvements of wafer efficiency and cost of photovoltaic (PV) Chines manufacturers [38]. A study by Bointner et al., (2016) reveals the difficulty to track funding trends on energy R&D, especially in the EU. This reduces clarity on how energy policy interventions impacts on R&D funding and vice versa [5].

Kim (2015) argues that transformational knowledge could be generated through R&D, such as the use of a different substrate for solar PV devices that would not have happen during technology deployment. Which shows that such R&D resulted in the reduction of the cost of production by maintaining the same slope; thus, shifting the learning. It also makes the starting cost and quantity remain the same, while the new production cost is lower than the original cost. This type of R&D is a fundamental in transformational knowledge results which aims at modifying the processes of production. In many cases, it is usually funded with budgets from government agencies and research undertaken by academic institutions, government-sponsored laboratories, and sometimes-private industry. For instance, research on hybrid PV-thermal solar energy systems, and advanced materials for PV, including perovskites solar cell funded by the U.S. Department of Energy, is technologies that could look great after commercialization, and whose development could as well have a significant impact on the costs and performance of solar energy systems [39,40]. This assembles, this type of transformational knowledge ‘curve-shifting’ R&D.

Danieles et al. argue for R&D as a shift of innovation in the creation of hybrid enterprises and joint innovative projects in the modern economy requires a bilateral interaction, which they called double helices to interactions of a triple helix that consist of government, research institutions and industry relationships. According to their framework, this fosters innovation and constitute an innovation ecosystems [41].

The underinvestment in transformational R&D by government and corporate organisation might be due to lack of interest [42]. While some private businesses make huge investment in R&D is targeted at incremental improvements of their processes and production which could reduce cost and maximize profit and/or gain a larger share in the market. However, as good as transformational R&D could be it requires long time to produce better outcomes [43]. Study by de Negri et al. (2020) also support the view that companies were sceptical about revealing their R&D information, which makes it difficult to track private research funding trends. Nevertheless, other studies emphasize the importance of public funding of energy R&D in order to support efficient transitions studies [44]. A study by Gallagher (2017) revealed that corporate organisations especially in the U.S are mostly interested in short-term investments on energy innovation R&D, which could provide return on their investments within two to three years [45]. It is recognisable, that underinvestment in transformational R&D is sometimes because the research outcomes may not be entirely accepted by private businesses [17].

However, despite government willingness to invest in transformational R&D, its somewhat constrained by budgetary allocation, whereas most of private firms and entrepreneurs do not have the courage for competitive market and risk bearing from generated knowledge [32]. For instance, Scott & Powells (2020) support the social practice theory in considering the future impact of hydrogen, whether in its pure form or blended with natural gas might have on cooking and heating, as “embodied, materially mediated arrays of human activity centrally organised around shared practical understanding” (p.3) which is a form social practice theory that is entirely acceptable norms [46]. Some barriers mentioned by Hess (2020) was that, since the 1990s research on energy and social science studies indicate that researchers in science, technology, and society have increased their interest in climate change and energy topics especially with emphases on electricity and mobility systems which equally underscore our earlier submission about social practice theory on generated knowledge from transformational R&D [47].

Knowledge translation, which is the scientific study of methods of promoting the use of generated knowledge from transformational research (i.e., commissioned research), could be another tools for research funders who might also want to promote knowledge transfer by developing their own strategy for knowledge translation, involving end users in research funding implementation and prioritizing research topics and methods as well as in the disseminating information about funded and completed research [48]. For example, the European Strategic Energy Technology Plan is set to outline the strategies for research and innovation priorities that will allow the EU to achieve its ambitious energy and climate targets. SET-Plan was launched in 2008; it sets out funding opportunities for the EU Horizon 2020’s energy work Programmes. The plan also provides opportunities for dissemination of generated knowledge and research findings to wider community [49]. Another approach to mobilize public interest in science, technology, and society (STS) point of view is to cross-examine how social movement studies could be to modified in engaging researchers and broader end users with societal needs [50].
Studies suggest two class strategies about research projects, has granted versus non-granted researchers [51]. With respect to Africa, for example, a recent study found that most research were funded directly by donor agencies, rather than research councils. Also, the funding of certain low-carbon development projects such as waste and transportation in Nairobi (Kenya), was financed by religious organisation (Islamic Development Bank), and non-governmental organisations play critical roles. However, it was exceptionally difficult to track funding flows [52]. According to Overland et al. (2021) research institutions across the world, Africa’s climate research related topics attracted funding amounted to only $620 million, or 3.8% of total global share of funding between 1990 and 2020 funding. Based on this research, the UK, the USA and the EU are major funders for climate research that are mostly Africa-related [52], which also conforms with our finding about the only one Africa country that made top ten largest research funding countries.

Fig. 4. Public research and developing funding on energy and climate across five key topical areas from 1990 to 2020 (in US$2020). Source: Authors. Top diagram shows total funding amounts in USD, bottom panel shows patterns as a % of total funding for that area.
The role funding agencies in research into topics of climate change, energy systems, transport, and industrial decarbonisation in social science and humanity (SSH) implies that research funding for varying systems of transportation including cycling, walking, train, car, etc., energy, infrastructures, and development of capability of the professionals that would drive the sectors. Merlin (2019) finds that among SSH researchers across disciplines and intersectional disciplines such as tourism and gender studies, the decarbonisation of transport sector is the much-researched [53]. The decarbonisation of the transport sector involves research into different modes of transport, technologies requirements and behavioural shift [12]. The Sweden research policy Programme for instance, is designed to promote basic research among academics, where third-party funding is credible to make available public funds solely to generate transformational knowledge with positive impact from basic research [54]. Jacobs, (2011) revealed that in national institutes of health (NIH) researchers can access more funding, when knowledge and value generated from their research findings can make a transformational change [55].

3. Research design and analytical protocol

This paper is novel in many ways: it a) focuses on funding agencies as a major player in science and technology development, rather than a component of the research community and the end users as previous authors have done, b) examines critical areas especially in Western countries, in relation to the funding agencies objectives, and c) prioritizes national systems of innovative research and conceptualize research funds as an instrument to answer both current and emerging issues that have the potential of improving the welfare of people. Policy makers, industries, academics, and other service delivery organisations such as hospital and healthcare departments that are wholly depends on research funding agencies as pillars for cutting-edge research and innovation required to address the challenges of their societies [56].

Building a comprehensive and empirical data about research funding agencies and academics research projects could be a way of promoting knowledge translation in several ways, as they are critical to influence transformative innovation and generated knowledge translation activities. Research funding institutions often emphasize the importance of addressing knowledge translation processes during the research grant proposal, as they consider it as a fundamental aspect of the research process. Another instance is funders could seek researchers to work closely with the end users such as industries, policymakers as partners from the processes of grant proposal writing to conducting and implementation of the research findings [57].

The principal overarching research question addressed in this study is: What are the dynamics of global public research funding across the domains of climate change, energy systems, transport, and industrial decarbonisation? This principal question will address various components on climate change (including adaptation, resilience, geo-engineering and climate engineering), energy systems (including fossil fuel and low-carbon sources), transport (including mixed modes such as

| No. | Institution Name and country                        | Amount funded (US $2020) |
|-----|-----------------------------------------------------|--------------------------|
| 1   | Lancaster University, United Kingdom                | 97,956,500               |
| 2   | University of Edinburgh, United Kingdom             | 75,232,620               |
| 3   | University of Oxford, United Kingdom                | 72,544,343               |
| 4   | University of Leeds, United Kingdom                 | 66,403,724               |
| 5   | University College London                           | 60,437,745               |
| 6   | Imperial College London                             | 48,053,210               |
| 7   | Newcastle University, United Kingdom                | 43,386,507               |
| 8   | University of Cambridge, United Kingdom             | 41,460,849               |
| 9   | NERC Centre for Ecology and Hydrology, United Kingdom | 40,891,577              |
| 10  | University of Birmingham, United Kingdom            | 35,874,254               |
| 11  | National Oceanography Centre, United Kingdom        | 32,605,899               |
| 12  | University of Southampton, United Kingdom           | 26,732,700               |
| 13  | NERC British Geological Survey                      | 24,321,677               |
| 14  | University of Sussex, United Kingdom                | 23,277,799               |
| 15  | London Sch of Hygiene and Trop Medicine, United Kingdom | 23,159,624             |
| 16  | Aalborg University, Denmark                         | 20,000,000               |
| 17  | University of Exeter, United Kingdom                | 22,382,173               |
| 18  | National Research Institute for Agriculture, Food and the Environment (INRAE), France | 22,000,000             |
| 19  | University of Manchester, United Kingdom            | 21,504,246               |
| 20  | University of Surrey, United Kingdom                | 19,499,491               |

Source: Authors

![Fig. 5. Public research and developing funding on energy and climate across core academic disciplines from 1990 to 2020 (in US $2020).](image-url)
passenger vehicles, rail, freight, and aviation), industrial decarbonisation (including Distributed generation/co-generation, Process emissions, Industrial feedstocks, Industrial carbon capture and utilization (CCSU) and Energy storage). In unpacking this question, the sub-questions include:

1. What are the countries, technologies, and institutional dynamics of public research funding?

### Table 5

Public research and developing funding on energy and climate across specific academic disciplines from 1990 to 2020 (in US$2020).

| No | Discipline                                      | Total funding (US$2020) | Percent of total funding |
|----|-------------------------------------------------|-------------------------|--------------------------|
| 1  | Computer Sciences                               | 360,731,433             | 16.7%                    |
| 2  | Energy Studies                                  | 200,783,258             | 9.3%                     |
| 3  | Chemical Engineering                            | 177,665,399             | 8.2%                     |
| 4  | Economics and Econometrics                      | 153,694,651             | 7.1%                     |
| 5  | Behavioral sciences and social psychology       | 142,838,725             | 6.6%                     |
| 6  | Mechanical, Aeronautical and Manufacturing Engineering | 130,500,697         | 6.1%                     |
| 7  | Development Studies                             | 103,280,248             | 4.8%                     |
| 8  | Communication Studies                           | 98,849,538              | 4.6%                     |
| 9  | Architecture                                    | 68,370,058              | 3.2%                     |
| 10 | Accounting and Finance                          | 60,871,362              | 2.8%                     |
| 11 | Data Sciences                                   | 55,198,664              | 2.6%                     |
| 12 | Area Studies                                    | 52,637,662              | 2.4%                     |
| 13 | Business and Management Studies                 | 48,441,002              | 2.2%                     |
| 14 | Geography, Regional Studies, and Urban Studies  | 42,732,431              | 2.0%                     |
| 15 | Earth Sciences                                  | 40,651,328              | 1.9%                     |
| 16 | Cultural and Media Studies                      | 36,811,789              | 1.7%                     |
| 17 | Art and Design                                  | 34,834,133              | 1.6%                     |
| 18 | Metallurgy and Materials                        | 30,061,158              | 1.4%                     |
| 19 | Archaeology                                     | 29,802,091              | 1.4%                     |
| 20 | Mineral and Mining Engineering                   | 29,515,067              | 1.4%                     |
| 21 | Biological Sciences                             | 24,251,820              | 1.1%                     |
| 22 | Electrical and Electronic Engineering           | 22,334,839              | 1.0%                     |
| 23 | General Engineering                             | 22,230,354              | 1.0%                     |
| 24 | Civil engineering                               | 22,067,714              | 1.0%                     |
| 25 | Chemistry                                       | 19,410,621              | 0.9%                     |
| 26 | Environmental Sciences and Ecology              | 18,422,831              | 0.9%                     |
| 27 | Agriculture                                     | 16,469,663              | 0.8%                     |
| 28 | Health Sciences                                 | 16,397,435              | 0.8%                     |
| 29 | Anthropology                                    | 14,182,472              | 0.7%                     |
| 30 | English and Literature                          | 8,311,067               | 0.4%                     |
| 31 | Nanotechnology                                  | 8,188,166               | 0.4%                     |
| 32 | Dance and Performing Arts                       | 8,072,266               | 0.4%                     |
| 33 | Public Policy and Administration                | 7,842,613               | 0.4%                     |
| 34 | Education Studies                               | 7,747,291               | 0.4%                     |
| 35 | Sociology                                       | 5,852,522               | 0.3%                     |
| 36 | Astronomy and Cosmology                         | 5,285,487               | 0.2%                     |
| 37 | Medicine and Medical Sciences                   | 4,824,842               | 0.2%                     |
| 38 | Town and Country Planning                       | 3,470,747               | 0.2%                     |
| 39 | Geology                                         | 3,128,729               | 0.1%                     |
| 40 | Social Work                                     | 2,485,000               | 0.1%                     |
| 41 | Pharmacology                                    | 2,447,420               | 0.1%                     |
| 42 | Applied Mathematics                             | 2,406,968               | 0.1%                     |
| 43 | Philosophy                                      | 2,126,403               | 0.1%                     |
| 44 | Dentistry                                       | 2,031,183               | 0.1%                     |
| 45 | Physics                                         | 1,965,347               | 0.1%                     |
| 46 | American Studies                                | 1,267,209               | 0.1%                     |
| 47 | Clinical Psychology                             | 1,038,765               | 0.0%                     |
| 48 | Theology                                        | 1,000,000               | 0.0%                     |
| 49 | Divinity and Religious Studies                  | 796,572                 | 0.0%                     |
| 50 | Food Science & Technology                       | 793,985                 | 0.0%                     |
| 51 | Neuroscience                                    | 485,000                 | 0.0%                     |
| 52 | Sports Studies                                  | 250,000                 | 0.0%                     |
| 53 | Classics                                        | 200,000                 | 0.0%                     |
| 54 | Total                                          | 2,155,826,057           | 100%                     |

Source: Authors

### Table 6

Top social science disciplines (top panel) and countries funding social science (bottom panel) from 1990 to 2020.

| A. Top disciplines receiving funding | No. | Social science discipline | Total funding (US$2020) | Percent of total funding |
|-------------------------------------|-----|---------------------------|-------------------------|--------------------------|
| 1 | Energy Studies                     | 1   | 200,783,258               | 23.7%                   |
| 2 | Economics and Econometrics         | 2   | 153,694,651               | 18.1%                   |
| 3 | Behavioral sciences and social psychology | 3 | 142,838,725               | 16.9%                   |
| 4 | Development Studies                | 4   | 103,280,248               | 12.2%                   |
| 5 | Accounting and Finance             | 5   | 60,871,362                | 7.2%                    |
| 6 | Business and Management Studies    | 6   | 48,441,002                | 5.7%                    |
| 7 | Geography, Regional Studies, and Urban Studies | 7 | 42,732,431               | 5.0%                     |
| 8 | Cultural and Media Studies         | 8   | 36,811,789                | 4.3%                    |
| 9 | Anthropology                       | 9   | 14,182,472                | 1.7%                    |
| 10 | Public Policy and Administration   | 10  | 7,842,613                 | 0.9%                    |

| B. Top countries or entities disbursing social science funding | No. | Country          | Total funding (US$2020) |
|---------------------------------------------------------------|-----|------------------|-------------------------|
| 1 | United Kingdom                                 | 1   | 777,105,022      |
| 2 | European Commission                           | 2   | 496,779,298      |
| 3 | Germany                                       | 3   | 169,485,593      |
| 4 | Norway                                        | 4   | 163,759,927      |
| 5 | Australia                                     | 5   | 105,627,756      |
| 6 | India                                         | 6   | 105,564,056      |
| 7 | Qatar                                         | 7   | 104,941,370      |
| 8 | Rwanda                                        | 8   | 100,000,000      |
| 9 | France                                        | 9   | 97,652,939       |
| 10 | Italy                                         | 10  | 97,585,876       |

Source: Authors

Fig. 6. Classification of publicly funded R&D projects from 1990 to 2020 as transdisciplinary.
Table 7
Disciplinary inclusion (top panel) and technological diversity (bottom panel).

A. Top 10 projects in terms of disciplinary inclusion

| No. | Project Name                                                                 | Host Institution                 | Number of disciplines | funding/time-start | funding/time-end | Budget (US $2020) |
|-----|------------------------------------------------------------------------------|----------------------------------|-----------------------|-------------------|------------------|-------------------|
| 1   | Centre for Research on Energy Demand Solutions (CREDs)                        | University of Oxford             | 33                    | 04/01/2018        | 03/01/2023        | 28,216,000        |
| 2   | Climate Change and Malaria (CCM)                                             | Vellore Institute of Technology  | 23                    | 03/17/2021        | 12/31/2021         | 2,200,000         |
| 3   | Rural Economy and Land Use Programme                                         | Newcastle University             | 21                    | 12/01/2003        | 03/31/2013         | 24,000,000        |
| 4   | Project MAIN                                                                 | MIT Harvard                      | 21                    | 02/01/2021        | 03/31/2021         | 765,765           |
| 5   | Urban Resilience to Extreme Sustainability Research Network                  | Arizona State University         | 19                    | 07/01/2005        | 08/31/2021         | 12,000,000        |
| 6   | Pyrolysis of Qatar Solid Waste Materials to Produce Agricultural/landscaping Biochars | Hamad Bin Khalifa University     | 19                    | 05/19/2018        | 05/18/2022         | 700,000           |
| 7   | Sensor Tipping and Cueing using Artificial Intelligence Techniques           | Consejo Superior de Investigaciones Cientificas | 17           | 09/03/2018        | 08/31/2022         | 2,854,102         |
| 8   | Merger Announcements and Stock price Behaviour                              | University of Leeds              | 17                    | 01/04/2018        | 03/31/2022         | 700,000           |
| 9   | TRUST - Transition to the urban water services of tomorrow                   | IWW Rheinisch-Westfälisches Institut für Wasserforschung gemeinnützige GmbH | 16               | 05/01/2011        | 04/30/2015         | 1,088,200         |
| 10  | Impact of climate change on water resources and development                  | Desert Research Center Egypt     | 15                    | 12/06/2017        | 03/01/2021         | 500,000           |

B. Top 10 projects in terms of technological and topical diversity

| No. | Project Name                                                                 | Host Institution                 | Diversity in number of technologies or topics checked | funding/time-start | funding/time-end | Budget (US $2020) |
|-----|------------------------------------------------------------------------------|----------------------------------|---------------------------------|-------------------|------------------|-------------------|
| 1   | NDC ASPECTS – Assessing Sectoral Perspectives on Climate Transitions to Support the Global Stocktake and Subsequent NDCs | Wuppertal Institute             | 33                 | 05/01/2021        | 04/30/2024        | 5,944,000         |
| 2   | Delivering on the Paris Agreement: A demand-driven, integrated assessment modelling approach | National Technical University of Athens (NTUA) | 33                 | 06/01/2019        | 05/31/2022        | 8,205,262         |
| 3   | Climate Change and Malaria                                                  | Vellore Institute of Technology  | 31                 | 03/17/2021        | 12/31/2021         | 2,200,000         |
| 4   | Centre for Research on Energy Demand Solutions                              | University of Oxford             | 28                 | 04/01/2018        | 03/01/2023         | 28,216,000        |
| 5   | Project MAIN                                                                 | MIT Harvard                      | 24                 | 02/01/2021        | 03/31/2021         | 765,765           |
| 6   | Impact of climate change on water resources and development                 | Desert Research Center Egypt     | 23                 | 12/06/2017        | 03/01/2021         | 500,000           |
| 7   | Global Excellence in Modelling of Climate and Energy (GEMCLIME)             | Charles University, Czech Republic | 22           | 10/01/2016        | 03/31/2021         | 2,539,152         |
| 8   | Green Innovation: Making it Work                                            | Nottingham Trent University      | 20                 | 10/01/2014        | 01/31/2017         | 30,000            |
| 9   | Research Centre on Innovation and Energy Demand (CIED)                      | University of Sussex             | 18                 | 06/10/2013        | 02/22/2019         | 4,908,790         |
| 10  | Rural Economy and Land Use Programme                                        | Newcastle University             | 17                 | 12/01/2003        | 03/31/2013         | 24,000,000        |

Source: Authors

1. a. Which sectors and technologies have received the most funding, as well as the least, over a 30-years (1990–2020) period?
   b. Which countries have funded the most energy, transport, climate change, and industrial decarbonisation research?
   c. Which institutions have been the most successful at attracting funding, and why?
2. What are the disciplinary distribution of public research funding?
   a. Which disciplines have received the most funding, and which countries have funded the most social science research?
   b. To what extent are funded projects interdisciplinary or trans-disciplinary?
3. What gaps need to be addressed?
   a. Which areas are underfunded?
   b. What gaps exist?

To answer these questions, we built an extensive original dataset of public research funding activity from 1990 to 2020 for publicly available data from national and regional research commissions, including the National Science Foundation in the United States, the European Commission (including Horizon 2020) and EU members states as well as United Kingdom, such as the Research Councils UK or the DFF in Denmark. This study covered a total number of 165 research councils and funding institutions including the European Commission (see Appendix I).

The building of the dataset considers many disciplines and five categorical topics i.e. climate-change adaptation, geoclimatic engineering, energy systems, transportation, and mobility as well as industrial decarbonisation. The disciplines searched and coded for are presented in Table 1, covering five categories and more than 60 specific disciplines.

Moreover, we examined five distinct classes or areas of technology spread across more than 60 specific applications, as summarized in Table 2.

Globally, 69 countries were catalogued out of which twenty-two countries were outside European Union. However, only sixteen countries made their R&D funding information public and those were the
countries that make up our dataset. The countries include the United Kingdom, the United States, Canada, Australia, Brazil, China, India, Israel, Japan, Morocco, New Zealand, Norway, Qatar, Rwanda, South Africa and Switzerland. The twenty-seven countries of the European Union were searched and grouped under European union commission funded projects such as Horizon 2020, FP7, FP6, FP5, FP4, FP3, ERC, intelligent energy agency, and Marie Curie.

In building our dataset, some of the research councils that made the list were in the United Kingdom engineering and physical sciences research council (EPSRC), Innovate UK (Innovate UK), biotechnology and biological sciences research council (BBSRC), department for environment food and rural affairs (DEFRA). Others are, medical research council (MRC), natural environment research council (NERC), economic and social research council (ESRC), arts and humanities research council (AHRC), science and technology facilities council (STFC), and British Academy (BA). Literature suggests that the Unites States funds substantially number of R&D, prompting us to search one hundred and forty-nine research councils. Data about research funding in the U.S shows sixty-nine funding agencies (see Appendices I for the extensive list of all the research councils).

As mentioned above, the dataset examined five (5) categories of field of research including arts and humanities, social science and economics, engineering and technology, life sciences and medicine as well as natural and physical sciences and 65 disciplines. The dataset revealed the collection of principal investigators name, project titles, project host institutions and email contacts of the PI. Analysis of the data collected revealed a total number 153,202 research projects.

After the cleaning of the datasets, a total number of 113,417 projects were geoengineering (only 2 in the top 20), and industrial decarbonisation (only one in the top 20).

### 4.1. Geography and country locations

Perhaps surprisingly, a small number of countries within our sample receive the lion’s share of public R&D funding on energy and climate. As Fig. 2 summarizes, our sample of 1000 projects involved a collective budget of about $2.1 billion (in US$2020). The European Commission (27%) United Kingdom (40%), and United States (11%) received in total almost four-fifths of all funding disbursed, whereas countries such as China, India, Israel, or Japan received very low amounts of funding. By limiting our dataset in this way it very likely overrepresents research projects in the Anglo-Saxon world, especially among the United Kingdom, Western Europe, and other smaller wealthy countries that can afford to publish research data in English.

### 4.2. Technological funding patterns

In terms of which sectors and technologies have received the most funding, as well as the least, over a 30-years (1990-2020) period, Fig. 3 tracks total funding disbursements according to five general areas. Climate change adaptation projects received more than one-third of all funding (36%), followed by climate mitigation via energy systems (28%) and transport and mobility (13%). The two general areas with the lowest amounts of funding were geoengineering and industrial decarbonisation.

Table 3 offers a far more nuanced assessment of funding patterns within specific technologies, showing the top 20 technologies in terms of public R&D funds received. Interestingly, energy efficiency, climate resilience, and climate information systems dominate the sample. However, the table also shows a relative dearth of transport topics (only 2 in the top 20), geoengineering (only 2 in the top 20), and industrial decarbonisation (only one in the top 20).

Fig. 4 depicts technological funding patterns over time, both in terms of total budget (top panel) and as a percentage of all funding for that area (bottom panel). As evident, funding peaks slightly in the early 1990s, most likely due to the Rio Convention and funding patterns attuned to the launch of the United Nations Framework Convention on Climate Change (which as signed in June 1992 and entered into force in March 1994). A similar jump in funding occurs around the year 2000, perhaps due to the Kyoto Protocol having its signing period end in 1999, and the Intergovernmental Panel on Climate Change launching their third Annual Assessment (AR3) in 2011. We finally see a massive surge in funding post 2008 to 2020, reflecting perhaps our current policy and
Fig. 7. Public research and developing funding on energy and climate across five key academic disciplines (in US$2020).
Source: Authors. Top panel shows funding amounts in absolute terms, bottom panel shows patterns of funding as a percentage of the total.
technology debates over net-zero and decarbonisation, as well as the targets from the Paris Accords. We also see a shift in funding patterns from exclusively focusing on mitigation (especially around 2000) to embrace a broad diversity of activities across all five general areas (mitigation but also adaptation, mobility, geoengineering, and industry).

4.3. Institutional champions within funding patterns

In terms of which institutions have been the most successful at attracting funding for social science in particular, Table 4 shows the top twenty recipients of collective social science funding. These 20 institutions received more than $820 million in direct funding, or a tremendous 96% of all funding spent on the social sciences, showing a clear concentration among top universities. Perhaps unexpectedly, the United Kingdom dominates the sample, with only two institutions (Aalborg in Denmark, INRAE in France) making the top twenty list. All other 18 are within the UK, including Lancaster (known for sociology), Edinburgh (known for science and technology studies), and Oxford (known for environmental social science).

5. Results: The disciplinary dynamics of funding

This section presents our second tranche of results, organised along the themes of funding patterns by discipline, projects classifying themselves as transdisciplinary, and specific projects that embraced a high degree of either disciplines (disciplinary inclusion) or studied a broad range of technologies (technological diversity).

5.1. Disciplinary funding patterns

In terms of the disciplines that have received the greatest amounts of funding over our 30-year period, Fig. 5 presents an unforeseen result: funding is almost evenly distributed across very different disciplines, with social sciences and economics coming second, and very close, to funding amounts received by engineering and technology. The arts and humanities received more funding than the natural and physical sciences, while the life sciences and medicine received more than 10% of funding. The share of funding on social science in Fig. 5 is surprising, but it is also confirmed in very recent research. Callaghan et al., (2020) also conclude that the social sciences were overrepresented in major publications such as the most recent assessment reports from the Intergovernmental Panel on Climate Change [58].

Table 5 presents the outcome of a deeper examination of specific funding within disciplines (we catalogued data cross 53 disciplines), and across all five general disciplinary areas. The results showcase a rich diversity of support. Although computer science, energy studies, and chemical engineering together capture about a third of funding, we still see significant funding disbursed to disciplines as diverse as communication studies, development studies, architecture, and accounting.

Given our research question initially focused on how much social science was being supported by donors, Table 6 illustrates funding patterns within this specific disciplinary category. It shows the top 10 social science areas funded in terms of discipline but also those countries funding the most social science. Although social science is well funded, very specific social science disciplines receive an asymmetrical amount of funding. Energy studies, economics, and the behavioural sciences received together almost 60% of all funding. In terms of countries, the United Kingdom has a strong lead on supporting social science research, even more than the European Commission, followed by Germany, Norway, and Australia. We were almost astounded that the United States did not make the top ten list—given it only funded a meagre $83.7 million in social science funding.

5.2. Embracing trans-disciplinarity

Not only do our results support the contention that social science and arts and humanities disciplines are well funded; most projects reported subscribing to transdisciplinary approaches, generally meant to capture projects that directly engage, work with, or involve nonacademic stakeholders and partners such as businesses, political bodies, users and consumers, or civil society and community groups [57,59,60]. When we asked our PIs to reveal the extent that their funded projects were transdisciplinary, an overwhelming majority (74.2%) indicated that they were, with only 20% indicating they were not (and 5.8% stating they were unsure), as Fig. 6 depicts. This clearly suggests that the energy and climate field have a strong proclivity to pursue transdisciplinary projects.

5.3. Disciplinary inclusion and diversity of topics

Our data reveals at the highly granular level of projects those that embraced the widest range of disciplines or supported the broadest portfolio of different technologies and topics. Table 7 depicts both sets of results. As the top panel indicates, out of the 1000 projects, the four most inter disciplinary projects within the sample are CREDS (33 disciplines supported), CCM (22), and the Rural Economy and Land Use Programme (21) and Project Main (21). CREDS is a very large, well-funded interdisciplinary project led by Oxford University in the United Kingdom that focuses on energy demand reduction, one that involved a mix of approaches including the social sciences and humanities but also engineering and physics. CCM focuses on climate change and health in India and sees broad support across the social sciences (especially business), life sciences (epidemiology), and energy modelling (engineering). The Rural Economy and Land Use Programme (RELUP), led by Newcastle University in the United Kingdom, explores business models (social sciences and economics), health (life sciences), and land management (natural and physical sciences). Project Main was led by a consortium of American universities (MIT, Harvard, and Duke) to investigate the challenge of mainstreaming low-carbon energy transitions, cutting across social sciences, modelling, economics, and the natural sciences.

As also revealed in the bottom panel of Table 7, the top three projects in terms of a broad multi-dimensional technology focus were NDC Aspects (33), Delivering on the Paris Agreement (33), and Climate Change and Malaria (31). NDC Aspects led by the Wuppertal Institute owes much of its technological diversity given its focus on providing roadmaps for policymakers on decarbonisation across the broad sectors of transport and mobility (land-based transport and international aviation & shipping), emission intensive industries, buildings, and agriculture, forestry & land-use. Delivering on the Paris Agreement led by NTUA in Greece was similarly broad given its emphasis on Integrated Assessment Modelling across multiple sectors and focal coverage. Climate Change and Malaria, already mentioned, was an Indian project looking at the drivers and effects of climate change on malaria, but it included a multi-sectoral focus including households, communities, urban areas and nation states.

6. Results: Temporality and shifting research priorities

Our final tranche of results shows the temporality or shifting priorities within funded research projects.

6.1. Shifting research priorities

Fascinatingly, almost no topic remaining as the “top” of the funding list for a given period or a given general area of technology. Table 8 shows how in 1990 the top funded climate adaptation area was climate resilience, but in 2020 it was adaptive capacity. In 1990, the top funded energy and climate mitigation technology was nuclear power, but in 2020 it was energy efficiency. The top geoengineering topic was ocean...
fertilization in 1990, but direct air capture in 2020. The top mobility option was passenger (conventional) transport in 1990, but electric vehicles in 2020. The top industrial topic in 1990 was process emissions, but in 2020 it was distributed generation.

6.2. Shifting disciplinary support

Priorities for topics have not only coevolved with research trends; so, have the disciplines supported. Fig. 7 reveals for example that engineering, and technology dominated funding patterns from 1998 to 2002. Perhaps more funding was committed to R&D in engineering to underpin technologies to reduce global warming to help the Kyoto Protocol, which entered into force in 1997. However, this changes markedly after that surge in technical funding. Writing in the late 1990s (53) hypothesized that the rise of climate change as a social challenge would counteract shrinking budgets for research into energy in the United States and the United Kingdom, and their prediction held true, with a surge in support for social science and humanities work taking off past 2005 to the point where the social sciences and humanities together received more funding in 2020 than any other group of disciplines, including engineering and technology (see Fig. 7).

7. Discussion: Emergent research gaps

Although one can debate whether their relative exclusion from existing research funding patterns is justified, or not, our data does enable an identification of six underfunded disciplines as well as six underfunded topics.

7.1. Underfunded academic disciplines

As already explored in Section 5.1, some specific disciplines such as computer sciences, energy studies, or chemical engineering are very well funded. Conversely, our data also depicts areas that received very low amounts of funding. These can be grouped into five clusters.

The disciplines of theology (the study of religion) and divinity and religious studies (the study of Christian theology and seminaries) received only 0.046% and 0.037% of funding respectively. Yet such disciplines can help researchers better understand deeper spiritual implications of low-carbon transitions including how they may reshape connections to the environment, or promote a new set of values or emotions geared towards sustainability (e.g. selflessness, or altruism, or frugality) [61,62].

The discipline of food science and technology received only 0.036% of funding, a troubling gap given that from farming activities to food processing and transportation of finished goods to consumption can have significant negative impacts on water consumption, energy consumption, climate change, and other environmental externalities. The food sector via agriculture consumes an estimated 200 Exajoules of energy per year, this alone is greater than either the national energy demand of China or the United State [63]. Taken together, 30% of global energy consumption goes into agricultural operations, food production, processing, distribution, and consumption with very large energy needs for food refrigeration and transport [63].

Neuroscience projects received only 0.022% of funding yet approaches combining social interventions that may hamper (or facilitate) behavioural changes, including strategies and biases that may guide and alter abilities of group of people or individuals through an effective mechanism for a behavioural response have studied into social neuroscience, psychology and cognitive neuroscience which have been studying as part of decision-making processes. Moreover, facing climate crisis and its consequences requires understanding the brain imaging, and neurophysiology as well as research on animal behaviour, and research findings have extensively described brain circuits governing behavioural responses to cognitive features, fear, emotional trauma that are engaged during extreme weather events while facing uncertainty [64–67].

Sports studies received (0.012% of funding), yet this is an important topic given that climate change and extreme weather events are already impacting major initiatives like the Olympics or impacting major sporting leagues including football and baseball [68]. Sporting venues also offer an excellent opportunity to demonstrate leadership on climate change or circulate pro-climate intervention messages among fans [67]. Finally, Climate change associated impacts have been described to have significant negative effect in human health and account for behavioural change in physical activity, with impacts on things like exercise, cycling, or walking [66].

Lastly, the discipline of “classics” or classical studies may seem the most remote from climate change, and it did receive only 0.00009% of funding. However, its focus on lessons from history, especially the Western World and the rise and fall of the Greek and Roman empires, offers plentiful historical lessons for modern researchers. Much can be learned here from Greco-Roman philosophy, history, and archaeology including a better sense for how archaeology and related areas of cultural heritage can inform discussions of global climate response [69]. Historians can better integrate new discoveries from archaeological remains in terms of contextualizing studies of social, economic, and political history [70]. Classical studies can last, and most critically, offer vivid models by which to understand the fall and collapse of empires, including those affected by environmental calamities [70]. Such previous societies have already had to grapple with environmental decline and mass population movements as diverse as the Great Bronze Age Collapse of ca. 1200-1100 BCE, the migration of Celts in the third century BCE, the threat of the Cimbri and Teutones to Rome in the second century, the Hunnic invasion of the Roman Empire and the subsequent collapse of the west in the fifth century CE, the sharp contraction of the Byzantine Empire in the seventh century CE, the movement of Slavs into the Balkans, the later devastation of classic Arabic lands by the Mongols, even the collapse of the Maya [71].

7.2. Underfunded topics, technologies, and geographical regions

Similar to underfunded disciplines, our data also demonstrates underfunded technologies. These, revealingly, all fall into the category of solar radiation management or solar geoengineering. Also known as “sunlight reflection methods” or “solar radiation modification”, these efforts all seek to control how much solar energy reaches the surface by manipulating the planet’s radiation budget to ameliorate the main effects of greenhouse gases (i.e., warming) [72]. Stratospheric aerosol injection (SAI) received only 0.2% of all funding, followed (in descending order) by marine cloud brightening (0.15%), ocean mirrors (0.15%), high-albedo crops and buildings (0.1%), space sun-shades (0.1%), and cloud-thinning (0%).

Although they may sound like science fiction, SAI techniques are actually technically feasible today and could enable near-term reduction of global warming. They have been openly discussed in major recent reports (e.g., Ref. [73] Committee on Geoengineering Climate 2015; National Academies of Sciences, Engineering, and Medicine 2021) and the scientific literature (e.g., Refs. [74–76]) as a climate intervention strategy that deserves more careful consideration within the community.

Marine cloud brightening and cloud-thinning are also seen as technically feasible ways to reduce global warming by altering clouds to reflect more solar radiation (National Academies of Sciences, Engineering, and Medicine 2021). Marine cloud brightening in particular could be deployed relatively quickly (using fleets of ships to spray sea water into the air below marine clouds, thereby increasing the clouds’ reflectivity and longevity) in a way that could counter-balance the warming caused by up to a doubling of atmospheric carbon dioxide [77].

Ocean mirrors and space-based sunshades work using the same principle, of placing scatterers, reflectors, or mirrors either across the
ocean (terrestrially based) or into the high atmosphere or outer space (above the atmosphere) to reduce the amount of sunlight entering the Earth, thereby reducing warming. The Committee on Geoengineering Climate (2015) noted that technologically feasible options include opaque disks, transparent prisms, solar sails, diaphanous scattering screens, or even millions of small spacecrafts placed in orbit or a large ring of space dust. Several of these ideas would enhance humanity’s ability to manufacture in space, and assist in the development of enhanced robotics, artificial intelligence, and microwave energy transmission [78].

Several studies have looked at the promise of albedo modification, which advocates claim that if less energy is absorbed by the Earth system, the surface of the Earth will cool on average. However, the potential to rapidly offset some of the consequences of global warming at non-significant cost requires such modification. This history is clearly demonstrated by the of past volcanic eruptions. For instance, the June 1991 eruption of the Mount Pinatubo in the Philippines, injected 20 million tons of sulphur dioxide into the stratosphere that increased Earth’s reflectivity (albedo) and decreased the amount of sunlight absorbed, causing globally averaged surface air temperatures to cool an estimated 0.3 °C for a period of three years. The idea is that technology can replicate such as task, and undertake cooling rapidly, within a year of deployment. Strategies discussed include albedo modification either via buildings (painting them white) or landscapes (managing cropland or marginal land) to better reflect sunlight, particularly in the Arctic but also in areas of high latitude, where sea ice and ice sheets can be protected [78,79].

Finally, in our preceding analysis, the study reveals the top 10 largest funders (countries) between 1990 and 2020 with Rwanda as the only African country in this category. Our findings show that no research institution from Africa made it to the top 10 most funded institutions, including the top 10 projects in terms of technological and topical diversity in our data, showing that most of the R&D funding were highly concentrated in the global north. This finding confirms the argument by Overland et al. (2021) that “there has also been little funding for research on major states like Egypt and Nigeria relative to their large population sizes. Overall, relatively little funding targets North and Central Africa compared to Southern and East Africa and most former British colonies and Anglophone countries” [80]. This also raise important questions around issues of justice and equity in funding for R&D especially on technology and innovation that could help address climate-related challenges, which are expected to adversely affect low-income countries disproportionately in achieving just-transitions.

8. Conclusions

This paper analysed the role of public research funding patterns between 1990 and 2020 looking holistically at the topics of climate change, energy, transport, and industrial decarbonisation. Our study examined 153, 202 projects funded by 154 research councils across 17 countries including 27 European Union. A deeper analysis was undertaken of 1000 representative projects with a total budget of $2.268 billion and some awards running till 2026.

Our data reveals that for the past three decades, research funding was asymmetically distributed. Our evidence reveals a small number of countries within our sample receiving the largest share of public R&D funding on energy and climate change research with United Kingdom (40%), European Union (27%) and United States (11%) receiving, in total, almost four-fifths of all funding disbursed. Countries such as China, India, Israel or Japan received very low amounts of funding; while developing countries, especially in Latin America and Africa hardly feature in the list. R&D funding for technologies during this period shows that climate change adaptation projects received more than one-third of all funding with (36%), energy systems; (28%), and transport and mobility; (13%), geo/climate engineering and industrial decarbonisation received 12% and 11% respectively. This assessment of funding patterns shows that energy efficiency, climate resilience, and climate information systems dominate our sample. Nevertheless, it also reveals that only two technologies in transport and geoengineering made the top 20 and only one in industrial decarbonisation. Perhaps, the technology funding patterns were probably driven by the global efforts from countries through international commitments from Rio convention to Kyoto protocol and from Durban platform to Paris Accords.

The paper equally alludes to research institutions areas of strength, which identified universities in the United Kingdom such Lancaster known for Sociology, Edinburg for science and technology studies, and Oxford for environmental social science made the top 20 institutions that received 96% of all funding on social sciences. The disciplinary funding patterns is almost evenly distributed across disciplines with engineering and technology received the highest of 28%, follow by social science and economics 27%, while 28%, 16% goes to arts and humanities and natural and physical sciences respectively and 11% was spent on life sciences and medicine. The implication is that countries had made significant efforts to invest in R&D technologies and innovation that may help subvert the catastrophic consequence of changing climate. Moreover, although public funding has been allocated to universities across the world in our dataset, there is a strong and noticeable concentration in the Global North.

Not all funding patterns are consolidated, and promote exclusivity. Promisingly, about three-quarters of all projects identified themselves as being transdisciplinary and directly engaging with non-academic stakeholders and partners. This finding suggests that many universities (and public research funding sponsors) are indeed taking calls for transdisciplinary research seriously, including the integration of impact and engagement into research and service missions, and also cooperating across institutions and sectors [77]. We also see multiple specific projects embracing deep interdisciplinarity with more than 300 projects embracing at least 10 different disciplines and some projects (such as CREDS, CCM, and Project Main), embracing more than 20 distinct disciplines in their research aims and objectives. Lastly, this study indicates that there is need for research community and funding agencies to promote more transparency and accountability in their funding patterns. This would facilitate a deeper understanding of spiritual and historical implications of low-carbon transitions, and connections between the extreme weather events and mother nature that could help set new drivers and dynamics geared towards low-carbon sustainability.

Credit author statement

Abbas AbdulRafiu contributed to: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing. Benjamin K. Sovacool contributed to: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing. Chux Daniels contributed to: Data curation, Formal analysis, Investigation, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank and acknowledge support for this paper from the Industrial Decarbonisation Research and Innovation Centre (IDRIC) in
[49] Ingebordur I, Heidenreich S, Ryghaug M, Skjølsvold TM, Foulds C, Robison R, et al. Expanding the scope and implications of energy research: a guide to key themes and concepts from the Social Sciences and Humanities. Energy Res Soc Sci 2020;63(February 2020):1019-38. https://doi.org/10.1016/j.erss.2019.101398.

[50] Mallaband B, Staddon S, Wood G. Crossing transdisciplinary boundaries within energy research: an ‘on the ground’ perspective from early career researchers. Energy Res Soc Sci 2017;26:107-11. https://doi.org/10.1016/j.erss.2017.01.021.

[51] Van den Besselaar P, Sandstrom U. Early career grants, performance, and careers: a study on predictive validity of grant decisions. J Informetr 2015;9(4):826-38. https://doi.org/10.1016/j.joi.2015.07.011.

[52] Overland I, Fossum Sagbakken H, Iatassa A, Kolodzinskaja G, Simpson NP, Trisos C, et al. Funding flows for climate change research on Africa: where do they come from and where do they go? Clim Dev 2021;1-20. https://doi.org/10.1080/17565529.2021.1976609.

[53] Merlin LA. Transportation sustainability follows from more people in fewer vehicles, not necessarily automation. J Am Plann Assoc 2019;85(4):501–10. https://doi.org/10.1080/01944363.2019.1637770.

[54] Bolt T, Somogyi F. Do competitively acquired funds induce universities to increase productivity? Res Pol 2011;40(6):864–74. https://doi.org/10.1016/j.ress.2010.10.001.

[55] Jacob BA, Lefgren L. The impact of NIH postdoctoral training grants on scientific productivity. Energy Res Soc Sci 2020 Feb 18;70:101617. https://doi.org/10.1016/j.erss.2020.101617.

[56] Mallaband B, Staddon S, Wood G. Crossing transdisciplinary boundaries within energy research: an ‘on the ground’ perspective from early career researchers. Energy Res Soc Sci 2017;26:107-11. https://doi.org/10.1016/j.erss.2017.01.021.

[57] Sovacool BK, Hess DJ, Amir S, Geels FW, Hirsh R, Rodriguez Medina L, et al. A topography of climate change research. Nat Sustain 2021;4(4):284-9. https://doi.org/10.1038/s41893-020-0399-9.

[58] Spreng D. Transdisciplinary energy research – reflecting the context. Energy Res Soc Sci 2020;70:101617. https://doi.org/10.1016/j.erss.2020.101617.

[59] Smith W, Wagner G. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. Environ Res Lett 2018;13(12). https://doi.org/10.1088/1748-9326/aac98d.

[60] Soovacol BK, Hess DJ, Amir S, Geels FW, Hirsh R, Rodriguez Medina L, et al. Sociotechnical agendas: reviewing future directions for energy and climate research. Energy Res Soc Sci 2020 Feb 18;70:101617. https://doi.org/10.1016/j.erss.2020.101617.

[61] Lutzenhiser L, Shove E. Contracting knowledge: the organizational limits to interdisciplinary energy efficiency research and development in the US and the UK. Energy Pol 1999;27(4):217-27. https://doi.org/10.1016/S0301-4215(99)00129-0.

[62] Koehrens J. Religious agency in sustainability transitions: between experimentation, upsaling, and regime support. Environ Innov Soc Trans 2018;27:4-15. https://doi.org/10.1016/j.eist.2017.09.003. May 2017.

[63] Soovacol BK, Bazilian M, Griffiths S, Kim J, Foley A, Rooney D. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. Renew Sustain Energy Rev 2021;143 (September 2020):110856. https://doi.org/10.1016/j.rser.2021.110856.

[64] Wang S, van den Berg B. Neuroscience and climate change: how brain recordings can help us understand human responses to climate change. Curr Opin Psychol 2021;42:126–32. https://doi.org/10.1016/j.copsyc.2021.06.023.

[65] Aron AR, Ivy RB, Jeffery KJ, Poldrack RA, Schmidt R, Summerfield C, et al. How can neuroscientists respond to the climate emergency? Neurosci 2020;106(1):17–20. https://doi.org/10.1016/j.neuron.2020.02.019.

[66] O’Donnell S. The neurobiology of climate change. Sci Nat 2018;105(1-2). https://doi.org/10.1007/s10111-017-1538-5.

[67] Edgar A. Sport and climate change. Sport Ethics Philos 2020;4(1):1–3. https://doi.org/10.1080/17513320.2020.1775190.

[68] Bernard P, Chevance G, Kingsbury C, Bailloit A, Romain AJ, Molinier V, et al. Climate change, physical activity and sport: a systematic review. Sports Med 2021;51(5):1041–59. https://doi.org/10.1007/s12722-021-01439-4.

[69] Rockman M, Hritz C. Expanding use of archaeology in climate change response by changing its social environment. Proc Natl Acad Sci U S A 2020;117(15):8295–302. www.pnas.org/cgi/doi/10.1073/pnas.1914213117.

[70] Post R. The environmental history of Classical and Hellenistic Greece: the contribution of environmental archaeology.Hist Compass 2017;15(10):e12392. https://doi.org/10.1111/hic3.12392.

[71] Sovacool BK. Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering. Energy Strat Rev 2021;35(April):100656. https://doi.org/10.1016/j.esr.2021.100656.

[72] National Academies of Sciences, Engineering, and Medicine. Reflecting sunlight: recommendations for solar geoengineering research and research governance. Washing-ton, DC: The National Academies Press; 2021. https://doi.org/10.17226/25762.

[73] Sunlight Reflecting. Climate intervention: reflecting sunlight to cool earth. Clim Interw: Reflect Sunlight Cool Earth 2015:1–244.

[74] Smith W, Wagner G. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. Environ Res Lett 2018;13(12). https://doi.org/10.1088/1748-9326/aac98d.

[75] Lawrence MG, Schafer S, Muri H, Scott V, Oschlies A, Vaughan NE, et al. Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. Nat Commun 2018;9(1). https://doi.org/10.1038/s41467-018-05938-3.

[76] Houghton JB, Koomrens B. Steering and influence in transnational climate governance: nonstate engagement in solar geoengineering research. Global Environ Polit 2020;20(3):93–111. https://doi.org/10.1162/glopol_a_00572.

[77] Chavez AE. Using legal principles to guide geoengineering deployment. SSRN Electron J 2015. https://doi.org/10.2139/ssrn.2600938.

[78] Russell LM. Climate intervention: reflecting sunlight to cool earth: a report from the NRC. In: 2015 AAAS annual meeting (12-16 february 2015); 2015. https://aaas.confex.com/aaas/2015/webprogram/Paper13873.html%5Cnpapers2://publica-
tion/uid/CE3144C4-8598-40E3-8878-2562125326AC.

[79] Kopp RE. Land-grant lessons for Anthropocene universities. Climatic Change 2021;165:28. https://doi.org/10.1007/s10584-021-00309-9.

[80] Overland I, Fossum Sagbakken H, Iatassa A, Kolodzinskaja G, Simpson NP, Trisos C, et al. Funding flows for climate change research on Africa: where do they come from and where do they go? Clim Dev 2021;1-20. https://doi.org/10.1080/17565529.2021.1976609.