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# Science for whom? Examining the data quality, themes, and trends in 30 years of public funding for global climate change and energy research

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ABSTRACT

Public spending for research and development is undoubtedly one of the most powerful tools for government policy in the areas of climate change and energy systems and technology innovation. However, existing datasets are currently fragmented, incomplete, and partial in their coverage. This study presents results from a more comprehensive, granular, and descriptive attempt to compile a dataset of global funding patterns on energy and climate research. To do so, it identified 114,201 potential projects funded by 154 research councils across 17 countries and the European Commission from 1990 to 2020 (with projected funding up until 2026). A smaller sample of 1000 illustrative projects were examined in greater detail. It finds that there are difficulties with accessible and available public data, including an inaccuracy of data on published websites or inadequate tracking and updating of project details. Research on energy and climate change is supported by a surprisingly broad base of inquiry, including research from the social sciences and economics but also the arts and humanities, engineering and technology, life sciences and medicine, and natural and physical sciences. Climate change adaptation research is the most funded general area, followed by climate mitigation via energy systems, transportation and mobility, geo/climate engineering, and industrial decarbonization. Funding has been allocated unevenly in favor of some specific technologies, e.g. resilience and adaption, energy efficiency, and electric vehicles. Publicly funded research benefits a very particular set of disciplines, e.g. communication studies, economics, computer science, and chemical engineering. Moreover, the funded projects reveal a striking diversity of methods, including literature reviews, surveys and original data collection, the development of intellectual property, case studies, qualitative research and energy modeling.

## 1. Introduction

Public spending for research and development is undoubtedly one of the most powerful tools for government policy in the areas of science, technology and innovation [1,2], and in particular energy and climate change [3]. Over the previous two decades, research funding systems have undergone major changes, such as approaches that involve end users in prioritizing research topics, (i.e., participatory research) and funding implementation research (i.e., the scientific study of methods to promote the use of research findings in practice) [4]. The efficacy of these changes on research practice, postdoctoral training, and scientific productivity is unclear [5,6].

Within this shifting landscape of funding, it is often claimed that interdisciplinary work and social science work remains marginalized. Multiple studies across fields as diverse as buildings, transportation, sustainability, the life sciences, and geography have argued that the social sciences must play a larger role in dominant energy and climate research topics [7–11]. Table 1 summarizes recent studies, using a variety of methods, that all conclude in some way that the social sciences are underrepresented in ongoing research projects or publication trends. Galvin [20] writes that social science-based energy research has not yet taken a strong interest in global discussions of energy, with important topics such as sociology of finance, poverty, or theories of money underexamined. More provocatively, Overland and Sovacool [15] analyzed one commercial dataset of public and private research funding, and noted that between 1990 and 2018, the natural and technical sciences received 770% more funding than the social sciences for research on issues related to climate change. By their calculation, only 0.12% of all research funding was spent on the social science of climate mitigation.

Nevertheless, such findings do not stand unchallenged. Callaghan et al. [21] employed topic modeling and content analysis to examine

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more than 400,000 publications from the Web of Science published on climate change from 1985 to 2000. They found, surprisingly, that the social sciences are over-represented in major publications such as the most recent assessment reports from the Intergovernmental Panel on Climate Change. They note, conversely, that technical studies from domains such as agriculture and engineering are under-represented. Cooper [22] also undertook a qualitative review of top energy journals and noted that many social science papers did not engage in meaningful research designs well suited for energy analysis or policymaking. As Cooper [22] noted: "too few social science studies integrate physical science to warrant the deep influence on energy policy many claim it should."

It is thus difficult to more deeply substantiate claims about the marginalization of social science work. Existing datasets for patterns of public research and development (R&D) on climate change and energy face multiple problems and suffer various limitations. Some datasets are proprietary and expensive to access; as one example the "Dimensions" database covers millions of research across 6 million grants and 142 million patents, but is extremely costly to purchase (between £20,000 and £2 million per institution per year in 2020). Other datasets are currently fragmented, i.e. spread across multiple institutions, especially for countries such as the United States, where one must tediously search up to one hundred *individual* funding institutions separately. Some datasets, such as those utilized by the European Union or European Commission, are incomplete, as they do not disclose full Principal Investigator information or grant descriptions; and they are partial, they lack granularity and the specific details one may need to explore disciplinary approaches and topics. Datasets for research in many non-English speaking countries (e.g., Russia, China, Brazil) are not even accessible in English.

Hence, the novelty of this study is clear: to build a more comprehensive, granular, and descriptive dataset of global funding patterns on energy and climate research. To do so, it identified 114,201 potential projects funded by 154 research councils across 17 countries and the European Commission from 1990 to 2020. A smaller sample of 1000 illustrative projects is examined in greater detail, projects with budgets totaling $2.268 billion, with projects awarded funded up until 2026 (although we present results only up to the year 2020).

Building this dataset and analyzing its trends enables the identification of data availability problems and countries that are not particularly transparent about their research streams – this could lead to further reforms concerning data access and transparency. It enables an assessment of past R&D trends over a longer timeframe of 30 years, revealing which areas were most funded but also which countries were most supported (or friendly to social science research), which disciplines were most awarded, and so on. It therefore facilitates a cataloging of recent "hot topics," the fastest growing areas of research over the period examined, along with gaps and missing areas, many of which may be fertile grounds for future research. Rather than look at climate funding compared to other areas, such as health or defense [15], the paper instead looks *within* a corpus of climate funding (inclusive of mitigation and adaptation but also related sectors such as energy, buildings, industry, and transport), to see what trends and possible trends and biases exist. Our assessment of global R&D patterns on energy and climate makes possible a comparison among research councils, technologies, topics and trends, which then facilitates evaluation and benchmarking. This is extremely relevant for policymakers and funders, as they have in recent years been struggling with the task of evaluating the performance of federal programs and agencies [23,24]. Science programs, in particular, have been seen as difficult to evaluate due to poor understanding of financing flows, unclear connections between research efforts supported disciplines, and potential biases within fields of study. Our study also reveals critically emergent gaps in data quality and availability, findings that can lead towards greater accountability and responsibility in the future.

**Table 1**
Overview of recent studies highlighting trends in climate or energy research and the marginalization of the social sciences and humanities.

| Study | Topical focus | Method | Sample | Core findings |
|---|---|---|---|---|
| Goodall [12] | 30 leading English-language management, economics, sociology, and political science journals | Content analysis | 1970 to 2006 | These top journals all collectively fail to publish on climate change |
| Sovacool [10,11] | Three leading energy journals (*Energy Policy, Electricity Journal, The Energy Journal*) | Content analysis | 4444 research articles involving 9549 authors and 90,079 references published from 1999 to 2013 | 19.6% of authors reported training in any social science discipline; 12.6% of articles utilized qualitative methods; less than 5% of citations were to social science and humanities journals |
| Green and Hale [13] | Top international relations journals | Descriptive statistics | 2014 TRIP faculty survey data | Although work focused on climate change has had a recent surge, overall environmental research is rarely published |
| Diaz-Rainey et al. [14] | Leading 21 finance journals | Content analysis | 20,725 articles published January 1998 and June 2015 | Only 12 articles (0.06%) are related in some way to climate finance |
| Overland and Sovacool [15] | Dimensions database | Descriptive statistics | 333 donors spanning 4.3 million awards worth $1.3 trillion from 1950 to 2021 | Between 1990 and 2018, the natural and technical sciences received 770% more funding than the social sciences for research on issues related to climate change. Only 0.12% of all research funding was spent on the social science of climate mitigation |
| Sending et al. [16] | Five top international relations journals | Content analysis | 2015–2019 | Only 0.77% of the articles were about climate change |
| Roos and Hoffart [17] | Web of Science, top economics journals | Bibliometric analysis | 15,000 PhD theses written at 152 North American universities | Argues that "climate change is of little research interest for young researchers"; climate change represents only 1.81% of all published economics articles |
| Royston and Foulds [18] | European trends in energy and climate research | Workshop, content analysis | European Commission published Research policy documents | Social sciences and humanities work is excluded due to expectations grounded in research enterprise, differing epistemic communities and differing notions of rigor and validity |
| Butler-Sloss and Beckmann [19] | Articles in the top 300 economics journals | Content analysis | 2000 to 2019 | 71% of journals have published under 1% on climate change; concludes that "economists' response to the planetary emergency has been incommensurate with the magnitude and urgency of this crisis." |

Note: studies are presented in chronological order.
Source: Compiled by the authors.

## 2. Research design and analytical protocol

Because no unified dataset of public R&D projects exists across research councils, our first step for this study was to build our own. The building of this original dataset involved filtering from more than 100,000 possible research projects across 154 research councils to a final sample of 1000 projects. This process took approximately 13 months.

We began by compiling an exhaustive list of publicly funded projects with a specific set of inclusion and exclusion criteria. Our inclusion criteria were that it had to be:

- Related to research, i.e. a research grant, network grant, coordinating grant, innovation grant, or fellowship;
- Funded by a public research council or grants body, with a budget of at least $1;
- Funded between 1990 and 2020 (although projects funded recently could extend into the future, as far as 2026);
- Focused explicitly on some aspect of climate change and energy (e.g. climate change adaptation, geo/climate engineering, energy systems, transportation and mobility, and/or industrial decarbonization)

This meant that we excluded projects that were:

- Not related to research, i.e. development aid, financing, business model support, or other forms of government intervention not connected to science;
- Not awarded or funded, or related to a no-cost extension;
- Funded by the private sector or non-public bodies;
- Funded prior to 1990;
- Not focused on climate change, energy, or transport.

Even with these inclusion and exclusion criteria, our approach enabled us to collect a broad diversity of grant or project types (cutting across basic science, applied science, R&D, commercialization, etc.) as well as funding types (e.g., Research and Innovation Actions, Coordination and Support Actions, etc.) and funding sources (including the European Commission and many research councils).

With these criteria in place, we began by compiling a list of relevant public research funding sources across 17 countries— Australia, Brazil, Canada, China, India, Israel, Japan, Morocco, New Zealand, Norway, Qatar, Rwanda, South Africa, Switzerland, United Kingdom, United States—and the European Commission. This resulted in a complete list of 154 research councils shown in Annex I. These research councils all publish details (in varying degrees of length and completeness) in English for the projects they fund. These research councils are also responsible for approximately $1.5 *trillion* in collective funding for climate change and energy topics [15]. We then searched for 71 search strings on each of these datasets, searching not only for the general area (see Annex II, categories A-E) but also the specific technology being mentioned (see Annex II technology categories 1–66) as well as specific disciplines funded (see Annex III's "Conceptualization of Academic Disciplines). We classified general areas and technologies according to a fivefold classification schema grounded in a book from Brown and Sovacool [25], but expanded to include industrial decarbonization efforts being advanced as a part of the Industrial Decarbonization Research and Innovation Centre, who helped fund this study. We classified academic disciplines according to a widely accepted schema utilized by the QS World University Rankings.

We assigned every relevant project a number, starting with 0001, and then tracked relevant information about the project such as the host institution(s), the principal investigator(s), and any relevant contact details (email, phone). Our initial scraping of the research councils created a dataset of 114,201 potential projects.

However, when we began to closely analyze these projects, we excluded any redundancies (some projects were listed on multiple research councils, especially those funded jointly), projects that had no funding (a budget amount of $0 or no-cost extensions), and lastly projects that did not have sufficient information about their activities or PIs. We also excluded projects with no start or end date, i.e. open ended ones. This dropped the sample by more than half, to 45,200 projects.

We then contacted all 45,200 principal investigators by email (in projects listing multiple Principal Investigators (PIs), we emailed all PIs listed). We lost a further 45% of projects (20,330) due to contact details being out of date/emails bouncing, or learning that the PIs were deceased. Of the remaining 24,870 projects, we randomly selected 1500 and contacted them by phone or email to complete a more in-depth questionnaire about the project (shown in Annex III). This questionnaire focused more deeply on the specific technologies covered by projects, the disciplines used, the research methodologies, involved, the budgets, and so on. Our completion rate was 66%, with two-thirds completing the questionnaire and one-third declining. The questionnaire was needed because much of the information we sought (such as the full range of technologies covered in a project, or the diversity of disciplines supported) were not published within the research council records or it wasn't in the format we needed. So, we deferred to relying on PIs to give us this knowledge as a more authoritative but also efficient process.

Although we intended our data collection process to be as extensive, comprehensive, and robust as possible, it does have some shortcomings. We would classify our sample of 1000 projects as illustrative, but by no means fully representative, because of potential (although unavoidable) selection issues that could entail forms of selection or sample bias. For instance, our selection process did involve removing projects for which PIs did not respond or refused to fill out our questionnaire. This could have been for myriad factors including lack of time; disclosure policies not permitting dissemination; not being able to remember much about the work; out of date or wrong contact information listed in grant portals; or PIs that may have passed away. These factors all narrow and shape our sample of projects, the types of PIs likely to respond, the thematic areas within the topic of climate change and energy, and the types of institutions that participated, in turn affecting the 1000 projects analyzed in depth. PIs may remember newer projects rather than older ones, especially those decades old, meaning our analysis may overrepresent more recent projects versus older projects.

Furthermore, we searched only for information and projects available in English, meaning we likely overrepresent projects in the Global North in our dataset. We did not examine individual European Union member states (e.g. the German, French, Italian councils, etc.) relying instead on the European Commission, because it published all of its funding results in English. Limiting our dataset in this way means 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. We built our dataset by searching the public records of research councils, meaning our results are only as complete as those records are. We would have missed any projects not captured by these records or projects that were rejected and unfunded. We also searched generally for words "energy" or "climate" and initially picked up projects that were not relevant, e.g. "energy intake" but for human nutrition, the "transport" of substances across cell membranes in egg and embryo development, or "regaining mobility" after a joint replacement. Admittedly, we look only at funding patterns and directions, a helpful proxy but not the same as looking at research that was effective or actually addressed social problems [26]. Finally, given that we harvested information via official research council records, especially abstracts or data from grant funding portals, it could be possible that elements of this data have been "sanitized" or "censured" for political reasons, especially in Canada [27] and the United States [28–30].

## 3. Results and discussion

This section organizes our core results according to four trends: those in data quality and responsibility, financial funding patterns (including top institutional funders of research), prominent technologies and themes (including those in climate change adaptation, geo/climate engineering, energy systems, transportation and mobility, and industrial decarbonization, and disciplinary and methodological preferences (i.e., top fields and favored research designs).

### 3.1. Data quality and availability

Our first finding is stark: the quality of available information on public R&D patterns, even though they involve billions of dollars in our sample (and trillions of dollars overall) is limited and inconsistent. More than half of the initial projects we scoped had insufficient information available about principal investigators, project descriptions, or contact information. More than 40,000 projects searched had no details about the project or (more commonly) no names or email addresses to contact. Then, of those that we *did* contact, another 45% (20,330 projects, almost half) had contact details listed that were out of date or incorrect. This all speaks to the difficulty of maintaining accurate and accessible records on publicly funded projects.

In terms of the 1500 final PIs that we did contact for more details about their grants, and that had emails that worked (or did not get returned as undeliverable), another 5% (79 PIs) said that they did not remember their projects, were not really the PI (they were "ghost" or "gift" PIs), or could not recall details about the project, a possible indication of difficulties in record keeping and administration. As some of these respondents communicated to us:

> *"I can't respond to this one. I was PI only in name, not in reality."*
>
> *"I'm sorry, but as much as I would like to help, I can't recall anything about that grant, even what we spent the money on, or if we even did so."*
>
> *"I have no idea exactly when this grant started or ended. I doubt if I was able to go to the office I would be able to find out either. Also I have no idea how much money came to us."*
>
> *"All this was done some years so I would not be able to resurrect any meaningful information."*
>
> *"I do not recall this project."*

This finding raises questions concerning the institutional memory of respondents, especially as we were asking only about fairly recent projects (in the past 30 years).

Moreover, within this final sample of 1500 PIs that we contacted with our questionnaire, many (421 projects) replied to us that they did not want to take the 5–10 min needed to complete our survey instrument, even though it was designed to be quick, and even though we were querying them about publicly funded projects. Typical responses included:

> *"I'll pass. Good luck."*
>
> *"Sorry I am tied up trying to get hydrogen vehicles funded. No time."*

In some perhaps more understandable cases, the research projects being queried were "classified" and respondents were not able to report more:

> *They are all United States Air Force Grants. Unfortunately, I am not at liberty to provide any more information than to say that they are classified for security reasons.*
>
> *The major aviation programs related directly to efficiency and reduced carbon usage are/were funded by NASA. I cannot give you any further information.*

All of these themes speak to the difficulty of convincing PIs to communicate to us, and other scientists, about the nature or scope of their publicly funded research. It implies that many do not believe in any perceived norm that publicly funded researchers have an obligation to respond to public inquiries about the nature of their research. It also may be due to desires to "guard" their own research, and control dissemination of results only to a limited number of stakeholders, something Gould and Valdez [31] term the "Gollum effect. The notion that PIs should make their data available on request could also be further eroded by emerging norms in competitive fields like management, where researchers may have spent years developing their database (and may also have had to provide assurances of confidentiality in obtaining some of the information).

### 3.2. Financial funding patterns

The financial and funding patterns for our 1000 projects revealed a total budget of $2.268 billion with a median budget of $629,062 and a mean budget of $2.3 million. The most expensive project across the sample was a $100 million project looking at energy-efficient turboshaft engines for military aircraft (hosted by the United States Air Force, United States Army, and the United States Army Corps of engineers), and the project with the smallest budget was a $5 research project examining magnets for energy storage in India (ostensibly with copious amounts of co-funding or host institutional sponsorship).

Table 2 reveals the top twenty research councils by funding. The European Commission dominated funding patterns, with its Horizon 2020, FP7, ERC, and LIFE programs reflecting 40.1% of all funded projects in our sample. The United Kingdom also had a strong role in funding patterns, reflecting another 36.2% of funded projects. The United States Air Force, Department of Energy, and National Science Foundation made it onto our list, along with the Australian Research Council, Canadian Foundation for Innovation and Natural Sciences and Engineering Research Council, and New Zealand Ministry of Business Innovation and Employment.

Fig. 1 shows country funding patterns over time in our sample, with significant increases post 2010 in funding patterns, especially for the United Kingdom and European Commission—a trend that also likely reflects a positive coevolution between the British and European funding system. The low amount of funding in the could be an indication then of fairly limited attention to climate change as a research topic, but it may also be due to the fact that multi-year funding before those years that continue into the 1990s are not reflected.

### 3.3. Prominent technologies and themes

In terms of the technologies supported and themes investigated, the projects covered a rich range of different technology areas, with climate change adaptation being funded the most (36.2% of projects) followed by energy systems (27.7%), transportation and mobility (13.1%), geo/climate engineering (11.7%), and industrial decarbonization (11.4%).

In terms of specific technologies supported, the top ten areas for climate change adaptation are shown in Table 3. This area of research was fairly consolidated among the first five topics (adaptation, resilience and adaptive capacity; climate information systems; managing risks; economic resilience; and drought). These five topics were investigated in about *half* of all related projects. Most of the policy dialogue surrounding global climate change has focused on reducing greenhouse gas emissions as a means of reducing the magnitude of climate change – something often termed "mitigation." However, if the goal is to reduce the harmful consequences of greenhouse gas induced climate change, then there is an array of options extending beyond mitigation. Deliberate actions can also be taken to reduce the vulnerability of humans and ecosystems to the effects of global climate change. These are called "adaptation" approaches, and they can be anticipatory or reactive. Adaptation refers to "changes made to better respond to present or future climatic and other environmental conditions, thereby reducing

**Table 2**
Top 20 research councils funding energy and climate research, 1990 to 2020 ($N = 154$).

| No. | Research council or funder | Total funding (US $2020) | |
|---|---|---|---|
| 1 | European Commission Horizon 2020 | 610,781,940 | 26.2% |
| 2 | United Kingdom Engineering and Physical Sciences Research Council (EPSRC) | 288,221,172 | 12.3% |
| 3 | United Kingdom Economic and Social Research Council (ESRC) | 286,302,442 | 12.3% |
| 4 | European Commission FP7 | 217,016,973 | 9.3% |
| 5 | United Kingdom Natural Environment Research Council (NERC) | 203,514,034 | 8.7% |
| 6 | United States Air Force (USAF) | 202,263,978 | 8.7% |
| 7 | United Kingdom Biotechnology and Biological Sciences Research Council (BBSRC) | 75,820,760 | 3.2% |
| 8 | European Commission ERC | 59,999,453 | 2.6% |
| 9 | European Commission LIFE | 47,399,950 | 2.0% |
| 10 | United Kingdom Arts and Humanities Research Council (AHRC) | 31,681,523 | 1.4% |
| 11 | Australian Research Council (ARC) | 30,934,703 | 1.3% |
| 12 | United Kingdom Innovate UK (Innovate UK) | 28,620,482 | 1.2% |
| 13 | United States National Oceanic and Atmospheric Administration (NOAA) | 23,000,000 | 1.0% |
| 14 | United States National Science Foundation (NSF) | 17,526,402 | 0.8% |
| 15 | Canada Foundation for Innovation (CFI) | 14,800,000 | 0.6% |
| 16 | Switzerland Swiss National Science Foundation (SNSF) | 13,765,000 | 0.6% |
| 17 | Canada Natural Sciences and Engineering Research Council (NSERC) | 12,738,760 | 0.5% |
| 18 | New Zealand Ministry of Business, Innovation and Employment (MBIE) | 8,000,000 | 0.3% |
| 19 | United States Department of Energy (DOE) | 7,390,196 | 0.3% |
| 20 | United Kingdom Medical Research Council (MRC) | 7,283,147 | 0.3% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total annual disbursement patterns from any specific research council or sponsor indicated.
Source: Authors.

harm or taking advantage of opportunity" ([32]: 11).

In order to ensure that global warming does not exceed 2 °C temperature levels, accumulative emissions since 1870 must remain under 3650 GtCO2 [33]. Following current CO2 emission rates and scenarios, this global emissions budget is used up within the next 20 years [34]. Thus, the IPCC's Fifth Assessment reported an important role for carbon dioxide removal in keeping temperatures below the 2 °C target. More recently, the Paris Agreement highlighted even more ambitious climate goals by declaring to pursue further efforts to limit global temperatures below 1.5 °C [35]. Carbon dioxide removal and "negative emissions" technologies are therefore important for achieving the Paris goals, and we see this reflected in our research patterns. Moreover, as climate change mitigation continues to face collective action problems, and given that carbon dioxide options may face tenacious barriers, some scholars have called for technical solutions to climate change such as geoengineering and solar radiation management [36]. If deployed, these could greatly transform climate policies and pathways post 2050. They could also make the United States, and other regions, effectively climate change resilient [37].

Carbon dioxide removal techniques were extremely popular within our general area of geoengineering and climate engineering (see Table 4), representing almost a quarter of all funded projects. Other very popular approaches supported by projects included BECCS, afforestation, direct air capture, and biochar [38]. BECCS involves utilizing specific energy crops such as perennial grasses, or short-rotation coppicing or increased forest biomass to replace fossil fuels as a source of thermal energy, capturing any carbon dioxide combusted and storing it. Afforestation refers to the planting trees or vegetation to absorb carbon dioxide growth, whereas direct air capture removes greenhouse gas from the atmosphere via sorbents or other energy-intensive techniques. Added to soils, biochar is a means to increase soil carbon stocks as well as improve soil fertility and other ecosystem properties.

Four topics—energy efficiency, energy storage, solar energy, and electricity transmission and distribution networks—accounted for approximately *half* of the total topics covered in projects looking at energy systems (see Table 5). Energy efficiency was the single most funded topic, perhaps because it involves such a broad menu of possible approaches and instruments including energy audits, energy labeling, fuel economy standards, demand response, appliance standards, and energy audits (to name a few) [39,40]. Energy storage remains a popular topic likely given the many ways it can improve energy security or promote grid resilience (e.g., batteries, pumped hydro, compressed air energy storage, even vehicle-to-grid) [41]. The services offered by such storage systems include ancillary services, spinning reserves, load following, bulk storage, distributed storage, bulk supply, and demand-side management and load shedding [42]. Solar represents a compelling topic likely given extremely rapid reductions in cost per installed Watt, high rates of learning, modularity and prices at grid parity or less [43–45] compared to energy prices overall for many other systems, which are expected to rise [46].

Table 6 shows the most frequently studied topics for transport and mobility, and these include all the three "revolutions" in transport (electrified, automated, and shared mobility) [47]. Electric mobility was by far the most frequently studied, having experienced several cycles of societal hype and disappointment [48]. This area of research includes plug-in electric vehicles, battery electric vehicles, plug-in hybrid electric vehicles (PHEVs) that can be plugged-in or powered by an internal-combustion engine (typically gasoline or diesel), and even electric bikes and scooters. Alternative fuels came second as a studied topic, a term that captures various types of research on biofuel, notably ethanol, biodiesel, and palm oil [49]. Ethanol is derived by fermenting grains, cereals, sugar crops, and other starches, predominantly corn and sugarcane. Crushing and soaking processes remove the sugar from these crops and then ferment it in alcohol using yeasts. Feedstocks for biodiesel, by contrast, tend to be oil-rich crops such as soybean, jatropha, palm oil, rapeseed (canola) and sunflower seeds [50,51]. Research on passenger vehicles including conventional cars came third, a topic that some may find surprising until they realize that most major automobile manufacturers market an array of increasingly fuel-efficient models that are achieving similar $CO_2$ reductions to electrification that can be gained by improving efficiency in conventional models. Many emerging technologies, such as variable valve timing and lift, superchargers, direct fuel injection, and automated manual transitions, are expected to significantly improve internal combustion engine vehicle efficiency over the next two decades [52,53]. In addition, reductions in vehicle weight, improved aerodynamics, and size decreases could improve fuel efficiency. It has been estimated that a 20% vehicle weight reduction in an average vehicle is possible over the next 25 years, producing a further 12–20% reduction in fuel consumption [52].

Finally, Table 7 showcases projects looking at industrial decarbonization, options for net-zero industry or more energy-efficient industrial processes. This matters because sectorally, global industrial carbon emissions make up 24% of the total emissions of carbon dioxide each year [54]. To meet the Sustainable Development Goals, industries need to annually reduce emissions by 1.2% to 7.4 GtCO2 by 2030 [54]. This requires decarbonization of industries using innovative technologies, including an expanded use of renewable energy and energy efficiency. Energy storage was the most studied topic in this domain, for reasons perhaps similar to those already mentioned above when discussing energy systems in Table 4 (where it came second). Controlling process emissions is key, as the literature suggests multiple ways that one can abate these emissions: (1) targeting the leak-tightness of equipment containing industrial gases, (2) encouraging increased reclamation of used gases, (3) banning the use of certain potent gases in some applications for which more environmentally superior alternatives are available, and (4) a mandatory phase-down scheme [55,56]. Industrial heating and cooling also account for 12.2% of projects, a topic salient

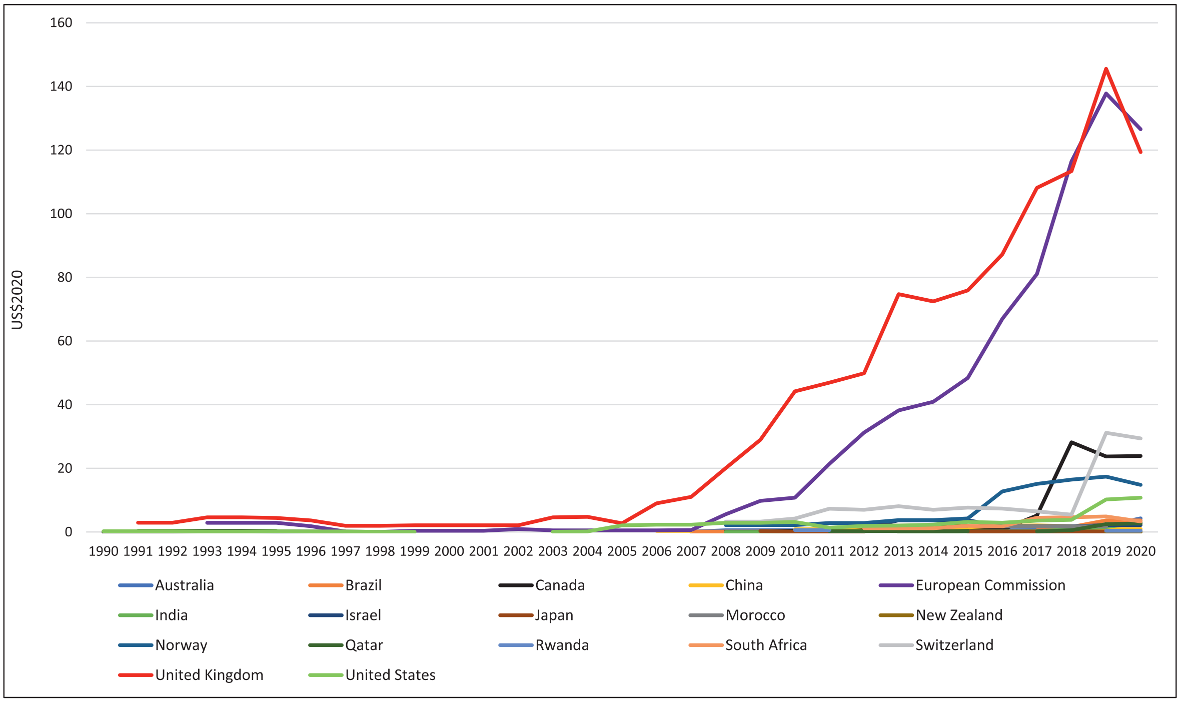



**Fig. 1.** Public research and development funding on energy and climate across 17 countries and the European Commission (in millions of US$2020).
Note that funding trends post 2019 do not reflect any de facto decline in funding, just the anticipated end of projects funded up until 2020. The data only includes projects that started between 1990 and 2020, so that post 2020 funding is only represented by multi-year projects that started before. The top 6 funders in order of magnitude (from top to bottom of the graph) are the United Kingdom (red), European Commission (purple), Switzerland (grey), Canada (black), Norway (dark blue) and the United States (light green). Funding patterns are from a sample of only 1000 projects and will not match total annual disbursement patterns from any specific research council or sponsor indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: Authors.

**Table 3**
Top ten climate change adaptation topics funded by energy and climate research, 1990 to 2020 ($N = 918$).

| No. | Technology or topic | Number of projects supporting technology or climate change adaption topic | |
|---|---|---|---|
| 1 | Adaptation, resilience and adaptive capacity | 157 | 17.1% |
| 2 | Climate information systems | 102 | 11.1% |
| 3 | Managing climate risks | 94 | 10.2% |
| 4 | Economic resilience | 59 | 6.4% |
| 5 | Drought | 33 | 3.6% |
| 6 | Early warning systems | 31 | 3.4% |
| 7 | Researching drought resistant crops | 27 | 2.9% |
| 8 | Coastal protection | 24 | 2.6% |
| 9 | Climate-resilient irrigation design | 16 | 1.7% |
| 10 | Mangrove regeneration and plantation management | 15 | 1.6% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

**Table 4**
Top ten geo/climate engineering topics funded by energy and climate research, 1990 to 2020 ($N = 296$).

| No. | Technology or topic | Number of projects supporting technology or topic | |
|---|---|---|---|
| 1 | Carbon dioxide removal | 69 | 23.3% |
| 2 | Bio-energy with carbon capture and sequestration (BECCS) | 32 | 10.8% |
| 3 | Afforestation | 23 | 7.8% |
| 4 | Direct air capture with carbon capture and storage (DACCS) | 18 | 6.1% |
| 5 | Biochar | 17 | 5.7% |
| 6 | Enhanced Weathering | 12 | 4.1% |
| 7 | Solar radiation management | 11 | 3.7% |
| 8 | Ocean Alkalinity Enhancement | 6 | 2.0% |
| 9 | Ocean Fertilization | 5 | 1.7% |
| 10 | Aerosol injection | 4 | 1.4% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

due to the need for both high- and low-temperature heating for industrial purposes (e.g., steel casting, smelting, brewing, baking) but also energy-intensive needs for refrigeration and air conditioning [57].

Rather than taking a static view, our data also enables one to capture the dynamically shifting research priorities across time. As Table 8 summarizes, the top climate change adaptation priorities have shifted within the sample from coastal afforestation and mangroves to drought resistance, managing climate risks and glacial flood control. Energy projects began by focusing on centralized technologies such as nuclear power and hydroelectricity (along with experimental work on fusion in the 1990s) towards fossil fuels such as coal and natural gas in the 2010s towards energy efficiency and energy storage in 2020. Geoengineering work has shifted away from ocean fertilization in the 1990s towards BECCS and CDR in the 2010s and most recently direct air capture, solar radiation management, and biochar in 2020. Mobility and transport research has evolved beyond passenger transport and aviation towards electrification, passenger rail and alternative fuels such as hydrogen and ethanol. Process emissions remain a constant theme within the topic of industrial research, but priorities have shifted to focus more on heating and cooling, distributed generation, and energy storage in the past decade.

Fig. 2 visualizes funding patters over time for all five of our core

**Table 5**
Top ten energy systems topics funded by energy and climate research, 1990 to 2020 ($N = 702$).

| No. | Technology or topic | Number of projects supporting technology or topic | |
|---|---|---|---|
| 1 | Energy efficiency, demand response, load management, demand side management | 183 | 26.1% |
| 2 | Energy storage, distributed storage and batteries | 73 | 10.4% |
| 3 | Solar energy (including solar PV as well as solar thermal or Concentrated Solar Power) | 65 | 9.3% |
| 4 | Electricity Transmission & Distribution | 50 | 7.1% |
| 5 | 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) | 46 | 6.6% |
| 6 | Heating and cooling (including district heating, combined heat and power) | 40 | 5.7% |
| 7 | Wind energy (including onshore and offshore turbines) | 37 | 5.3% |
| 8 | Biofuels (generally in the form of biodiesel and ethanol) | 31 | 4.4% |
| 9 | Hydroelectricity | 25 | 3.6% |
| 10 | Hydrogen (generally meant to encompass fuel cells using renewable fuels and at times natural gas) | 24 | 3.4% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

**Table 6**
Top ten transport and mobility topics funded by energy and climate research, 1990 to 2020 ($N = 332$).

| No. | Technology or topic | Number of projects supporting technology or topic | |
|---|---|---|---|
| 1 | Electric vehicles (including PHEVs, BEVs, e-bikes and scooters) | 54 | 16.3% |
| 2 | Alternative fuels (biofuel, synfuel, ethanol, biodiesel, hydrogen fuel cells) | 42 | 12.7% |
| 3 | Passenger vehicles (internal combustion engines, scooters, motorbikes) | 30 | 9.0% |
| 4 | Freight (heavy duty vehicles, commercial vehicles, and trucks) | 22 | 6.6% |
| 5 | Aviation and aircraft | 22 | 6.6% |
| 6 | Ridesharing and carpooling | 20 | 6.0% |
| 7 | Automated vehicles | 20 | 6.0% |
| 8 | Passenger rail (including metros and trams) | 16 | 4.8% |
| 9 | Marine shipping and transport (including ferries, barges, and container ships and tankers) | 16 | 4.8% |
| 10 | Petroleum fuels (oil, gasoline, diesel, petrol) | 14 | 4.2% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

climate and energy areas: adaptation, geoengineering, energy, mobility, and industry. It shows a very dynamic research landscape with almost constantly shifting priorities. Panel A reveals how climate resilient design for flooding has seen an incredible increase in recent funding trends, with general work on adaptation and adaptive capacity operating as a consistent foundation for research across all thirty years. Panel B shows geoengineering trends and depicts how these were initially dominated by BECCS, but have shifted in more recent year to Carbon Dioxide Removal techniques, and very recently towards space sunshades and solar radiation management techniques. Panel C illustrates energy systems trends, highlighting an initial wave of fusion research before moving towards a more diversified mix of renewable energy sources as well as energy efficiency and heating and cooling systems. Panel D shows how transport research was initially dedicated to looking at aviation and (conventional) passenger transport before shifting towards more recent work on ridesharing and carpooling, electric vehicles, and alternative fuels such as hydrogen and biofuel. Panel E visualizes industrial decarbonization work, indicating that it was dominated by energy storage and heating and cooling initially, before moving more recently to work on CCUS and industrial hydrogen.

**Table 7**
Top five industrial decarbonization topics funded by energy and climate research, 1990 to 2020 ($N = 288$).

| No. | Technology or topic | Number of projects supporting technology or topic | |
|---|---|---|---|
| 1 | Energy storage | 57 | 19.8% |
| 2 | Process emissions | 41 | 14.2% |
| 3 | Heating and cooling (including district heating, combined heat and power) | 35 | 12.2% |
| 4 | Distributed generation/co-generation | 34 | 11.8% |
| 5 | Industrial feedstocks | 27 | 9.4% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

### 3.4. Disciplinary and methodological preferences

As shown in Annex III, our dataset also involved tracking the specific disciplines utilized or supported by projects across five general areas. Interestingly, projects were distributed across these areas more evenly than we had expected, with the arts and humanities supported in 18% of projects, the social sciences and economics in 27%, engineering and technology 28%, life sciences and medicine 11%, and the natural and physical sciences 16%. These five areas collectively covered 65 distinct disciplines also mentioned in Annex III.

Table 9 shows the top five funded disciplines for each of the five general areas across all of the projects. The arts and humanities funding were highly consolidated in the three disciplines of communication studies, architecture, and area studies, which accounted for almost two-thirds of funding in that area. The social sciences were similarly dominated by energy social science work, economics, and the behavioral sciences, which accounted for 58.7% of funding. The computer sciences had the greatest single share of any general area, responsible for 42.4% of funding alone in engineering and technology. The life sciences saw biology, agriculture, and health sciences reach more than 70% of total funding. The natural sciences were similarly well represented by earth sciences, materials science, and chemistry, accounting for more than 70% combined.

A final aspect of research we investigated were the research designs and methods reported by PIs, useful to comprehend the degree to which human-centered approaches are utilized [58], as well as how rigorous researchers are and the codes of research practice they follow [59]. We categorized eight core research designs often present within the energy studies and climate change fields.

Experiments involve human participants and seek to test for causal relationships between variables, while isolating the study or relationship from (or controlling for) other potentially influential variables [60,61]. "True experimental designs" are distinguished by: a) random selection and/or assignment of participants; and b) researchers having control over extraneous variables [62]. In contrast, quasi-experimental designs seek to identify the causal effect of some treatment or effect, but lack random assignment to treatment groups [63,64]. As Fig. 3 indicates, these approaches were used in about 9% of projects.

Literature reviews refer to compilations and integrations of existing research, typically with the aim of identifying the current state of knowledge or different kinds of research gaps. Reviews typically involve repeated searches of databases using specific keywords in order to

**Table 8**
Top three topics funded by energy and climate research for each of 1990, 2000, 2010, and 2020 ($n = 1000$ projects).

| | 1990 | 2000 | 2010 | 2020 |
|---|---|---|---|---|
| Climate change adaptation | 1. Climate resilience<br>2. Coastal afforestation<br>3. Mangrove regeneration | 1. Mangrove regeneration<br>2. Climate resilience<br>3. Economic resilience | 1. Drought resistant crops<br>2. Hurricane recovery<br>3. Earthquake management | 1. Adaptation and adaptive capacity<br>2. Managing climate risks<br>3. Glacial flood control |
| Climate mitigation/energy systems | 1. Nuclear power<br>2. Fusion<br>3. Hydroelectricity | 1. Coal<br>2. Natural gas<br>3. Hydrogen | 1. Energy efficiency<br>2. Natural gas<br>3. Biogas and bioenergy | 1. Energy efficiency<br>2. Energy storage<br>3. Electricity transmission and distribution |
| Climate geo-engineering | 1. Ocean fertilization<br>2. Enhanced weathering<br>3. High-albedo crops and buildings | 1. High albedo crops and buildings<br>2. Carbon dioxide removal<br>3. Ocean fertilization | 1. Bioenergy with carbon capture and storage (BECCS)<br>2. Carbon dioxide removal<br>3. High albedo crops and buildings | 1. Direct air capture<br>2. Solar radiation management<br>3. Biochar |
| Low-carbon mobility and transport | 1. Passenger (conventional) cars<br>2. Aircraft and aviation<br>3. Marine shipping | 1. Passenger (conventional) cars<br>2. Aircraft and aviation<br>3. Marine shipping | 1. Passenger rail<br>2. Aviation and aircraft<br>3. Alternative fuels (biofuel and hydrogen) | 1. Electric vehicles<br>2. Passenger rail<br>3. Alternative fuels (biofuel and hydrogen) |
| Industrial decarbonization | 1. Process emission<br>2. Combined heat and power<br>3. Industrial hydrogen | 1. Process emission<br>2. Heating and cooling<br>3. Energy storage | 1. Heating and cooling<br>2. Energy storage<br>3. Carbon capture and storage (CCS) | 1. Distributed generation<br>2. Process emission<br>3. Energy storage |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

identify large bodies of evidence, and they can be systematic, aimed at meta-analysis, or more commonly used as qualitative sections of research papers [65,66]. They were used in about 16% of projects.

Survey methods were used in about 17% of projects. They involve data collection using a survey instrument or structured questionnaire with a sample of respondents from a relevant target population. Surveys are used extensively within many disciplines, but both the practices and norms associated with implementing surveys and the interpretation of results can differ between those disciplines [67].

Data analysis and statistics—of primary data, or many times of secondary datasets compiled by others e.g. the Census Bureau or different government offices—utilizes statistical techniques, though norms of implementation can again vary between disciplines, as can the relative use of specific techniques (e.g. MANOVA versus multivariate regression). These were used in 18% of projects.

Quantitative energy models were used in about 5% of projects. Such models may focus upon energy demand (e.g. vehicle stock model), energy supply (e.g. linear programming model of electricity generation) or whole energy systems; their scope may range from the very narrow (e.g. electricity distribution within a single city) to the very wide (e.g. the global energy system); they may utilize a range of behavioral assumptions (e.g. full or bounded rationality) and mathematical techniques (e.g. systems dynamics, agent based); and they may be integrated to a greater or lesser degree with broader economic models [59].

Qualitative research was used, perhaps surprisingly, the most across all projects at 18.5%. Qualitative research designs cover a range of techniques for collecting and analyzing data about the opinions, attitudes, perceptions and understandings of people and groups in different contexts. Qualitative research methods differ according to the nature of data collection, as well as the means of analyzing that data. In energy social science, the most popular approaches to qualitative data collection tend to be semi-structured interviews, focus groups, direct observation, participant observation and document analysis [68–70]. What each of these methods has in common is that they are inductive and exploratory by nature, seeking to access a particular perspective in depth, rather than to test a specific hypothesis. The more frequent use of qualitative methods could be because social scientists are now added to more teams when doing collaborative projects. Even those projects using experimental or quantitative techniques could now have social scientists within the project utilizing qualitative methods. Or it could be because social science methodologies can be scalable and cost effective (i.e., cheaper), that is they may be used more frequently than research designs that are more expensive (i.e., the use of supercomputing facilities or costly randomized clinical trials, which can cost millions of dollars for a single experiment.

Case studies and cross-case comparisons were used by almost 10% of projects. Rather than using statistical analysis of data from a large sample, case study methods often involve detailed, longitudinal assessments of single or multiple cases - which may be individuals, groups, organizations, policies or even countries [71,72]. Case studies can use both quantitative and qualitative research techniques, lending themselves also to mixed-methods studies.

Technical innovation, engineering development and/or the creation of patents were applied in 6.2% of projects. Such technical development often attempts to promote a linear model of innovation, often envisioning a sequence of basic research progressing to applied research and commercialization [73]. Another common approach is to promote research across various Technology Readiness Levels, or TRLs [74]. These chart research across 9 levels:

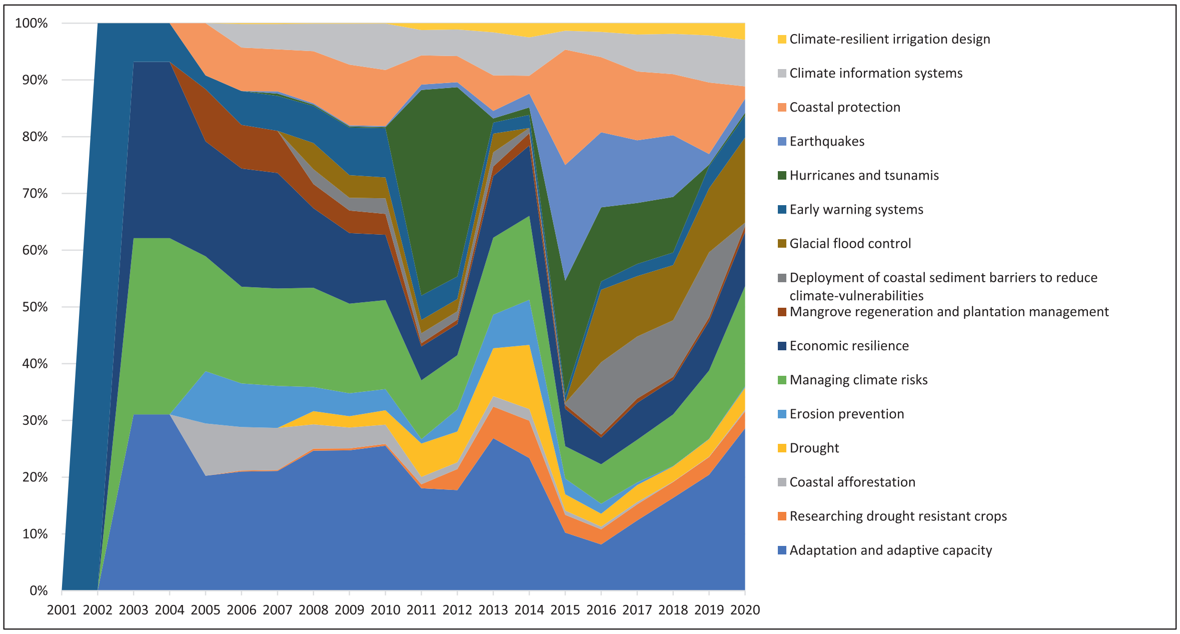
1. Initial idea: basic principles have been defined
2. Application formulated: concept and application of solution have been formulated
3. Concept needs validation: solution needs to be prototyped and applied
4. Early prototype: prototype proven in test conditions
5. Large prototype: components proven in conditions to be deployed
6. Full prototype at scale: prototype proven at scale in conditions to be deployed
7. Pre-commercial demonstration: solution working in expected conditions
8. First-of-a-kind commercial: commercial demonstration, full-scale deployment in final form
9. Commercial operation in relevant environment: solution is commercially available, needs evolutionary improvement to stay competitive

The International Energy Agency [75] recently added two other levels to modify this approach in the energy systems sector: integration (number 10) and growth (number 11).

## 4. Conclusions

Research councils around the world have a long history of supporting research on energy systems and climate change. Between 1990 and 2020, we identified 114,201 potential projects funded by 154 research

*A. Climate adaptation*




*B. Geoengineering*

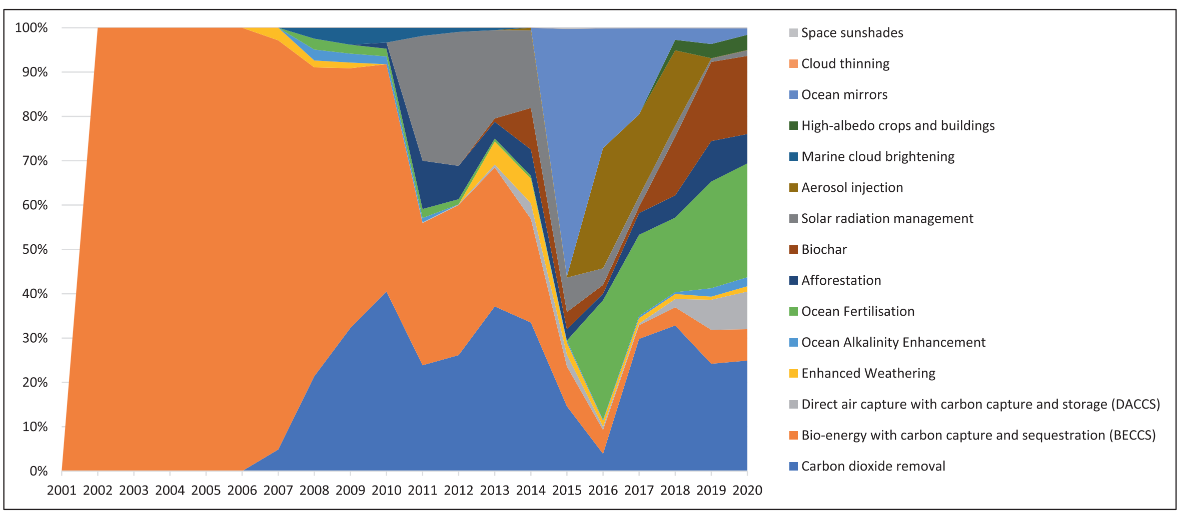


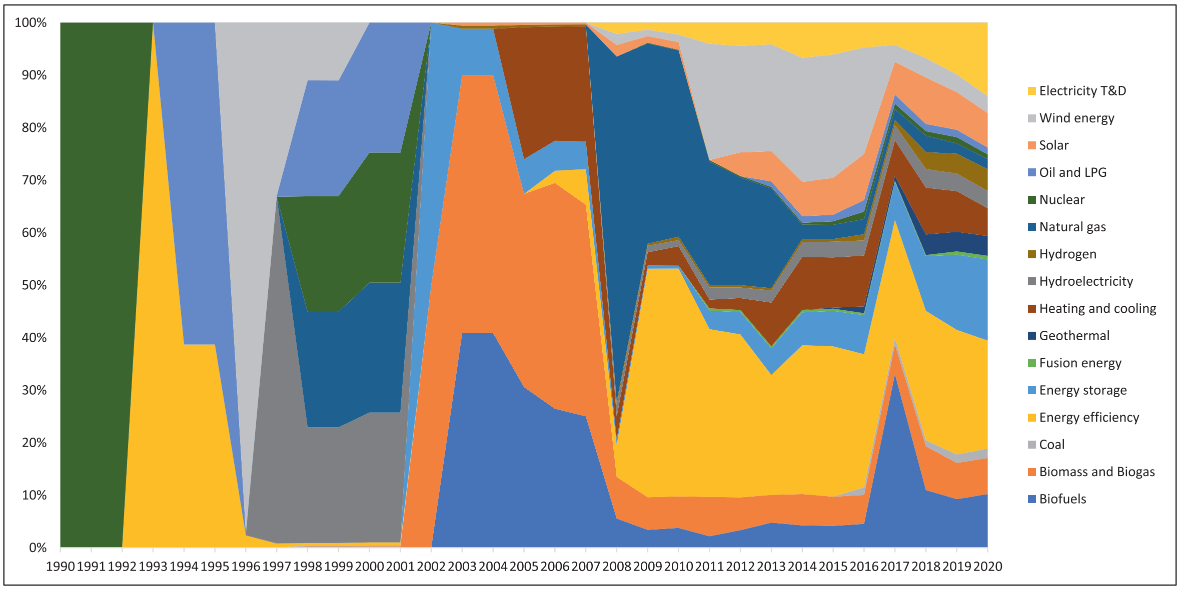

**Fig. 2.** Public research and development funding on energy and climate across five key topical areas (as a % of total funding for that area).
A. Climate adaptation; B. Geoengineering, C. Climate mitigation via energy systems; D. Transport and mobility; E. Industrial Decarbonization.
Note: All graphs depict funding as a stacked area chart, useful for showing part-to-whole relationships and how each category contributes to the cumulative total. Colors always correspond with the legend from top to bottom. Panels A (climate adaptation), B (geoengineering) and E (industrial decarbonization) show only more recent date ranges to reflect the most sufficient data. Funding trends post 2020 do not reflect any de facto decline in funding, just the anticipated end of projects funded up until 2020. Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

councils across 17 countries and the 28 member states (at the time of our data coverage) within the European Commission. A smaller sample of 1000 projects had budgets totaling $2.268 billion, with projects awarded funded up until 2026.

Granted, due to limitations in space and resources, we are unable to fully explore the potential of our dataset. Future research could for example correlate or aggregate our findings and data with secondary data funding disbursements but also other metrics such as greenhouse gas emissions or gross domestic product. This would enable researchers to explore whether democratic or authoritarian political systems are correlated with greater or fewer funding, for instance; or whether large emitters fund more energy and climate mitigation research, or if countries facing greater climate risks fund adaptation research. Future work could also examine more deeply thematic priorities among specific countries. This work could reveal how country characteristics shape, and are shaped by, the relative size and scope of energy and climate funding, and vice versa. It is with these goals and future research avenues in mind that we are willing to share our full dataset with future researchers or practitioners (by request).

Nevertheless, there are substantial problems with existing publicly available data, including an inaccuracy of data on published websites or inadequate tracking and updating of project details. More than half of

*C. Climate mitigation via energy systems*




*D. Transport and mobility*

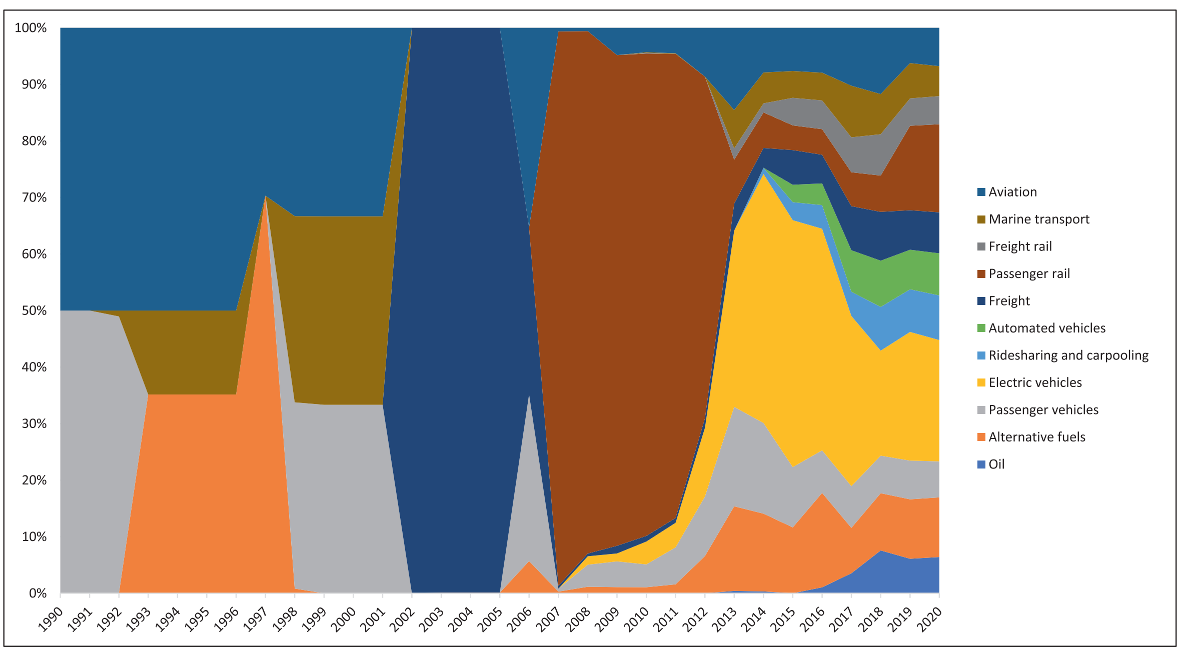



**Fig. 2.** (*continued*).

the initial projects we scoped had information sufficient to describe the project or its Principal Investigators; and then another 45% of projects posted information that was incorrect (it did not match the project, or more commonly listed contact details were out of date). Dozens of contacted PIs could not even recall their projects. Granted, PIs themselves are not entirely to blame here; some may have dozens and dozens of projects over their career, making it hard to remember. Others may have changed affiliations or left projects early. Still others may be struggling with age and health and memory problems.

Regardless of the causes, however, the limitations in existing data strongly supports the creation of some sort of single, harmonized dataset on public projects that can be vetted and checked for quality and accuracy. In support of this aim, research councils could at a minimum ensure that adequate information exists about projects online, and mandate PIs to update their details if they leave their position or change their points of contact. This will help to shift the burden of responsibility in data accuracy and transparency from PIs to research councils and data managers.

In highly competitive research environments, researchers may treat their data as proprietary and confidential, leading to further reasons not to share results. These practices against openness and transparency could be mitigated by adherence to emerging norms about open science—and the active and open sharing of data—as well as requirements from funders that researchers place data obtained from funded projects into a publicly available archive of some type. Moreover, in some cultures, political sensitivities mean researchers or funders avoid the use of words climate change or global warming. There is no way for us to overcome this limitation, although we hope it was limited in time and scope (i.e., the Trump Administration in the United States).

Although we were keen to explore the role of social science projects (representing about 27% of our smaller sample), research on energy and climate change is supported by a surprisingly broad base of other

*E. Industrial Decarbonization*

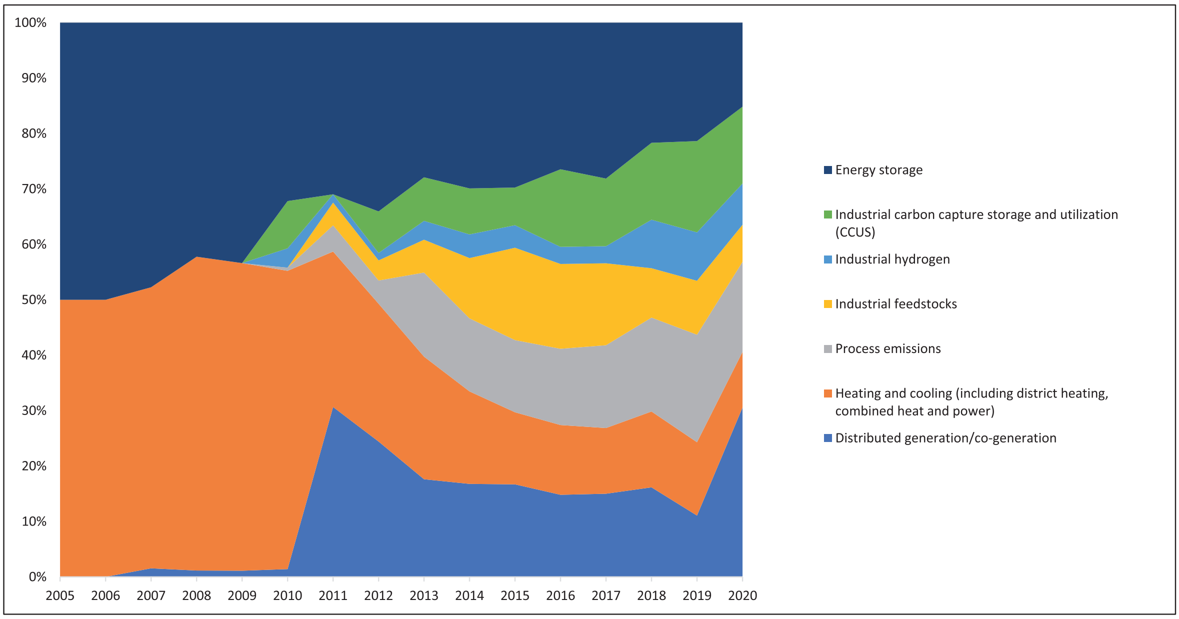



**Fig. 2.** (*continued*).

**Table 9**
Top five disciplines funded for energy and climate research by general area, 1990 to 2020 ($N = 65$).

| General area | Most funded disciplines | Total funding amount (US $2020) | Percentage of total funding for general area |
|---|---|---|---|
| Arts and humanities | Communication Studies | 98,849,538 | 27.9% |
| | Architecture | 68,370,058 | 19.3% |
| | Area Studies | 52,637,662 | 14.9% |
| | Art and Design | 34,834,133 | 9.8% |
| | Archaeology | 29,802,091 | 8.4% |
| Social sciences and economics | Energy Studies | 200,783,258 | 23.7% |
| | Economics and Econometrics | 153,694,651 | 18.1% |
| | Behavioral sciences and social psychology | 142,838,725 | 16.9% |
| | Development Studies | 103,280,248 | 12.2% |
| | Accounting and Finance | 60,871,362 | 7.2% |
| Engineering and technology | Computer Sciences | 360,731,433 | 42.4% |
| | Chemical Engineering | 177,663,399 | 20.9% |
| | Mechanical, Aeronautical and Manufacturing Engineering | 130,500,697 | 15.3% |
| | Data Sciences | 55,198,664 | 6.5% |
| | Mineral and Mining Engineering | 29,315,067 | 3.4% |
| Life sciences and medicine | Biological Sciences | 24,221,820 | 30.0% |
| | Agriculture | 16,469,663 | 20.4% |
| | Health Sciences | 16,397,455 | 20.3% |
| | Medicine and Medical Sciences | 4,824,844 | 6.0% |
| | Pharmacology | 2,447,420 | 3.0% |
| Natural and physical sciences | Earth Sciences | 40,851,328 | 31.9% |
| | Metallurgy and Materials | 30,061,158 | 23.4% |
| | Chemistry | 19,410,621 | 15.1% |
| | Environmental Sciences and Ecology | 18,422,831 | 14.4% |
| | Astronomy and Cosmology | 5,285,487 | 4.1% |

Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

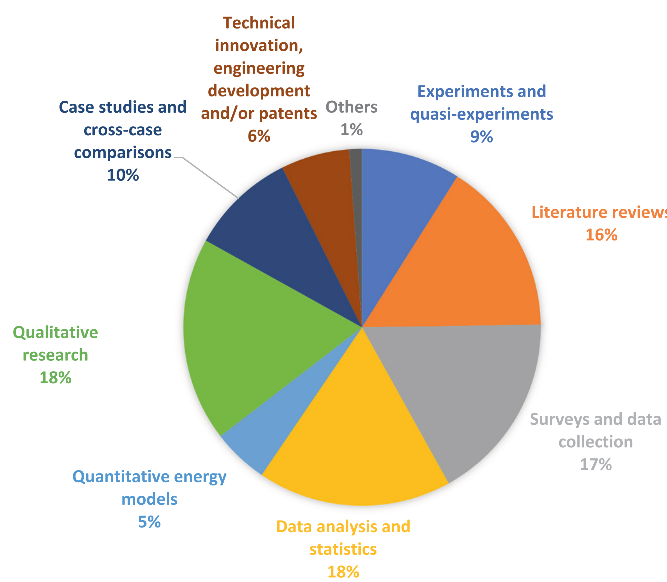



**Fig. 3.** Research designs reported by project principal investigators for sampled energy and climate change projects, 1990 to 2020 ($N = 1000$).
Note: Funding patterns are from a sample of only 1000 projects and will not match total funding patterns from all research councils examined.
Source: Authors.

disciplines and approaches. This includes research from the arts and humanities (18% of projects by funding), engineering and technology (28% by funding), life sciences and medicine (11% by funding), and the natural and physical sciences (16% by funding). This diversification of disciplines supported underscores the multidisciplinary aspect of energy and climate funding, and resulting research trends. It also shows that social sciences research, contrary to earlier findings in the literature, are no longer marginalized, coming second (and still very close) to the amounts of funding awarded to engineering and technology, and ahead of all other general disciplinary areas covered in this study. This surge in relative funding for the social sciences and humanities could reflect greater recognition among funders to the value of social science as a whole, and it may also reveal a growing appreciation that energy and climate problems will not be remediated or successfully "solved" by technology alone.

Despite this diversity and appreciation for non-technical disciplines and approaches, it is possible to identify clusters of funding. Climate change adaptation research is still the most funded (36.2% of projects), followed by energy systems (27.7%) and transportation and mobility (13.1%). Far less funding was spent on geo/climate engineering (11.7%) or industrial decarbonization (11.4%). Furthermore, funding has been allocated unevenly in favor of some specific technologies. In the domain of climate adaptation, the topics of resilience and adaptive capacity and climate information systems account for one-quarter of all projects—but glacial flood control or coastal afforestation techniques are hardly studied (less than 1% each). In the domain of geo/climate engineering, carbon dioxide removal and BECCS account for about one-third of all projects, whereas space sunshades or cloud thinning are neglected (less than 1% each). Energy efficiency alone accounts for more than one-quarter of all projects in the general area of energy systems, followed by energy storage, but geothermal energy, fusion, and nuclear fission are rarely studied (each less than 2%). Transport and mobility research is dominated by electric vehicles, biofuel, and passenger vehicles (more than one-third of projects involved at least one of these). But rail is far less common (less than 3%). Industrial decarbonization techniques such as energy storage, process emissions, or heating and cooling are very common foci (almost *half* of all projects in this area examined them), yet industrial hydrogen or carbon capture and storage funding is almost absent (less than 3%).

Additionally, the research supported benefits a particular set of disciplines. Within the arts and humanities, communication studies and architecture receive the lion's share of funding. Within the social sciences, it is energy social science, economics, and behavioral science. Within engineering and technology, computer science and chemical engineering. Within life sciences and medicine, it is biology and agriculture. Within the natural sciences, it is earth sciences and materials science.

Moreover, the funded projects sponsor a striking diversity of methods. Support is distributed across projects utilizing literature reviews, surveys and original data collection, the development of intellectual property, case studies, qualitative research and energy modeling (to name a few). The collective research community seems to prioritize and value intellectual, theoretical, methodological, and empirical diversity—a promising virtue to guide its future research efforts.

## 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.

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## Appendix A. Annex I: full list of 154 research councils searched over 17 countries

1. Australia Australian Nuclear Science and Technology Organisation
2. Australia Australian Research Council (ARC)
3. Australia Cancer Australia (CA)
4. Australia Fisheries Research and Development Corporation (FRDC)
5. Australia National and Medical Research Council (NHMRC)
6. Brazil National Council for Scientific and Technological Development (CNPq)
7. Brazil São Paulo Research Foundation (FAPESP)
8. Canada Institutes of Health Research (CIHR)
9. Canada Foundation for Innovation (CFI)
10. Canada Alberta Innovates (AIHS)
11. Canada Fonds de Recherche du Québec – Nature et technologies (FRQNT)
12. Canada Fonds de Recherche du Québec – Santé (FRQS)
13. Canada Fonds de Recherche du Québec – Société et culture (FRQSC)
14. Canada Foundation for Innovation (CFI)
15. Canada Institutes of Health Research (CIHR)
16. Canada Ministry of Research, Innovation and Science (MRIS)
17. Canada Natural Sciences and Engineering Research Council (NSERC)
18. Canada Natural Sciences and Engineering Research Council of Canada (NSERC)
19. Canada Research Manitoba (MHRC)
20. Canada Social Sciences and Humanities Research Council of Canada (SSHRC)
21. Canada Social Sciences and Humanities Research Council (SSHRC)
22. Canada Sustainable Development Technology Canada (SDTC)
23. China Chinese Academy of Agricultural Sciences (CAAS)
24. China Chinese Academy of Medical Sciences
25. China Fundamental Research Funds for the Central Universities
26. China Joint Research Fund for Overseas Chinese Scholars and Scholars in Hong Kong and Macao
27. China National Key R&D Programme (NKP)
28. China National Natural Science Foundation of China (NSFC)
29. China National Social Science Foundation of China (NSSFC)
30. China Peking Union Medical College (PUMC)
31. China Scholarship Council
32. China University Grants Committee (UGC)

33. China Zhejiang Provincial Natural Science Foundation (ZJNSF)
34. European Commission ERC
35. European Commission FP3
36. European Commission FP4
37. European Commission FP5
38. European Commission FP6
39. European Commission FP7
40. European Commission Horizon 2020
41. European Commission ICT
42. European Commission Intelligent Energy Programmes
43. European Commission LIFE
44. European Commission Marie Curie
45. India Defence Research & Development Organisation (DRDO)
46. India Department of Biotechnology (DBT)
47. India Department of Ocean Development (DOD)
48. India Department of Science and Technology (DST)
49. India Indian Council of Agricultural Research (ICAR)
50. India Indian Council of Medical Research (ICMR)
51. India Indian Council of Social Science Research (ICSSR)
52. India Indian Space Research Organisation (ISRO)
53. India National Board for Higher Mathematics (NBHM)
54. India Naval Research Board (NRB)
55. India Science and Engineering Research Board (SERB)
56. India Technology Information, Forecasting and Assessment Council (TIFAC)
57. Israel Israel Science Foundation (ISF)
58. Israel United States-Israel Binational Science Foundation (BSF)
59. Japan German Centre for Research and Innovation Tokyo (DWIH Tokyo)
60. Japan Japan Aerospace Exploration Agency (JAXA)
61. Japan Japan Science and Technology Agency (JST)
62. Japan Japan Society for the Promotion of Science (JSPS)
63. Japan National Institute for Materials Science (NIMS)
64. Japan National Institute of Advanced Industrial Science and Technology (AIST)
65. Morocco ISESCO Centre for Promotion of Scientific Research (ICPSR)
66. New Zealand Auckland Medical Research Foundation (AMRF)
67. New Zealand Engineering and Physical Sciences Research Council
68. New Zealand Health Research Council of New Zealand (HRC)
69. New Zealand Marsden Fund
70. New Zealand Ministry of Business, Innovation and Employment (MBIE)
71. New Zealand Royal Society of New Zealand (RSNZ)
72. Norway NordForsk (NordForsk)
73. Norway The Research Council of Norway (RCN)
74. Qatar National Research Fund
75. Qatar Qatar Foundation (QF)
76. Rwanda National Commission for Science and Technology (NCST)
77. South Africa National Research Foundation (NRF)
78. Switzerland Commission for Research Partnerships with Developing Countries (KRPE)
79. Switzerland Human Frontier Science Program (HFSP)
80. Switzerland Innosuisse - Swess Innovation Agency
81. Switzerland Leenaards Foundation
82. Switzerland Persilized Health and Related Technology (PHRT)
83. Switzerland Swiss Cancer Research foundation
84. Switzerland Swiss National Science Foundation (SNSF)
85. United Kingdom Arts and Humanities Research Council (AHRC)
86. United Kingdom Biotechnology and Biological Sciences Research Council (BBSRC)
87. United Kingdom British Academy (BA)
88. United Kingdom Department for Environment Food and Rural Affairs (DEFRA)
89. United Kingdom Economic and Social Research Council (ESRC)
90. United Kingdom Engineering and Physical Sciences Research Council (EPSRC)
91. United Kingdom Innovate UK (Innovate UK)
92. United Kingdom Medical Research Council (MRC)
93. United Kingdom Natural Environment Research Council (NERC)
94. United Kingdom Science and Technology Facilities Council (STFC)
95. United States Advanced Research Projects Agency-Energy (ARPA-E)
96. United States Air Force (USAF)
97. United States Army (USA)
98. United States Army Corps of Engineers (CoE)

99. United States Biological and Environmental Research (BER)
100. United States Canada-California Strategic Innovation Partnership (CCSIP)
101. United States Center for Information Technology (CIT)
102. United States Centers for Disease Control and Prevention (CDC)
103. United States Council for International Exchange of Scholars (CIES)
104. United States Defense Advanced Research Projects Agency (DARPA)
105. United States Defense Health Program
106. United States Defense Logistics Agency (DLA)
107. United States Defense Microelectronics Activity
108. United States Defense Threat Reduction Agency (DTRA)
109. United States Department of Agriculture
110. United States Department of Commerce
111. United States Department of Defense (DOD)
112. United States Department of Education (DoED)
113. United States Department of Energy (DOE)
114. United States Department of Health and Human Services (HHS)
115. United States Department of Homeland Security (DHS)
116. United States Department of Interior
117. United States Department of the Air Force (DAF)
118. United States Department of the Army (DA)
119. United States Department of the Interior (DOI)
120. United States Department of the Navy (DON)
121. United States Department of Transportation (USDOT)
122. United States Department of Veterans Affairs (DVA)
123. United States Domestic Nuclear Detection Office
124. United States Environmental Protection Agency (EPA)
125. United States Food and Drug Administration (USFDA)
126. United States Forest Service (USFS)
127. United States Geological Survey (USGS)
128. United States Institute of Education Sciences (IES)
129. United States Marine Corps (USMC)
130. United States Missile Defense Agency (MDA)
131. United States National Aeronautics and Space Administration (NASA)
132. United States National Cancer Institute (NCI)
133. United States National Center for Advancing Translational Sciences (NCATS)
134. United States National Endowment for the Humanities (NEH)
135. United States National Energy Technology Laboratory (NETL)
136. United States National Geospatial-Intelligence Agency (NIMA)
137. United States National Institute of Environmental Health Sciences (NIEHS)
138. United States National Institute of Food and Agriculture (NIFA)
139. United States National Institute of General Medical Sciences (NIGMS)
140. United States National Institute of Justice (NIJ)
141. United States National Institute of Standards and Technology
142. United States National Institutes of Health (NIH)
143. United States National Library of Medicine (NLM)
144. United States National Oceanic and Atmospheric Administration (NOAA)
145. United States National Science Board (NSF NSB)
146. United States National Science Foundation (NSF)*
147. United States National Security Agency (NSA)
148. United States Nuclear Regulatory Commission (NRC)
149. United States Office for Chemical and Biological Defense
150. United States Office of Information and Resource Management (NSF OIRM)
151. United States Office of Nuclear Energy (NE)
152. United States Office of Science (DOE SC)
153. United States Office of the Secretary of Defense (OSD)
154. United States Special Operations Command

*Note Under NSF, we have grouped together the separate categories of:

- United States National Science Foundation Office of the Director (NSF OD)
- United States National Science Foundation Directorate for Biological Sciences (NSF BIO)
- United States National Science Foundation Directorate for Computer & Information Science & Engineering (NSF CISE)
- United States National Science Foundation Directorate for Education & Human Resources (NSF GOVERNMENT)
- United States National Science Foundation Directorate for Engineering (NSF ENG) United States Directorate for Geosciences (NSF GEO)
- United States Directorate for Mathematical & Physical Sciences (NSF MPS)
- United States Directorate for Social, Behavioral & Economic Sciences (NSF SBE)

## Appendix B. Annex II: core climate change areas, technologies examined in our assessment

### Conceptualization of Areas and Technologies

| Area | Technology |
|---|---|
| A. 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 |
| | 8. Mangrove regeneration and plantation management |
| | 9. Deployment of coastal sediment barriers to reduce climate-vulnerabilities |
| | 10. Glacial flood control |
| | 11. Early warning systems |
| | 12. Hurricanes and tsunamis |
| | 13. Earthquakes |
| | 14. Coastal protection |
| | 15. Climate information system |
| | 16. Climate-resilient irrigation design |
| B. Geo/climate engineering | 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 Fertilization |
| | 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 |
| C. Energy systems | 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 |
| D. Transportation and mobility | 49. Petroleum fuels (oil, gasoline, diesel, petrol) |
| | 50. Alternative fuels (biofuel, synfuel, ethanol, biodiesel, hydrogen fuel cells) |
| | 51. Passenger vehicles (internal combustion engines, scooters, motorbikes) |
| | 52. Electric vehicles (including PHEVs, BEVs, e-bikes and scooters) |
| | 53. Ridesharing and carpooling |
| | 54. Automated vehicles |
| | 55. Freight (heavy duty vehicles, commercial vehicles, and trucks) |
| | 56. Passenger rail (including metros and trams) |
| | 57. Freight rail (including diesel and electrical) |
| | 58. Marine shipping and transport (including ferries, barges, and container ships and tankers) |
| | 59. Aviation and aircraft |
| E. Industrial decarbonization | 60. Distributed generation/co-generation |
| | 61. Heating and cooling (including district heating, combined heat and power) |
| | 62. Process emissions |
| | 63. Industrial feedstocks |
| | 64. Industrial hydrogen |
| | 65. Industrial carbon capture storage and utilization (CCUS) |
| | 66. Energy storage |

## Appendix C. Annex III: core disciplines considered in our assessment

### Conceptualization of Academic Disciplines

| General area | Discipline |
|---|---|
| Arts and humanities | Archaeology |
| | American Studies |
| | Architecture |
| | Area Studies |
| | Art and Design |
| | Classics |
| | Communication Studies |
| | Dance and Performing Arts |
| | Divinity and Religious Studies |
| | English and Literature |
| | History |
| | Language and Linguistics |
| | Music |
| | Philosophy |
| | Theology |
| Social sciences and economics | Accounting and Finance |
| | Anthropology |
| | Behavioral sciences and social psychology |
| | Business and Management Studies, |
| | Cultural and Media Studies |
| | Development Studies |
| | Economics and Econometrics |
| | Education Studies |
| | Energy Studies |
| | Geography, Regional Studies, and Urban Studies |
| | Law and Legal Studies |
| | Library and Information Management |
| | Politics and International Studies |
| | Public Policy and Administration |
| | Sociology |
| | Social Work |
| | Sports Studies, |
| | Town and Country Planning |
| Engineering and technology | Chemical Engineering |
| | Civil engineering |
| | Computer Sciences |
| | Data Sciences |
| | Electrical and Electronic Engineering |
| | General Engineering |
| | Mechanical, Aeronautical and Manufacturing Engineering |
| | Mineral and Mining Engineering |
| | Nanotechnology |
| Life sciences and medicine | Agriculture |
| | Biological Sciences |
| | Clinical Psychology |
| | Dentistry |
| | Food Science & Technology |
| | Health Sciences |
| | Medicine and Medical Sciences |
| | Neuroscience |
| | Nursing |
| | Pharmacology |
| | Psychiatry |
| | Public Health |
| | Veterinary Science |
| Natural and physical sciences | Applied Mathematics |
| | Astronomy and Cosmology |
| | Chemistry |
| | Earth Sciences |
| | Environmental Sciences and Ecology |
| | Geology |
| | Metallurgy and Materials |
| | Physics |
| | Pure Mathematics |

## Appendix D. Annex IV: research questionnaire sent to project Principal Investigators

**Research Project**
**Global public research funding on climate, energy, and transport**
**University of Sussex**
**January 2021**

1. What is your unique participant number (this is at the top of your email)
2. What is the name of your funded project, center, or network?
3. What is the host institution or institutions?
4. What year did it start?
5. What year did or will it end?
6. What was its total budget? (please specify currency and year also)
7. What countries were directly funded by the project (list all that apply)?
8. What research council(s), or institution(s), funded the project (list all that apply)?
9. Generally, which general areas or disciplines were funded and supported by the project (select all that apply—for ease of reference you can just bold or highlight them)?

| General area | Discipline |
|---|---|
| Arts and humanities | Archaeology |
| | American Studies |
| | Architecture |
| | Area Studies |
| | Art and Design |
| | Classics |
| | Communication Studies |
| | Dance and Performing Arts |
| | Divinity and Religious Studies |
| | English and Literature |
| | History |
| | Language and Linguistics |
| | Music |
| | Philosophy |
| | Theology |
| Social sciences and economics | Accounting and Finance |
| | Anthropology |
| | Behavioral sciences and social psychology |
| | Business and Management Studies, |
| | Cultural and Media Studies |
| | Development Studies |
| | Economics and Econometrics |
| | Education Studies |
| | Energy Studies |
| | Geography, Regional Studies, and Urban Studies |
| | Law and Legal Studies |
| | Library and Information Management |
| | Politics and International Studies |
| | Public Policy and Administration |
| | Sociology |
| | Social Work |
| | Sports Studies, |
| | Town and Country Planning |
| Engineering and technology | Chemical Engineering |
| | Civil engineering |
| | Computer Sciences |
| | Data Sciences |
| | Electrical and Electronic Engineering |
| | General Engineering |
| | Mechanical, Aeronautical and Manufacturing Engineering |
| | Mineral and Mining Engineering |
| | Nanotechnology |
| Life sciences and medicine | Agriculture |
| | Biological Sciences |
| | Clinical Psychology |
| | Dentistry |
| | Food Science & Technology |
| | Health Sciences |
| | Medicine and Medical Sciences |
| | Neuroscience |
| | Nursing |
| | Pharmacology |
| | Psychiatry |
| | Public Health |
| | Veterinary Science |

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| | |
|---|---|
| Natural and physical sciences | Applied Mathematics<br>Astronomy and Cosmology<br>Chemistry<br>Earth Sciences<br>Environmental Sciences and Ecology<br>Geology<br>Metallurgy and Materials<br>Physics<br>Pure Mathematics |

10. Generally, which topical area and technologies were funded and supported by the project (select all that apply—for ease of reference you can just bold or highlight them)?

| Area | Technology |
|---|---|
| Climate change adaptation | Adaptation and adaptive capacity<br>Researching drought resistant crops<br>Coastal afforestation<br>Drought<br>Erosion prevention<br>Managing climate risks<br>Economic resilience<br>Mangrove regeneration and plantation management<br>Deployment of coastal sediment barriers to reduce climate-vulnerabilities<br>Glacial flood control<br>Early warning systems<br>Hurricanes and tsunamis<br>Earthquakes<br>Coastal protection<br>Climate information systems<br>Climate-resilient irrigation design |
| Geo/climate engineering | Carbon dioxide removal<br>Bio-energy with carbon capture and sequestration (BECCS)<br>Direct air capture with carbon capture and storage (DACCS)<br>Enhanced Weathering<br>Ocean Alkalinity Enhancement<br>Ocean Fertilisation<br>Afforestation<br>Biochar<br>Solar radiation management<br>Aerosol injection<br>Marine cloud brightening<br>High-albedo crops and buildings<br>Ocean mirrors<br>Cloud thinning<br>Space sunshades |
| Energy systems | Biofuels (generally in the form of biodiesel and ethanol)<br>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)<br>Coal (including coke, coal-to-liquids, and clean coal)<br>Energy efficiency, demand response, load management, demand side management<br>Energy storage, distributed storage and batteries<br>Fusion energy<br>Geothermal energy (including heat pumps)<br>Heating and cooling (including district heating, combined heat and power)<br>Hydroelectricity<br>Hydrogen (generally meant to encompass fuel cells using renewable fuels and at times natural gas)<br>Natural gas (including conventional and unconventional gas as well as liquefied natural gas and shale gas)<br>Nuclear power plants<br>Oil and LPG (including conventional and unconventional resources as well as refined gasoline and diesel)<br>Solar energy (including solar PV as well as solar thermal or Concentrated Solar Power)<br>Wind energy (including onshore and offshore turbines)<br>Electricity Transmission & Distribution<br>Pipelines |
| Transportation and mobility | Petroleum fuels (oil, gasoline, diesel, petrol)<br>Alternative fuels (biofuel, synfuel, ethanol, biodiesel, hydrogen fuel cells)<br>Passenger vehicles (internal combustion engines, scooters, motorbikes)<br>Electric vehicles (including PHEVs, BEVs, e-bikes and scooters)<br>Ridesharing and carpooling<br>Automated vehicles<br>Freight (heavy duty vehicles, commercial vehicles, and trucks)<br>Passenger rail (including metros and trams)<br>Freight rail (including diesel and electrical) |

(*continued on next page*)

(*continued*)

| | |
|---|---|
| | Marine shipping and transport (including ferries, barges, and container ships and tankers) |
| | Aviation and aircraft |
| Industrial decarbonisation | Distributed generation/co-generation |
| | Heating and cooling (including district heating, combined heat and power) |
| | Process emissions |
| | Industrial feedstocks |
| | Industrial hydrogen |
| | Industrial carbon capture storage and utilization (CCUS) |
| | Energy storage |

11. Generally, which of the following research methods or designs were supported by the project (select all that apply)?

a. Experiments and quasi-experiments
b. Literature reviews
c. Surveys and data collection
d. Data analysis and statistics
e. Quantitative energy models
f. Qualitative research
g. Case studies and cross-case comparisons
h. Technical innovation, engineering development and/or patents

12. Is there a transdisciplinary element to your project or centre, defined roughly as the involvement of non-academic or other broad stakeholders (yes/no)?

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