Getting to the bottom of research funding.

Acknowledging the complexity of funding dynamics

Kaare Aagaard^{1, 2}, Philippe Mongeon¹, Irene Ramos-Vielba¹, Duncan A. Thomas¹

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Abstract

Research funding is an important factor for public science. Funding can affect which research topics get addressed, and what research outputs are produced. However, funding has often been studied simplistically, using top-down or system-led perspectives. These can restrict analysis to national funding landscapes or single funding organisations and instruments in isolation. This overlooks interlinkages and potentially broader funding that researchers might access. We instead frame an alternative ‘bottom-up’ approach, using individual researchers as the entry point. For two test research fields (food science, renewable energy research) we analyse articles published 2009–18 as an example funded research activity. Here we trace researcher funding via article funding acknowledgements (FAs) of researchers affiliated to Denmark, the Netherlands or Norway. We then map field-level ‘co-funding networks’. These turn out to include heterogeneous funding from inside, outside and across these test countries. We further study article-level ‘funding amalgamations’ – the sum of all authors’ reported funding per article. These similarly show highly varied (co-)funding by funder ‘type’ (public, private, university or non-profit) and ‘origin’ (domestic, foreign or supranational). We note this approach has certain limitations but suggest it does advance our understanding of research funding dynamics. It provides an additional perspective, and appears adaptable to further analyses (e.g. of potential influences of co-funding). We lastly suggest several implications for science policy stemming from this bottom-up approach.

¹ Department of Political Science, Danish Centre for Studies in Research and Research Policy, Aarhus University, Aarhus, Denmark.

² Corresponding author: ka@ps.au.dk

Introduction

Ways and means to allocate research funding are considered one of the most influential elements in any attempts to govern contemporary public science. Funding is assumed to affect which topics get addressed, and the scope, content, direction, outputs and even potential impacts of public research (e.g. Edqvist, 2003; Heinze, 2008; Sörlin, 2007; Aagaard, 2017). Funding secures the livelihood of researchers so is an indispensable prerequisite for almost all research (Gläser and Serrano Velarde, 2018). Yet our knowledge of how funding affects research remains fragmented and inconclusive. This stems in part from how research funding has been studied. In this paper we develop and test an approach that attempts to broaden how such studies are framed, aimed at improving understanding of research funding dynamics.

Limitations of existing research funding studies we believe stem from insufficient attention to growing heterogeneity, complexity and related trends in contemporary research funding (Gläser and Serrano Velarde, 2018; Lepori and Reale, 2019). There have been few attempts to acknowledge and identify the wide variety of potentially interlinked sets of funders now operating in scientific fields. Similarly, there has been insufficient exploration of the characteristics of the assorted funding instruments researchers may now use and combine to do research. Instead, most literature has typically studied single funding instruments and single funding organizations (see e.g. Franssen, Scholten, Hessels, and de Rijcke, 2018; Heinze, 2008) or has analysed strictly-confined national funding landscapes from a top-down/system-led perspective (Auranen and Nieminen, 2010; Lepori, 2006; Reale, 2017; Aagaard, 2017). However, the underlying assumptions justifying these approaches may no longer be adequate, and impede deeper understanding of how researchers' research funding may be composed and influence research (Wagner, 2019).

Existing approaches are particularly challenged by (claims of) increasing developments towards more complicated, border-crossing funding landscapes, where regional, national and supranational funders have proliferated from public, private and non-profit sectors (Gläser and Serrano Velarde, 2018; Lepori, 2011; Sörlin, 2007; Wagner, 2019). Despite recent calls for studies of this emerging research funding reality (Cocos and Lepori, 2020; Gläser and Serrano Velarde, 2018) most scholarly claims remain

based on general observations rather than on systematic, empirical studies (Gläser, 2019). An accurate understanding of how funding works is however a precondition, we believe, for more realistic study of potential effects upon research of different kinds and combinations of funding. Improved understanding here we expect might also improve research governance, could reveal unsuspected funding synergies or discourage use of problematic research funding designs.

Behind these dynamics is the notion that research funding can also embody signals about needs that government(s), their agencies, industries and societies expect funded research to address (Veletanlić and Sá, 2020). An indicative example is research funded to address Grand Societal Challenges (SCs). For instance in Europe, dedicated SC-related funding is expected to support research aiming to address pressing global problems (e.g. food security, energy security, public health, impacts of a changing climate). Policy or funder attempts to (re)direct such research to address these challenges however is mediated by what research funding researchers actually mobilise and combine to do their research. This may include more than one funding source, potentially leading researchers to face multiple (different) signals from multiple funders.

The funding individual researchers encounter is a crucial element. This is because researchers here are an acknowledged obligatory passage point between research funding and research (Laudel and Gläser, 2014). Approaches to study research funding therefore must explore the roles of funding from their viewpoint, i.e. from researchers' perspective rather than just from top-down/system-led lenses. For this reason, our approach takes this researcher-led perspective. We describe this as adopting a 'bottom-up approach', entering the science system at the grassroots level of individual researchers and their funding, followed by increasing levels of aggregation. We further connect this perspective with relevant funding dynamics by testing it, initially, with two suitable SC-related fields where we know multiple funders operate, and likely provide varied kinds of funding – i.e. 'Food Science' and 'Renewable Energy Research'.

Given their high availability, we study funding acknowledgements (FAs) reported in researchers' articles to provide test funding data. To restrict ourselves to a manageable scale for a test, we explore funding of researchers affiliated to research organisations (ROs) in three particular test countries (i.e.

Denmark, Norway, the Netherlands). This gives us variety but not excessively so, as these are small, somewhat similar yet still intensive research funding countries.

Our aims for this paper then are first to frame a bottom-up, researcher-led perspective on research funding dynamics. Second, we use FAs to test an analysis of research funding from this perspective. These aims relate to a key assumption we wish to test, which is whether high levels of varied co-funding dynamics become visible when studied from a bottom-up, researcher-led perspective. Specifically, we test this assumption in our selected fields and countries using two analytical levels that we will define:

- Research field ‘co-funding networks’, where we expect to be able to explore prevalence of ‘type’ (public funders, private companies, non-profit foundations and universities) and ‘origin’ (domestic, foreign and supranational funders) characteristics from our coding of FAs.
- Article level ‘funding amalgamations’, where we anticipate being able to reveal ‘type’ and ‘origin’ based co-funding dynamics.

We therefore structure our paper as follows: the next section justifies why we believe adding a bottom-up perspective is needed and might improve understanding of research funding dynamics. This is followed by a section presenting our approach then a section to explore strengths and weaknesses of previous FA-based studies, as a background for our specific analysis. The subsequent section describes our test case selection, research field delineations, data collection, cleaning and coding. Our test findings are then presented, exploring field co-funding networks, and article funding amalgamations. Finally, we reflect on what we believe this bottom-up/researcher-led approach contributes to understanding of research funding dynamics, and conclude with several implications for science policy and further research directions.

Why add a bottom-up perspective on research funding?

To understand the value of adding the bottom-up perspective, we note that most previous approaches to research funding studies have relied on a top-down/system-led approach. This means that

to observe funding dynamics at different levels of aggregation, studies have started from features of national or otherwise geographically confined funding landscapes (e.g. Auranen and Nieminen, 2010; Lepori, 2006; Öquist and Benner, 2015; Aagaard and Schneider, 2016). Alternatively they have examined effects of single funding organizations or single funding instruments within the science system, attempting to isolate effects for just one single funding source (e.g. Reale, 2017).

There are sound, pragmatic, methodological and conceptual reasons for this situation. Clear delineations and boundaries for funders' assumed spheres of operation and influence, drawn from the top-down, isolate effects of specific funding organizations or instruments from many extraneous factors. They also likely service the interests of funders aiming to document effects of their own specific investments. Likewise, a national focus may align with vested interests of national policy makers and stakeholders (Wagner, 2019) to legitimise use of public resources.

These positions have also generated important insights. Top-down approaches – typically based on data from OECD Main Science and Technology Indicators (MSTI), Eurostat, national statistics or comprehensive cross-country studies – have provided broad overviews of central components of national funding systems. These enable comparative insights into important characteristics at country level, such as volume of R&D funding, balances between institutional funding and project funding, distribution of funding between disciplines, and allocation mechanisms for institutional funding (e.g. Lepori, 2006; Aagaard, 2011, 2017). Studies of individual funders and single funding instruments have provided insight into key characteristics and mechanisms, like how selection procedures in funding instruments might enable support of exceptional research (e.g. Heinze, 2008; Luukkonen, 2012) or how funding properties, and properties of the research funded, can become integrated for specific funding instruments (e.g. Franssen et al., 2018; Lal et al., 2011; Wagner and Alexander, 2013).

Both positions however also have limitations. Most importantly they are based on two key assumptions that may have become increasingly questionable over time. First, they assume national funding landscapes mapped and studied from the top down provide a relatively complete picture of funding mobilised by researchers working within a given national system. Second, they assume individual funders and funding sources in most cases operate in isolation – and hence can and should be studied as

such. These assumptions may once have been appropriate, but they are now challenged by multiple, interrelated developments in science and science policy.

First, funding has shifted from internal/institutional to external/project-based in most countries (Bourke and Butler, 1999; Geuna and Martin, 2003; Heinze, 2008; Langfeldt, 2001; Laudel, 2006). Second, research policy scope has broadened to direct funding towards more diverse goals, e.g. promoting 'excellence' in science, providing solutions to economic and social problems, and fostering technology and innovation (Lepori and Reale, 2019). Project funding instruments and funders have thus multiplied and become increasingly differentiated (Lepori, 2006). In addition, public knowledge production has become more integrated into society, creating an 'extended peer community' (Nowotny, Scott, and Gibbons, 2001; Ravetz, 1999) where non-governmental actors are increasingly involved as funders, collaborators or stakeholders. Thirdly, increased globalization of science has made international research collaboration far more widespread (Wagner, 2019), increasing the importance of non-national funding used in international collaborations. This includes different types of EU allocations, funding from public, non-profit and private sources, and funding from other countries either directly or indirectly (i.e. through collaboration with international colleagues). All three challenges are potentially in play at once. Consequently science organization ever more does not follow national borders, and instead features trans-national, trans-sectoral, multi-/inter-/trans-disciplinary academic communities or fields, and is characterised by pervasive boundary-crossing (Klein, 1996; Wagner, 2019).

Contemporary research is therefore likely to rely on multiple, increasingly heterogeneous funding. Blends of funding instruments mobilised from the bottom up will reflect this development towards increasingly multi-level, multi-actor governance systems, differing substantially from traditional perceptions of research funding driven by national, public authorities (Gläser and Serrano Velarde, 2018; Lepori and Reale, 2019; Sörlin, 2007). Studying funding dynamics therefore must now address not only how national funding systems are designed from the top down, but also how funding is mobilised and combined by researchers from the bottom up.

While these challenges are increasingly acknowledged, the majority of literature has so far largely overlooked the implications of these trends. However, recent studies have begun to call for a 'reality

check' (see e.g. Cocos and Lepori, 2020; Gläser and Serrano Velarde, 2018; Lepori, 2011; OECD, 2018). It is being recognised that changed research funding dynamics require new approaches and the limitations of traditional approaches are increasingly being highlighted (Cocos and Lepori, 2020; Lepori, 2011; Lepori and Reale, 2019). Instead it is being argued that research funding might be better treated as sets of interlinked spaces of interaction between different layers of funders and performers (Lepori, 2011). These spaces are recognised as not exogenously defined by legal or geographical distinctions, but should be empirically observed (Lepori, 2011). The increasing importance of charities, supranational funding agencies (Luukkonen, 2012; Nedeva, 2013), and the emergence of new funding schemes for science (Lepori et al., 2007) are also explicitly mentioned here. New approaches tailored to capture these more complex funding dynamics are therefore needed (Gläser and Serrano Velarde, 2018).

Most studies are further challenged by the analytical level adopted. The typical emphasis on aggregating at national level may mask important field differences within countries. There may be large differences across scientific fields in relation to say, the balance between institutional and project funding (Aagaard and Schneider, 2016). The roles of non-public or non-national funders may vary across fields associated with the same national system. In some fields public sources may dominate whereas private foundations, patient organisations, companies or other actors might in others. Field-specific funding organizations or funding instruments may be marginal for a national picture but nevertheless play substantial roles at lower levels of aggregation; similarly, the role of non-national funding may vary across fields.

National or international research-related statistics organisations are seldom able to capture the full extent of research fields to guide funding studies. Empirically-delineated research fields often will not correspond to the organizational or disciplinary categories that nation-oriented bodies use. Even statistical data at disaggregated levels, if originally framed by national levels, may introduce demarcation problems. Therefore as science organization and funding have become more complex over time; unsurprisingly the availability of appropriate statistics has struggled to keep pace (Lepori and Reale, 2019).

Overall, how science and policy have developed has increasingly challenged traditional top-down/system-led approaches to research funding studies. Coupled with field delineation and statistics

shortcomings, we find problematic assumptions about research funding. At the same time, we believe research funding literature has not yet fully embraced the implications of these changes. For us this justifies our exploration of a new perspective and complementary approach better suited to tackle current funding dynamics, to sit alongside the strengths more traditional approaches can provide (e.g. regularity, standardization).

Our bottom-up approach

We frame our approach as getting to the bottom of the science system at the grassroots level of individual researchers, and their funding, through two further levels of aggregation. This is first through delineation of a research field and its associated ‘co-funding network’. The second is through the ‘amalgamation’ of all or part of a researcher’s own funding with that of other researchers used to undertake collaborative research activities together (CRAs, e.g. co-authoring of research articles). At the bottom of the science system, we position individual researchers, who work at one or more research organisations (ROs) and each have some ‘configuration’ of research funding instruments. Here we consider a ‘funding instrument’ to be the lowest identifiable level, discrete resource unit provided by any funder (e.g. a grant not the broader programme or family of grants above it, and the funder could be internal or external). Table 1 shows the resulting shift in perspective and analysis of funding dynamics associated with these levels.

Table 1. Top-down and bottom-up approaches to research funding.

	Top-down	Bottom-up
Perspective	System-led, nationally-bounded	Researcher-led, boundary-spanning
Analysis of funding dynamics	National funding landscapes	Co-funding networks
	Single funding organisations	Funding amalgamations
	Single funding instruments	Funding configurations

We can also visualise this bottom-up approach (Fig 1). For the bottom level, we see individual researchers, associated with a research organisation (RO). Each researcher has their own specific funding, a particular set of assorted funding instruments (FIs), which at individual level we call a ‘funding configuration’ (i.e. level A in Fig 1). A researcher may then mobilise all or part of their funding configuration to do research – either alone or for a CRA, like co-authoring an article. In these CRAs, the (partial) funding configurations of each researcher can become mixed, producing a higher level of aggregation, i.e. ‘funding amalgamations’ (level B, Fig 1).

Fig 1. Schematic of our bottom-up approach to research funding.

CRA = collaborative research activity (e.g. a co-authored research output/publication); FI = funding instrument; RO = research organisation.

Aggregating all funding amalgamations across all chosen CRAs studied and associated to a delineated field, and filtered by particular researcher affiliation country (e.g. Country 1 for Fig 1) brings us to the 'co-funding network' for that specific field (level C). (Our illustrative data for 'Food Science' and 'Renewable Energy Research', addressing Denmark, the Netherlands and Norway author affiliations, therefore generates six such networks.) We consider this network as emergent (c.f. Wagner, 2019). It is co-shaped by the action of researchers mobilising particular funding when engaging in specific CRAs. These three levels – i.e. funding configurations (level A), funding amalgamations (B), and field co-funding networks (C) – together frame our understanding of a bottom-up/researcher-led perspective on research funding.

These levels also can guide exploration of deeper dimensions of funding (and in future research, how underlying funding instrument characteristics might influence, e.g. what research topics pursued, which research outputs produced and so on). Here the aim would be to go beyond nominal funder and funding instrument names. For level A, this would imply exploring funding configurations as mixes of funding characteristics. For level B one could analyse the multi-configuration, funding amalgamations used for specific CRAs. At Level C one could then explore field co-funding networks to study the roles and effects of specific funders and funding instruments.

For this paper, our illustrative analysis focuses on one particular type of CRA to explore the validity and some capabilities of this bottom-up approach. We choose published articles as the CRA. This is desirable because of the large-scale availability of funding information from article FAs. However, this choice limits us to illustrating only funding amalgamations and co-funding networks.

Our funding acknowledgements-based method

There are a number of potential methods to explore this bottom-up approach via the CRA of articles. Different methods here would have trade-offs regarding resource intensity, intrusiveness and coverage. For instance, we could address a survey to researchers in a particular field, and for specific RO affiliations, to ask directly about their funding instruments and/or funding configurations. We could

similarly survey research groups, teams or networks about funding amalgamations for, e.g. a funded research centre of excellence (taking a different example of a CRA). Such surveys would elicit self-reported data on research funding, although with potential issues of memory recall and incompleteness. Surveying at researcher level (i.e. level A, Fig 1) might also be resource-intensive and demanding for a given population of researchers across specific fields and countries.

We chose a FA-based method to test our bottom-up approach, with research articles as the CRA. This brings certain advantages and disadvantages regarding analysis of funding dynamics, and introduces both method strengths and weaknesses due to the nature and characteristics of FAs available from global databases of published scientific literature. FAs are paratexts that can be automatically extracted, at scale, from suitable publication databases. This data source choice is therefore both cost-effective and enables large-scale and unobtrusive study of research funding at two of the three levels in our bottom-up approach, i.e. funding amalgamations and co-funding networks.

In theory, FAs also allow access to our bottom-level of individual researcher, funding configurations (level A). However, in reality current FAs obscure it due to data noise. The choice to use FAs and publications then provides coverage limitations but eliminates time-consuming, costly disclosure of funding-related data by research funders, any need for privileged access to funder databases followed by significant manual data analysis (Gök, Rigby, and Shapira, 2016; John Rigby, 2013; Schmutz et al., 2019; Wang and Shapira, 2011) or having to engage researchers via intensive survey methods to test our approach.

A FA-based approach is also scalable and repeatable longitudinally and/or can sample multiple time periods with little marginal cost (if relevant periods are covered by publication datasets). Exploring FAs registers patterns of research co-funding and combinations of multiple grants (or equivalent) acknowledged to have supported publications. FAs also address limitations of not looking from the researcher perspective, as the funding data is reported by researchers themselves. FAs therefore afford, subject to caveats noted below, researcher-side, self-reported accounts of funding realities, and are becoming more available, consistent and stable over time.

Relation to previous FA-based studies

Numerous FA-related studies have been produced since FA data became systematically available in large-scale publication databases from late-2008. Simply using FAs is not inherently novel, as FAs have previously been studied to demonstrate co-funding patterns (e.g. in nanotechnology; see Shapira and Wang, 2010; Wang and Shapira, 2011). FAs have also shown multiple funding can be co-acknowledged in papers, e.g. single publications can acknowledge support from mixes of say, both public and private funders (B. Álvarez-Bornstein, Díaz-Faes, and Bordons, 2019). What previous studies have not aimed to do, however, is to use FAs within a changed perspective on funding. Similarly, across such studies funding has often not been considered the object of analysis in its own right.

Our approach therefore is different in two respects. First, we are interested in FAs as an available, unobtrusive data source that enables a more fundamental exploration of funding dynamics from the bottom up. We know researchers can draw upon multiple funding instruments even when producing single-authored research. This situation only gets more complicated when co-authoring then mixes potentially different funding types brought in by each author. We wish to be able to explore these largely unexplored but potentially significant funding combination and interaction dynamics. However, here FAs alone make little sense without associated analytical steps, i.e. careful research field delineation, funder/funding name disambiguation and cleaning, and – most crucially – analytically-informed FA coding. We draw this from our bottom-up perspective.

Second, we consider FAs not only in light of traditional research policy concerns, centred around nation-based science systems, but also as traces of more complex, adaptive, global contemporary science, involving many funding actors. A bottom-up perspective is not constrained by assumed, often artificial boundaries. Article FAs are ideal here in that they report actual funding used by researchers, similarly blind to border issues. And of course researchers can and do reach both below and above traditional national levels with their topics, and similarly can and do configure their funding to transcend geographically-constrained or sector-specific research funding constraints (Wagner, 2019, p. 92).

Limitations of using FAs

Article-level FAs do allow us to cover two levels of our bottom-up approach, but they have at least two types of limitations. First, they have functional limits, as set out in Table 2.

Table 2. Functional limitations that affect study of FAs.

Issue	Explanation
Availability	Not always present because some publishers and funders do not mandate them.
Correctness	Self-reported by authors with possibly imperfect recall, which can be compounded by weak oversight or accountability regarding FA accuracy and consistency. Possibilities for potential indexing errors in publication databases.
Standardisation	Neither uniformly structured nor all-encompassing, because different publishing outlets apply differing acknowledgement practices and templates or even provide no guidelines or guidance about FAs at all.
Quality	Often require manual cleaning and disambiguation of misspelled and/or inconsistently abbreviated or translated funder names, and may have similar errors for grant numbers. Funder names also change, new funders enter and old ones exit over time.
Completeness	Information about funding amount(s) and specific grant numbers is often missing.
Usage	Offer limited reliability to link funding with performance/impact of publications, e.g. via citations, or to attribute specific outputs to particular grants, because published findings may follow after funding or vice versa, and most grants are usable in highly flexible ways (e.g. what research and publications actually are pursued).
Scope	Largely available only for papers published after August 2008, when Web of Science (WoS) began to index FAs, then with more consistency from 2009 (Scopus began to index in July 2013). FA indexed in databases still often have limited coverage of non-English paratexts.

(See B. Álvarez-Bornstein et al., 2019; Belén Álvarez-Bornstein, Morillo, and Bordons, 2017; Costas and van Leeuwen, 2012; Cronin and Shaw, 1999; Díaz-Faes and Bordons, 2014; Giles and Councill, 2004; Grassano, Rotolo, Hutton, Lang, and Hopkins, 2017; Morillo and Álvarez-Bornstein, 2018; Paul-Hus et al., 2017; J. Rigby, 2011; John Rigby and Julian, 2014; Shapira and Wang, 2010; Sirtes, 2013; Tang, Hu, and Liu, 2017; Wang and Shapira, 2011)

Second, FAs are affected by researchers' acknowledging behaviours. Funders and authors increasingly consider FAs as required or good practice. However, authors' compliance in making FAs can vary from researcher to researcher, between country/language groupings and across fields. Consequently, FAs can under- and/or over represent funding. They may also obscure some funding information, or equate all funding as seemingly equal when it may be not (see Table 3).

Table 3. Limitations in studying FAs due to author acknowledging behaviours.

Issue	Explanation
Under-representation	Funding may be under-represented, as not all sources are always self-reported. Funders may be unacknowledged if authors win multiple sources to research very similar topics but do not wish this widely known. Commercial and charitable sources may be undisclosed due to vested interests or secrecy. Use of institutional internal university funding is commonly underreported.
Over-representation	Funding may be over-represented, e.g. to boost apparent outcomes of grants and/or author reputations (by over-emphasizing or spuriously naming prestigious funders) even when little or no relationship exists between acknowledged funding and the published research.
Obscuration	Difficult to decouple and disentangle to attribute funding to authors in multi-authored papers that acknowledge many funders, unless authors make this information explicit (i.e. estimations are thus often used).
Equation	FAs shed little light on the relative importance of sources acknowledged, because authors often omit any such information. All acknowledged funding may therefore superficially appear to have equal significance or weighting when in reality funding varied in terms of size, type, origin or other important characteristics.

(See B. Álvarez-Bornstein et al., 2019; Belén Álvarez-Bornstein et al., 2017; Costas and van Leeuwen, 2012; Giles and Councill, 2004; Grassano et al., 2017; Gök et al., 2016; Kundu and Matthews, 2019; J. Rigby, 2011; John Rigby, 2013; John Rigby and Julian, 2014; Sirtes, 2013; Wang and Shapira, 2011)

Due to these limitations, FAs cannot (currently) provide a reliable picture of individual researcher funding configurations. However, they do provide a valuable register of our more aggregated levels, i.e. funding amalgamations and co-funding networks. These would be difficult to map without using FAs

(Costas and van Leeuwen, 2012; Schmutz et al., 2019). Clearly, FAs must be interpreted with caution and do not currently fully substitute other sources, like top-down funding statistics.

Using FAs to study funding amalgamations and co-funding networks

To use FAs to study funding amalgamations and co-funding networks from the bottom up, we must first affiliate researchers to one or more of our test countries based on their reported author affiliation(s) in articles within our two test fields. For the test cases, FAs then describe the funding amalgamations (level B, Fig 1) associated with that researcher at the article level. However, here there are two issues. First, many articles are co-authored. Second, the funding amalgamation data string is an order-indifferent list of acknowledged funding that cannot be attributed directly back to particular, individual authors/researchers. In other words, a co-authored article mixes each researcher's funding. However, whose funding is whose, and how funding is mixed is not something FAs can indicate. We might assume co-authors bring in their own funding instruments to support their collaborative research activity of co-authoring the article. However, the vast majority of FAs do not report which specific author had which particular funding, or what specific role each acknowledged funding has played in producing a published research article.

Next, aggregating all FA-based funding amalgamations at field and/or country level shows the co-funding network (level C, Fig 1). For these networks we label the nodes with the funder names whose funding instruments have been acknowledged in article FAs. Here, node size indicates relative prevalence of FAs mentioning that funder. It provides a proxy of apparent funder influence. Network line thickness represents strength of co-occurring FAs of connected nodes/funders.

Article FAs in most cases only provide funder/funding instrument names. From these we have to determine what funding characteristics are meaningful to code. Based on previous literature we collected we decided to code 'type' of funder, and 'origin' level. These likely capture potentially different sets of key funding characteristics. By coding funding type, we distinguish between public, private, non-profit or university funders. These types likely signify particular kinds of funding instruments these bodies typically provide (see Bozeman and Gaughan, 2007; Braun, 1998; Gläser and Serrano Velarde, 2018; Lepori, 2017;

Reale, 2017). Deliberately here we include internal and external funder types, particularly as the role of university/internal funding is quite unexplored (e.g. institutional/block grant funding of salaried research time or special internally funded research activities) (see OECD, 2018).

We also code funding instrument/funder names by origin. Following established practices in use of FAs (e.g. B. Álvarez-Bornstein et al., 2019), here we code domestic, foreign or supranational. This again is intended to capture distinct sets of typical characteristics. For example, domestic (national or sub-national) funding may differ widely from foreign funding (i.e. non-domestic national or sub-national). Similarly, supranational funding/funders likely have specific associated characteristics due to their geographical scope of operation or focus on particular challenges, economic and/or societal missions (e.g. for the EU, multinational corporations, and international non-governmental organisations).

Our test case selection

We selected ‘Renewable Energy Research’ and ‘Food Science’ fields as they involve varied funding and assorted funders, given their breadth of research topic/keyword coverage (e.g. see Rizzi, van Eck, and Frey, 2014). They feature fundamental science and applied research, and have long traditions of involving industry, public authorities, other collaborators and research users. These fields are thematically oriented, and can engage grand SC themes, United Nations Sustainable Development Goals (SDGs), and related policies and politics. We do not expect them to be generally representative of the global science system. However, they are reasonable, multi-faceted candidates to test and illustrate our bottom-up/researcher-led approach. They represent a confirmatory case selection, where the two fields provide similar heterogeneity, yet sufficient variation to enable multiple tests of our approach.

We selected authors/researchers affiliated to research organisations (ROs) in Denmark, the Netherlands and/or Norway to additionally explore how national contexts may register even when adopting a bottom-up perspective (i.e. an approach that technically could ignore geographical boundaries altogether). All three countries are small, advanced, Western European economies with similar Humboldt-inspired university systems, relatively high shares of institutional funding, and traditional public research

councils (Öquist and Benner, 2015). They also have some country specific funder/funding variations (e.g. Denmark has relatively clear demarcation between scholarly and societally oriented funders; Norway is more centralized with a broad, unified research council). All three affiliation countries also have notably active Food Science and Renewable Energy Research sectors.

This selection process generated six cases, i.e. from the sum of the two fields and three author affiliation countries.

Field delineations and choice of time horizon

To delineate our two test fields, we adopted Whitley's notion of 'intellectual fields' as a 'broader and more general social unit of knowledge production and co-ordination' than say, disciplines (Whitley, 2000, p. 7). We see research 'fields' here as fairly broad units of knowledge production that can engage activities outside academia, knowledge co-production with industry or other societal collaborators, whilst still involving public research organisation-related social and organisational structures.

To delineate fields in this sense we included multiple elements. First, we retrieved all Web of Science (WoS) publications with at least one author with an institutional affiliation to a RO located in Denmark, the Netherlands or Norway. We then created separate 'Renewable Energy Research' and 'Food Science' publication datasets using a core/expansion approach. This included both multiple elements of WoS records (i.e. journal, subject categories, keywords, title, abstracts, authors, cited references) and relevant topic data infrastructure resources from The Centre for Science and Technology Studies (CWTS) in Leiden, Netherlands. We further used an author-name disambiguation algorithm (Caron and van Eck, 2014) and micro-level clustering of WoS publications based on citation relationships (c.f. Traag, Waltman, and van Eck, 2019; Waltman and Van Eck, 2012).

To include data for a reasonable period, we set our time horizon at 10 years. This led us to cover all relevant publications for 2009–18. This had the advantage of starting the datasets soon after WoS began to systematise and make available suitable FA metadata. We used no specific time criterion for author inclusion, i.e. whether a particular author-researcher had to appear multiple times within the

period to be considered ‘active’. This gave us our publications dataset, covering all six cases, and which we could filter by field and country.

Disambiguating and coding funding/funder data

We next cleaned and coded all the FA data in the overall dataset of publications. The FAs come from the ‘funding agencies’ metadata field of WoS records. This metadata field provides funder organisation names, names of sub-divisions of these funders, and sometimes funding grant numbers or funded project names, as extracted from article FAs.

First, we retrieved 25,423 distinct funder strings from the FAs. Here we had to disambiguate funder names since no cleaning had been performed inside the WoS records. We also grouped any funder sub-divisions under the named main funder. We manually disambiguated the resulting 5,802 funder strings at a threshold of at least two occurrences in the dataset over the 2009–18 period. This led us to combine 19,140 (75.3%) of the 25,423 original funder strings into a finalized list of 2,128 unique funding organizations for analysis.

Given the issues with FAs (e.g. functional limitations) we had to disambiguate and classify funders to obtain sufficient information available to code our chosen funding type and origin categories. For funding ‘type’, we coded four possible values:

- Public – typically research councils and public/state authorities like ministries and agencies (but including supranational organizations like the EU, and regional and local authorities).
- Private – predominantly companies/corporations.
- Non-Profit – including private non-profit organizations, patient organisations, national and supranational non-governmental organizations (NGOs) and related others.
- University – internal funding acknowledged as having come directly from a university (most likely either institutional funding or else competitively awarded university funds).

For funding ‘origin’, we coded three values:

- Domestic – Danish, Norwegian or Dutch (respective to author affiliation).
- Foreign – funding from all other countries except the domestic country affiliation.

- Supranational – e.g. funders like the EU, OECD and UN agencies.

Table 4 shows the final number of articles collected, the number and percentage of those papers with at least one acknowledged funder, and the share of those FAs coded for type and/or origin (i.e. between 68.0% and 77.8% for type, and between 70.8% and 81.2% for origin). We also sampled the non-coded FAs to check for any systematic bias. We found the characteristics were acceptably similar to our coded proportion.

Table 4. Fully coded articles for Renewable Energy Research and Food Science, 2009–18.

Case	Publications		Funding acknowledgements (FAs)		
	Number of articles	% with FA	Total number of FAs	% identified type	% identified origin
Energy-A-DK	6960	73.7	11817	77.8	81.2
Energy-A-NL	7390	70.0	12417	71.2	74.4
Energy-A-NO	3369	76.8	6540	72.1	75.0
Food Science-A-DK	5093	77.4	10163	71.0	74.9
Food Science-A-NL	6228	69.9	11023	68.0	70.8
Food Science-A-NO	4312	79.3	8890	70.3	72.8

We use 'A' (for 'affiliated') for each of the six cases to stress these are not 'country' cases.

Illustrative findings

We next analysed the associated co-funding networks (i.e. field level), and funding amalgamations (i.e. article level) from our six cases. For the field co-funding networks, we aimed to test if we could illustrate relative acknowledged prevalence of funders and register diversity of funder types and origins. For the article-level funding amalgamations we wanted to test if we could explore patterns of co-acknowledged funders, number of FAs, and authors.

We should stress this was a ‘proof-of-concept’ test of our approach, not a comprehensive study of ‘Renewable Energy Research’ and ‘Food Science’ fields. Hence, what follows are selected illustrative insights and visualisations. We do however show illustrative findings of different kinds for both fields and for all three author country affiliations. This allows us to explore if similar or different patterns of funding characteristics are present in and across the cases, as a way of testing whether our test cases are overly idiosyncratic. This is a major benefit of our choice of two different but similarly quite applied and interdisciplinary fields. These fields are good candidates to test our approach because we expect they will likely have sufficient funding variety to supply suitable data for our categories and levels. At the same time the countries and fields are different enough that we can still test whether our approach captures patterns of characteristics that do vary among these cases.

Field co-funding network tests

The co-funding networks for each of the six cases show funding-related dynamics in our selected fields that clearly stretch beyond – and that might not be accounted for if we bounded or constrained them as – national funding landscapes. We can also speculate that using individual researchers as our entry point, additionally suggests probably different prevalence of specific funders than might be assumed from, for instance, nationally-supplied research funding statistics. Using the bottom-up approach captures a broad and diverse number of acknowledged funders.

For example, the overall ‘Renewable Energy Research’ co-funding network, aggregated across all three country affiliations (Fig 2), has many instances of multiple rather than simplistic links between funders (nodes). We see a co-funding network that is highly complicated. Many apparent associations emerge, some of which may be expected (e.g. the apparent centrality of the EU, and of the unified Research Council of Norway); others perhaps less so.

Fig 2. Co-funding network for Renewable Energy Research, all affiliation countries, 2009–18.

Colours for 'origin': red = domestic (Denmark); green = foreign (Netherlands); pink = foreign (Norway); blue = foreign (all other countries); orange = Supranational (e.g. EU, EU-ERC). Node size indicates number of FAs mentioning that funder. Links indicate summed article funder co-incidences (i.e. connected funders co-occurring within the same article's FAs). Further exploration of all cases can be done online via: https://pmongeon.shinyapps.io/Prosecon_networks_updated/.

Fig 3 and Fig 4 show two co-funding networks, i.e. 'Renewable Energy Research' articles with Norway-affiliated authors, and 'Food Science' articles with Denmark-affiliated authors, respectively. Each has labelled the most acknowledged funders, for the sake of illustration.

Fig 3. Co-funding network of Norway-affiliated authors for Renewable Energy Research, 2009–18.

Cleaned names of the most acknowledged funders shown. Colours for 'origin': orange = domestic; blue = foreign; green = supranational.

Fig 4. Co-funding network of Denmark-affiliated authors for Food Science, 2009–18.

Cleaned names for the most acknowledged funders shown. Colours for 'origin': orange = domestic; blue = foreign; green = supranational.

Exploring across all six co-funding networks underlines that the funders acknowledged are highly heterogeneous. Traditional public funding sources (including the EU) are still prevalent. However, they clearly operate far from in isolation. They are part of larger networks of interlinked funders.

Amongst the cases we also see specific co-funding network features. For instance, the EU appears a central funding 'hub' both for articles with Denmark- and Netherlands-affiliated authors (e.g. Fig 4). By contrast, the case for Norway-affiliated articles (Fig 3) suggests the Norwegian Research Council has a similar apparent 'hub' function in that co-funding network. We can see links ties between more traditional national public funders and non-public, foreign or supranational funders. By contrast, we can also see field-specific funders standing out in certain cases only, e.g. oil companies acknowledged only for the Norway-affiliated 'Renewable Energy Research' case.

At the same time, we also find repeated features. For instance, the EU is – perhaps not surprisingly – an apparently important funder in all six cases. This is likely because it is active in funding across the multiple countries here, and across many topics being researched in and across these two fields. Additionally, the co-funding networks show several more niche funders that might have been overlooked by a more top-down view.

It is however important to note the bottom-up approach does not discard entirely the notion of 'country'. On the contrary, we still see and can explore national funding. These funders seemingly remain important in spite of emerging multi-level, multi-actor 'global science' (c.f. Wagner, 2019). For example, we capture the centrality, in the Norway affiliation case, of the Research Council of Norway. At the same time, we can provide more nuance and detail and show how traditional funders like this may still operate in heterogeneous, variously interlinked ways between other funders of differing types and origins.

Further research using the same approach could go further, e.g. to explore field-nexus funding dynamics, e.g. energy-food co-funding networks (this would make sense in instances both with suspected research topic links between fields and to reveal links in unsuspected multi-field cases). Overall, this bottom-up approach seems to enable identification of potentially useful insights.

Funder prevalence and variety tests

We can also show differing prevalence and variety of acknowledged funders. We do this by ranking acknowledged funders based on their share of total coded FAs. For example, Table 5 shows the 30 most acknowledged funders from FAs in ‘Renewable Energy Research’ for articles with at least one Danish affiliated author.

Table 5. The 30 most acknowledged funders from Renewable Energy Research, 2009–18.

Funder	Funding acknowledgements	
	n	%
EU	1161	10.8
Danish Council for Strategic Research	947	8.8
National Natural Science Foundation of China	434	4.0
Danish Energy Agency	377	3.5
Danish Council for Independent Research	374	3.5
Energinet.dk	343	3.2
Innovation Fund Denmark	340	3.2
Danish National Research Foundation	285	2.6
Technical University of Denmark	220	2.0
Danish Ministry of Science, Technology and Innovation	210	2.0
U.S. Department of Energy	157	1.5
Chinese Government	132	1.2
Danish Ministry of Food, Agriculture and Fisheries	132	1.2
Research Council of Norway	111	1.0
Villum Foundation	99	0.9
Danish National Advanced Technology Foundation	96	0.9
Carlsberg Foundation	95	0.9
Center for Materials Crystallography (CMC)	95	0.9

Spanish Government	90	0.8
EU – European Research Council (ERC)	87	0.8
National Science Foundation (NSF), USA	85	0.8
Aalborg University, Denmark	78	0.7
DONG Energy	77	0.7
China Scholarship Council (CSC)	67	0.6
Novo Nordisk Foundation	67	0.6
Nordic Energy Research	66	0.6
Aarhus University	62	0.6
Copenhagen University	57	0.5
Swedish Research Council	53	0.5
FCT – Foundation for Science and Technology	51	0.5
Total	6448	59.8

Articles with at least one Danish affiliated author.

Here, the 737 cleaned, named funders, acknowledged over 6,960 articles with Danish affiliated authors in ‘Renewable Energy Research’, show a complex funding reality even at article/funding amalgamation level. This context may again be more complicated than perhaps imagined if one’s perspective was confined to a national system-based view (e.g. of ‘Danish national science system’ or ‘Danish Renewable Energy Research’). Significantly, no single funder alone seems highly prevalent. Acknowledged funding is from a diverse set of funders, each of which likely has specific characteristics. Certain funders noted here may also be ‘off the radar’ of national policymakers and funding datasets from national statistics. Overall, this suggests both distributed research governance and possibly highly mediated influence of specific individual funders.

Indeed, looking across all six cases, we see only a few funders account for above 5% of total FAs per case. Only one funder per case accounts for above 10%. Even The Research Council of Norway, which is heavily acknowledged in both ‘Food Science’ and ‘Renewable Energy Research’ publications, and seems

a central national funder, still accounts for only around 20–25%. This seems to challenge any simplistic views of funding systems even when they have centralisation, i.e. one apparently dominant funder.

Similarly, even with a relatively inclusive threshold point for ‘most acknowledged funders’, taking as much as the top 30 shares of total FAs, this threshold still only accounts for 40–60% of FAs. This implies a ‘long tail’ of funders supporting, and perhaps influencing in some way, research in these fields here. Individually such funders may play only marginal roles. Together they may account for a substantial collective share of potential influence. Any study of funding dynamics here that ignored these seemingly could only provide a partial or misleading account of funding roles and potential funding effects.

Finally, the heterogeneity of co-funding is substantial, even only considering the most acknowledged funders. We do not see only traditional national research council funding. Instead multiple other public bodies are acknowledged (e.g. sector ministries and agencies). Specialised funders relevant only in specific sectors also appear, as do private companies, university internal funding, non-profit foundations and ‘foreign’ sources (from both proximate or neighbouring countries and more distant countries, e.g. China, USA).

Funding types and origins tests

We can also explore co-funding patterns by funding type (public, private, university, non-profit) and origin (domestic, foreign, supranational). Here, we should keep in mind that the number of acknowledged funders does vary by article (Fig 5). The majority of articles either have no acknowledgements or only one. Nonetheless across all six cases on average 40–50% of articles have two or more acknowledgements, and 10–15% acknowledge four or more funders. Country-affiliation differences are more pronounced here than field-related ones – mirroring our earlier observation that country differences were visible in the co-funding networks.

Fig 5. Frequency distributions of numbers of FAs at article level for all six cases, 2009–18.

Looking at funding types explores if different funders supporting research are co-acknowledged in specific ways that might suggest shared influence (see Table 6). Overall the most prevalent form here is public-public funding amalgamations. This is co-funding of an article via two or more (different) public funders being acknowledged. In ‘Renewable Energy Research’ for Dutch- and Danish-affiliated publications, this public-public funding amalgamation type accounts for 62.4% of FA cases; for Norwegian-affiliations, it is 42.7%.

Table 6. Share of articles according to funding type, 2009–18.

		Renewable Energy Research				Food Science			
		Non-profit	Private	Public	University	Non-profit	Private	Public	University
A-Denmark	Non-profit	1.1	1.5	8.8	1.2	2.5	4.8	17.4	4.9
	Private	1.5	2.5	14.3	2.8	4.8	2.2	11.7	4.6
	Public	8.8	14.3	58.1	11.9	17.4	11.7	43.9	16.7

	University	1.2	2.8	11.9	0.8	4.9	4.6	16.7	1.5
A-Netherlands	Non-profit	0.2	0.8	3.5	0.6	3.8	2.9	9.4	2.4
	Private	0.8	1.7	6.9	0.8	2.9	3.4	9.3	3.0
	Public	3.5	6.9	60.7	8.7	9.4	9.3	44.7	9.8
	University	0.6	0.8	8.7	0.9	2.4	3.0	9.8	1.8
A-Norway	Non-profit	0.1	1.5	4.9	2.2	1.1	1.4	4.1	0.3
	Private	1.5	6.7	15.1	3.3	1.4	5.1	17.0	1.8
	Public	4.9	15.1	42.4	17.6	4.1	17.0	50.1	10.8
	University	2.2	3.3	17.6	1.5	0.3	1.8	10.8	1.5

Two or more funders acknowledged. Figures do not necessarily sum to 100%, as cells are non-exclusive.

We coded the EU as a public funder. Many public-public funding amalgamations feature the EU plus one national public funder, co-acknowledged. Public-private (companies) and public-university amalgamations are also prevalent. Norwegian-affiliated articles have the highest prevalence of these amalgamations; Dutch-affiliations have the lowest. Amalgamations without public funding types were rare. For Danish affiliations this form accounted for less than 10 percent; for Dutch and Norwegian-affiliations it was less than 20 percent.

Across all cases we found large shares of non-domestic funders acknowledged (i.e. foreign from the point of view of author affiliation). Our coding showed 40–60% of FAs as either foreign – i.e. national or sub-national level outside the domestic country, respective to author affiliation – or else as supranational. The highest share of domestic funding was for articles with Norway author affiliations; the lowest was for Dutch-affiliations. By contrast the highest share of supranational funding was for Netherlands-affiliated authors and the lowest was for Norwegian-affiliations (see Table 7). These findings suggest that specificities of funding amalgamations by origin depend more upon author country affiliations than field.

Table 7. Distribution of funding origin across all six cases, 2009–18.

	Renewable Energy Research						Food Science					
	A-Denmark		A-Netherlands		A-Norway		A-Denmark		A-Netherlands		A-Norway	
Type	n	%	n	%	n	%	n	%	n	%	n	%
Domestic	3059	47.5	2402	38.9	1725	55.5	2319	50.2	1777	37.0	2258	56.5
Foreign	2087	32.4	1850	30.0	862	27.7	1329	28.8	1801	37.5	1095	27.4
Supranational	1295	20.1	1918	31.1	522	16.8	967	21.0	1225	25.5	645	16.1

Finally, our approach also enables us to explore co-funding dynamics by funding origin, as shown in Table 8. Here, for ‘Food Science’, for Danish- and Norwegian-affiliated articles the most prevalent form is domestic-domestic funding amalgamations (36.1% and 37.2%, respectively). Interestingly there are many articles with no domestic funding acknowledged. This suggests numerous researchers publishing papers in which exclusively foreign and/or supranational funders are acknowledged (again, respective to author affiliation; articles with Dutch affiliations reported the fewest domestic funders).

Table 8. Share of articles according to funding origin, 2009–18.

		Renewable Energy Research			Food Science		
		Domestic	Foreign	Supranational	Domestic	Foreign	Supranational
A-Denmark	Domestic	33.7	27.7	20.7	36.1	19.6	15.5
	Foreign	27.7	26.0	14.2	19.6	22.8	14.0
	Supranational	20.7	14.2	2.4	15.5	14.0	1.8
A-Netherlands	Domestic	28.5	21.2	20.1	21.6	17.8	12.5
	Foreign	21.2	23.7	24.2	17.8	25.6	19.4
	Supranational	20.1	24.2	4.9	12.5	19.4	2.4
A-Norway	Domestic	28.3	25.3	13.5	37.2	20.0	12.1
	Foreign	25.3	21.6	10.7	20.0	17.7	14.3
	Supranational	13.5	10.7	1.1	12.1	14.3	2.2

Two or more funders acknowledged. Figures may not tally to 100% due to multiple possible, non-exclusive origin-origin and additional origin permutations.

There were also instances where the FAs revealed domestic-foreign and/or domestic-supranational funding amalgamations. These suggest boundary-crossing, origin co-funding was common, implying that funders operating in different countries and/or at different geographic scales were co-funding publications – intentionally or not (i.e. whether they had coordination efforts or not).

Discussion and conclusion

Overall, our test supported our key assumption that taking a researcher-led perspective to get to the ‘bottom’ of research funding can reveal varied co-funding realities. We followed through this approach for the specific collaborative research activity of research publications, and could highlight varying prevalence of funding types and origins for our six test cases. We also could map co-funding networks that likely complement top-down national system perspectives. Now we turn to the issue of what implications emerge from this approach in terms of any deeper understanding of research funding dynamics.

First, for our test ‘Renewable Energy Research’ and ‘Food Science’ fields, the co-funding networks we have produced clearly reflect globalisation of science or ‘global science’ dynamics (see Wagner 2019). For these test cases at least, the bottom-up perspective supports recent assertions that knowledge production is increasingly no longer (if indeed it ever was) the ‘product’ of any particular, single country or national science system. Here we understand this implies that not only individual researchers and their research institutions likely now need to navigate an increasingly complex globalised science system, but also that funders may need to understand and adapt to how they actually operate – as seen from a bottom-up perspective – in these highly interlinked, and thus potentially interdependent spaces (see Lepori, 2011). In our complex, heterogeneous co-funding networks we also saw co-involvement of a broad range of both domestic and foreign actors clearly transcending traditional public funders. Funding is operating in a multi-level fashion, spanning boundaries. Further research using the same approach with more fields, and even other CRAs, could allow us to speak more generally here about implications of

funding dynamics and complexity for researchers and funders throughout more of the global science system.

Second, our test also supports our assertion that a bottom-up, researcher-perspective entry point on research funding is valid and necessary. Seemingly it adds nuance and might enhance understanding of the complexity of contemporary, highly interlinked research funding realities. At the same time more research would be needed to contrast our test findings with top-down/system-led studies of the same cases, if possible.

Third, our test also revealed a high heterogeneity of funders co-acknowledged in article level funding amalgamations. Domestic, foreign and supranational funders from public, private and non-profit sectors were amalgamated together in varying ways. The implication for deeper understanding of funding dynamics is that co-authors together amalgamate multiple, assorted funding instruments to do their research. We also saw repeated features across our six cases, in the form of reasonable national and sectoral specificities. The bottom-up/researcher-led approach can therefore illuminate not only boundary-spanning dynamics but also the likely continued importance of national funding arrangements.

Fourth, the approach's ability to capture these funding dynamics could be used to provide intelligence for funders, policymakers or university research managers. Our approach is based on funding that has actually been used, but that *a priori* might not have been coordinated, intended or expected by these stakeholders (c.f. Paul-Hus, Desrochers, and Costas, 2016; J. Rigby, 2011; John Rigby and Julian, 2014; Wang and Shapira, 2011). Such data is unlikely available via other approaches. Our bottom-up, researcher-led approach might open fruitful avenues for funders' to look broadly and comprehensively at their own funding portfolios, coordination efforts and influence in the science system (c.f. Belén Álvarez-Bornstein et al., 2017; Grassano et al., 2017; Kundu and Matthews, 2019). The approach's bottom-up illustrations could potentially serve to guide higher resolution, more pragmatic funding designs, and to inform related decisions and actions.

There are however limitations both to our approach and our test of it. First our selected illustrative fields are both highly applied and interdisciplinary, and may have limited generalisability. Specifically, they might be 'extreme' cases, with perhaps idiosyncratic knowledge production dynamics

and collaborations that have little relevance elsewhere (e.g. in mono-disciplinary fields). Their similarity was useful here to supply the kinds of funding variety we wished for to be able to test our approach. For wider applicability the approach needs to be tested with more and different fields. Similarly, our co-funding network and funding amalgamation patterns are likely specific to these fields and Denmark, Netherlands and/or Norway affiliated researchers (i.e. operating in small but open economies with pre-existing strong international ties). These contexts might skew our senses of apparent complexity and internationality. Once again, further research here seems desirable.

A second limitation concerns our CRA type and article FAs as a data source. Improvement in guidelines for use of FAs seems vital here, e.g. journals could require unambiguous identification of which authors acknowledged what funding. If all future FA reporting was universally mandated to require all authors individually to identify their own funding in a fully traceable way, our approach could provide funding-author attribution. This is currently not possible. Nevertheless, it would remain challenging to attribute particular research content and insights in an article to specific, acknowledged funding. This is important to address for better understanding of, for example, do authors deploy their own funding somewhat in isolation, and their co-authors do the same with their own, separate, parallel funding (i.e. the funding amalgamation is just a juxtaposition)? Or do authors instead effectively fuse so that the amalgamation cannot be meaningfully disassociated into component funding parts? Additional methods would be required to elicit these types of further understanding.

Tentatively we can suggest some ways to tackle these limitations. First, it seems essential to confirm patterns that likely underpin our bottom-up, article FA-based analysis. We would do this by exploring the more fundamental funding configurations level for each author/researcher (i.e. level A in Fig 1). Currently we see a non-directly attributable trace of perhaps only part of this level. Second, we need to know more details about how funding amalgamations are composed, and when and how funding instruments are even co-mobilised by co-authoring researchers. Third, we might also like to know if researchers pursue particular funding strategies and/or shape their funding, e.g. through configuring specific funding instruments, through influencing funding provision, and so on (c.f. Gläser, 2019; Gläser

and Serrano Velarde, 2018). To address these two further areas of deeper understanding we would most likely need to combine interviews, bibliometrics, altmetrics, surveys and/or network analysis.

Looking ahead, next steps for this research approach would be to explore underlying funding characteristics for which type and origin are currently only proxies. This could involve, e.g. exploring what is distinctive about particular funding types and origins, looking at how researchers respond to funding of different kinds, and at their roles in particular configurations and/or amalgamations of funding. For this present paper, the bottom-up, researcher-led perspective clearly provides a proof-of-concept, more nuanced view, even using simple coding of article FAs alone. However, to be fully comprehensive it should most likely comprise one part of a new, broader framework and mixed methods toolkit, to address more aspects of contemporary research funding realities.

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Appendices

Appendix 1. Details of the core and expanded publication datasets

The core datasets for the two fields included all papers that met *all* these three criteria:

- Contains at least one of our search terms;
- Published in a relevant journal;
- Part of a relevant article-level cluster.

We built a list of search terms based on past research (Rizzi et al. 2014), several web searches, and our own judgement for the food science field. For renewable energy, we built the list based on our own judgement and multiple web searches. The relevant journals thus collated are a manually validated list of all journals with one of our search terms in their title, or included in relevant WoS subject categories (for food science, these were “agriculture, dairy & animal science”, “agricultural economics & policy”, “agriculture, multidisciplinary”, “agricultural experiment station reports”, “food science & technology” and “agricultural engineering”; for renewable energy they “energy & fuels” and “green & sustainable science & technology”). Finally, we manually identified the article-level clusters that are clearly related to the two fields. There were a total of 4,535 micro-level clusters, so we limited our manual identification to those clusters with at least five publications containing one of our keywords (the list of search terms, relevant journals, and relevant article-level clusters for food science and renewable energy are in Appendices 2 and 3, respectively).

We then expanded these two core datasets by including all papers that met any three of the following five criteria:

- Contains at least one of the search terms;
- Is published in a relevant journal;
- Is part of a relevant article-level cluster;
- Cites or is cited by a publication in the core set;
- Shares an author with a publication in the core set.

Finally, we included in each field dataset all papers in the micro-clusters for which more than one third of publications had already been included at that point. This resulted in over 18,000 publications in the full Food Science field dataset, and over 14,000 for Renewable Energy (see Table 9). Each field’s full dataset contains fewer papers than the sum of each row of country affiliations. This is because there may be, e.g. a Denmark-affiliated and a Netherlands-affiliated author on the same paper, and other multiple permutations of the three country affiliations.

Table 9. Number of papers in the datasets to delineate the fields and the author country affiliations.

Field	Affiliation(s)	Number of papers in the core dataset	Number of papers added in the expansion step	Total number of papers in the full dataset
Food Science	Denmark	1,131	5,226	6,397
	Netherlands	1,592	6,838	8,430
	Norway	660	3,692	4,352
	Full dataset (Food)	3,217	14,834	18,051
Renewable Energy Research	Denmark	1,100	4,458	5,558
	Netherlands	1,052	5,099	6,151
	Norway	462	2,548	3,010
	Full dataset (Energy)	2,494	14,204	14,204

Appendix 2. Core keywords, journals, and article-level clusters for 'Food Science'

Keywords

green farm*, sustainable farm*, renewable farm*, renewable food*, green food*, sustainable food*, green agr*, sustaineable agr*, renewable agr*, food*, animal*, fish*, crop*, dairy*

Journals

Acta agriculturae scandinavica section a-animal science, Acta alimentaria, African journal of agricultural research, Agrarforschung, Agrarforschung schweiz, Agrekon, Agribusiness, Agricultural and food science, Agricultural economics, Agricultural economics-zemedelska ekonomika, Agricultural history, Agricultural sciences in china, Agricultural systems, Agriculture and human values, Agriculture ecosystems & environment, Agrociencia, Agroecology and sustainable food systems, Ama-agricultural mechanization in asia africa and latin america, American journal of agricultural economics, American journal of enology and viticulture, Analytical methods, Animal, Animal biotechnology, Animal feed science and technology, Animal frontiers, Animal genetics, Animal nutrition and feed technology, Animal production science, Animal reproduction, Animal reproduction science, Animal science journal, Animal science papers and reports, Animals, Annals of animal science, Annals of applied biology, Annual review of animal biosciences, Annual review of food science and technology, Annual review of resource economics, Antioxidants, Applied animal behaviour science, Applied biological chemistry, Applied economic perspectives and policy, Applied engineering in agriculture, Aquacultural engineering, Archiv fur geflugelkunde, Archiv fur tierzucht-archives of animal breeding, Archives animal breeding, Archives of animal nutrition, Asian-australasian journal of animal sciences, Australian journal of agricultural and resource economics, Australian journal of dairy technology, Australian journal of grape and wine research, Avian biology research, Berichte uber landwirtschaft, Biomass & bioenergy, Bioresource technology, Bioscience biotechnology and biochemistry, Bioscience journal, Biosystems engineering, Biotechnology progress, Boletim do centro de pesquisa de processamento de alimentos, Bragantia, Brazilian journal of poultry science, British food journal, British poultry science, Buffalo bulletin, Bulgarian journal of agricultural science, Cahiers agricultures, California agriculture, Canadian journal of agricultural economics-revue canadienne d agroeconomie, Canadian journal of animal science, Cereal chemistry, Cereal foods world, Chemical senses, Chemosensory perception, Chilean journal of agricultural research, China agricultural economic review, Ciencia e agrotecnologia, Ciencia e investigacion agraria, Ciencia e tecnica vitivinicola, Comprehensive reviews in food science and food safety, Computers and electronics in agriculture, Critical reviews in food science and nutrition, Crop & pasture science, Cuadernos de desarrollo rural, Cuban journal of agricultural science, Current opinion in food science, Custos e agronegocio on line, Cyta-journal of food, Czech journal of animal science, Czech journal of food sciences, Dairy science & technology, Deutsche lebensmittel-rundschau, Domestic animal endocrinology, Elelmiszervizsgalati kozlemenyek, Emirates journal of food and agriculture, Engenharia agricola, European food research and technology, European journal of lipid science and technology, European poultry science, European review of agricultural economics, Flavour and fragrance journal, Fleischwirtschaft, Food & function, Food & nutrition research, Food additives & contaminants part b-surveillance, Food additives and contaminants part a-chemistry analysis control exposure & risk assessment, Food analytical methods, Food and agricultural immunology, Food and bioprocess technology, Food and bioproducts processing, Food and chemical toxicology, Food and drug law journal, Food and energy security, Food and nutrition bulletin, Food australia, Food biophysics, Food bioscience, Food biotechnology, Food chemistry, Food control, Food engineering reviews, Food hydrocolloids, Food hygiene and safety science, Food microbiology, Food packaging and shelf life, Food policy, Food quality and preference, Food research international, Food reviews international, Food science & nutrition, Food science and biotechnology, Food science and human wellness, Food science and technology, Food science and technology international, Food science and technology research, Food security, Food structure-netherlands, Food technology, Food technology and biotechnology, Foodborne pathogens and disease, Foods, Fournages, Genetics selection evolution, German journal of agricultural economics, Global food security-agriculture policy economics and environment, Grasas y aceites, Grassland science, Icelandic agricultural sciences, Indian journal of agricultural sciences, Indian journal of animal research, Indian journal of animal sciences, Industrial crops and products, Innovative food science & emerging technologies, Inra productions animals, International dairy journal, International food and agribusiness management review, International food research journal, International journal of agricultural and biological engineering, International journal of agricultural sustainability, International journal of agriculture and biology, International journal of dairy technology, International journal of food engineering, International journal of food microbiology, International journal of food properties, International journal of food science and technology, International journal of food sciences and nutrition, International sugar journal, Irish journal of agricultural and food research, Italian journal of animal science, Italian journal of food science, Itea-informacion tecnica economica agraria, Jarq-japan agricultural research quarterly, Journal fur verbraucherschutz und lebensmittelsicherheit-journal of consumer protection and food safety, Journal of agricultural & environmental ethics, Journal of agricultural and food chemistry, Journal of agricultural and resource economics, Journal of agricultural economics, Journal of agricultural meteorology, Journal of agricultural science, Journal of agricultural science and technology, Journal of agricultural sciences-tarim bilimleri dergisi, Journal of agriculture and rural development in the tropics and subtropics, Journal of agriculture of the university of puerto rico, Journal of animal and feed sciences, Journal of animal and plant sciences, Journal of animal breeding and genetics, Journal of animal physiology and animal nutrition, Journal of animal science, Journal of animal science and biotechnology, Journal of aoac international, Journal of applied animal research, Journal of applied poultry research, Journal of aquatic food product technology, Journal of bioscience and bioengineering, Journal of cereal science, Journal of consumer protection and food safety, Journal of dairy research, Journal of dairy science, Journal of essential oil research, Journal of food agriculture & environment, Journal of food and drug analysis, Journal of food and nutrition research, Journal of food biochemistry, Journal of food composition and analysis, Journal of food engineering, Journal of food lipids, Journal of food measurement and characterization, Journal of food process engineering, Journal of food processing and preservation, Journal of food protection, Journal of food quality, Journal of food safety, Journal of food safety and food quality-archiv fur lebensmittelhygiene, Journal of food science, Journal of food science and technology-mysore, Journal of functional foods, Journal of integrative agriculture, Journal of irrigation and drainage engineering, Journal of land use science, Journal of medicinal food, Journal of muscle foods, Journal of oil palm research, Journal of oleo science, Journal of plant diseases and protection, Journal of poultry science, Journal of reproduction and development, Journal of sensory studies, Journal of sustainable agriculture, Journal of texture studies, Journal of the american oil chemists society, Journal of the american society of brewing chemists, Journal of the faculty of agriculture kyushu university, Journal of the institute of brewing, Journal of the japanese society for food science and technology-nippon shokuhin kagaku kogaku kaishi, Journal of the korean society for applied biological chemistry, Journal of the science of food and agriculture, Journal of wine economics, Korean journal for food science of animal resources, Landbauforschung, Large animal review, Listy cukrovarnicke a reparske, Livestock science, Lwt-food science and technology, Meat science, Milchwissenschaft-milk science international, Mitteilungen klosterneuburg, Mljekarstvo, Molecular nutrition & food research, Natural product communications, New mediterranean, New zealand journal of agricultural research, Njas-wageningen journal of life sciences, Oeno one, Outlook on agriculture, Packaging technology and science, Paddy and water environment, Pakistan journal of agricultural sciences, Pesquisa agropecuaria brasileira, Philippine agricultural scientist, Plant foods for human nutrition, Plant pathology journal, Polish journal of food and nutrition sciences, Postharvest biology and technology, Poultry science, Precision agriculture, Quality assurance and safety of crops & foods, Renewable agriculture and food systems,

Reproduction in domestic animals, Review of agricultural economics, Revista brasileira de engenharia agricola e ambiental, Revista brasileira de zootecnia-brazilian journal of animal science, Revista ciencia agronomica, Revista colombiana de ciencias pecuarias, Revista de la facultad de ciencias agrarias, Revista mexicana de ciencias pecuarias, Revista mvz cordoba, Revue suisse d agriculture, Rivista italiana delle sostanze grasse, Sciences des aliments, Scientia agricola, Semina-ciencias agrarias, Small ruminant research, South african journal of animal science, South african journal of enology and viticulture, Spanish journal of agricultural research, Starch-starke, Sugar industry-zuckerindustrie, Tarım bilimleri dergisi-journal of agricultural sciences, Técnica pecuaria en mexico, Transactions of the asabe, Trends in food science & technology, Tropical agriculture, Tropical animal health and production, Tropical grasslands-forrajes tropicales, World mycotoxin journal, World rabbit science, Worlds poultry science journal, Zemdirbyste-agriculture, Zuchtungskunde, Zywnosc-nauka technologia jakosc

Article-level clusters

Cluster # Top terms in clusters

521	anthocyanins; cyanidin; euterpe oleracea mart; blueberry; strawberry
540	marine spatial planning; governance; coastal management; marine reserf; small scale fishery
832	collembola; oligochaeta; acari; megascolecidae; lumbricidae
975	hemocyte; crassostrea virginica; pacific oyster; ruditapes philippinarum; eastern oyster
1010	glycemic load; risk; diabetes; rat; satiety
1594	inactivation; high hydrostatic pressure; high pressure processing; electric field; escherichia coli
1632	florfenicol; oxytetracycline; antibiotic residue; quinolone; chloramphenicol residue
1925	food; gmo; organism; biotechnology; gene flow
1960	agriculture; diet; meat; farm; organic farming
2202	intercropping; weed suppression; fertility level; brassica juncea; rainfed condition
2312	rice intensification; chlorophyll meter; alternate wetting; sri; ammonia volatilization
2390	deep fat frying; oil uptake; frying; potato chip; french fry
2812	potato tuber; solanum tuberosum l; glycoalkaloid; tuber; antioxidant activity
2993	beta galactosidase; lactose hydrolysis; human milk oligosaccharide; sialic acid; lactose
3328	acrylamide; glycidamide; potato chip; french fry; asparagine
3370	dairy product; dairy consumption; calcium; lactose intolerance; metabolic syndrome
3544	ice cream; perception; aroma release; saliva; headspace gas chromatography
4021	edible insect; tenebrio molitor; black soldier fly; growth performance; hermetia
3578	lepeophtheirus salmonis; sea lice; siphonostomatoida; caligidae; salmon louse
3273	food sovereignty; land grab; agroecology; large scale land acquisition; dispossession
2771	cassava; manihot esculenta crantz; tarhana; sourdough; euphorbiaceae
2590	odor; livestock building; broiler house; ammonia emission; hydrogen sulfide
2272	cocoa butter; enzymatic interesterification; diacylglycerol; palm stearin; lipase
2111	bangladesh; biofloc; periphyton; water quality; environmental impact
2040	machine vision; computer vision; image processing; vacuum cooling; image analysis
1675	boar taint; sow; piglet; androstenone; entire male pig
1674	sulforaphane; glucosinolate; broccoli; indole; carbinol
1620	digital dermatitis; footrot; lameness; dichelobacter nodosus; animal welfare
1474	campylobacter coli; arcobacter butzleri
1458	angiotensin; enzyme inhibitory peptide; ace; bioactive peptide; hypertensive rat
1451	white clover; seed yield; trifolium; structural characteristic; n alkane
1375	climate change; climate variability; crop model; vulnerability; aquacrop
1129	bovine mastitis; staphylococcus aureus; intramammary infection; somatic cell count; coagulase negative staphylococci
983	conservation agriculture; maize; technology adoption; western kenya; smallholder farm
969	genistein; isoflavone; daidzein; soy; phytoestrogen
952	nitrous oxide emission; denitrification; methanotroph; n2o emission; n2o
902	pectin; feruloyl esterase; pectic polysaccharide; xyloglucan; plant cell wall
808	high molecular weight glutenin subunit; dough; bread dough; dough rheology; wheat flour dough
802	volatile compound; wine; ethyl carbamate; oenococcus oeni; malolactic fermentation
778	advanced glycation end product; glyoxalase; methylglyoxal; glycation; ages
765	growth performance; aeromonas hydrophila; disease resistance; flavobacterium psychrophilum; aeromonas
755	varroa destructor; megachilidae; halictidae; apoidea; nosema ceranae
702	pig; phytase; acid digestibility; microbial phytase; soluble
688	naringenin; nobiletin; quercetin; fisetin; hesperetin
675	tenderness; sex; carcass characteristic; carcass; breed
647	growth trait; random regression model; genetic evaluation; pedigree analysis; genetic parameter estimate
636	stanniocalcin; hypoxia; osmoregulation; clove oil; eugenol
535	pesticide residue; dissipation; uncertainty; measurement uncertainty; grape
487	incubation; feather pecking; hatchability; furnished cage; ascite
440	soybean meal; fish meal; fatty acid composition; practical diet; digestibility
426	glyphosate resistance; amaranthus palmeri; selectivity; translocation; conyza canadensis
416	microbial transglutaminase; surimi; fillet; gelation; rainbow trout
398	air water interface; complex coacervation; water emulsion; cultivar; soybean
380	rice starch; amylopectin; granule; heat moisture treatment; adp glucose pyrophosphorylase
359	lactococcus lactis; streptococcus; cheddar cheese; cheese; casein micelle
342	progesterone; corpus luteum; mare; estrous cycle; luteolysis
278	solvent extract; total antioxidant capacity; total phenolic content; dpnh; antioxidant potential
271	methylcyclopropene; polyphenol oxidase; shelf life; ethylene; mcp
267	rhizobacteria; trichoderma spp; growth promotion; bacillus subtili; plant growth
174	length weight relationship; sardinops sagax; atlantic bluefin tuna; anchovy; thunnus thynnus

145 rice; oryza sativa l; cold tolerance; qtl detection; quantitative trait loci
 120 ochratoxin; aflatoxin; deoxynivalenol; zearalenone; mycotoxin
 45 aerobic stability; methane production; corn silage; methane emission; microbial protein synthesis

Appendix 3. Core keywords, journals, and article-level clusters for ‘Renewable Energy Research’

Keywords

renewable energ*, sustainable energ*, *power conver*, alternative energ*, electricity generat*, electricity system*, renewable*, sustainab*, bioenergy, alternative fuel*, biodiesel*, biofuel*, biogas*, biomass combustion, biomass gasification, biomass power, biomass production, biomass pyrolysis, biochar*, bioethanol, biomass energ*, biomass fuel*, biomass to energy, energy from biomass, palm oil, soybean oil, thermal water, hydro turbine*, hydro energ*, tidal energ*, tidal power, water power, tidal stream, wave energ*, wave power, photovoltaic generat*, photovoltaic module*, photovoltaic system*, solar air, solar concentrator*, solar energ*, solar thermal, photovoltaic*, solar thermal collector*, wind farm*, wind park*, wind turbine*, wind energ*, wind generat*, wind power, wind turbine generat*, Walney Extension, London Array, Gemini Wind Farm, Anholt, BARD Offshore 1, Gwynt y Môr, , ethanol biofuel*, ethanol, cellulosic ethanol, algae fuel*, Jatropha, PV, PV system*, PV power*, crystalline silicon, zero-emission fuel*, fuel-cell*, Hydrogen fuel*, steam reforming, steam-methane reforming, Green energ*

Note: **Bold** keywords are not from Rizzi et al. 2014.

Journals

Algal research-biomass biofuels and bioproducts, Alternative sources of energy, Bioenergy research, Biofuels bioproducts & biorefining-biofpr, Biofuels-uk, Biomass & bioenergy, Biomass conversion and biorefinery, Biomass, Bioresource technology, Biotechnology for biofuels, Energy & environment, Energy & environmental science, Energy for sustainable development, Energy sustainability and society, Environmental progress & sustainable energy, Fuel cells, Geothermal energy, Geothermics, Global change biology bioenergy, IEEE journal of photovoltaics, IEEE transactions on sustainable energy, IET renewable power generation, International journal of exergy, International journal of green energy, International journal of hydrogen energy, International journal of photoenergy, Journal of fuel cell science and technology, Journal of modern power systems and clean energy, Journal of photonics for energy, Journal of renewable and sustainable energy, Journal of solar energy engineering-transactions of the ASME, Progress in photovoltaics, Renewable & sustainable energy reviews, Renewable energy, Solar age, Solar cells, Solar energy materials and solar cells, Solar energy materials, Solar energy, Sustainable energy & fuels, Sustainable energy grids & networks, Sustainable energy technologies and assessments, Wiley interdisciplinary reviews-energy and environment, Wind energy

Article-level clusters

Cluster # Top terms in cluster

58 polymer solar cells; open circuit voltage; bulk heterojunction solar cell; photovoltaic performance; power conversion efficiency
 1889 wind turbine; wind farm; vertical axis wind turbine; large eddy simulation; complex terrain
 186 hydrogen production; anaerobic co digestion; food waste; dark fermentation; hydrogen
 908 switchgrass; biofuel; ethanol; miscanthus; energy crop
 1275 wind energy; wind; offshore wind farm; feed; energy return
 2714 sustainability transition; public procurement; multi level perspective; transition management; grassroots innovation
 60 beta glucosidase; bioethanol production; cellulase; endoglucanase; enzymatic hydrolysis
 347 corporate social responsibility; ISO; CSR; environmental performance; stakeholder
 668 light trapping; crystalline silicon solar cell; screen; broadband; absorption enhancement
 922 electric vehicle; vehicle; plug; smart home; demand side management
 115 zirconia; cerium; yttria; intermediate temperature solid oxide fuel cell; laser
 706 unit commitment problem; market power; transmission expansion planning; economic dispatch problem; valve point effect
 599 microalgae; Chlorella vulgaris; photobioreactor; nutrient removal; light intensity
 674 islanded microgrid; islanding detection; inverter; reconfiguration; distribution network reconfiguration
 1930 DFIG; induction generator; wind turbine; variable speed wind turbine; wind farm
 603 bio oil; hydrothermal liquefaction; hydrodeoxygenation; bio oil production; torrefaction
 615 climate sensitivity; international environmental agreement; emissions trading; geoengineering; carbon tax
 88 ethanol oxidation; Pt/C catalyst; Pt nanoparticle
 1040 microbial fuel cell; performance; electricity generation; bioelectrochemical system; Shewanella oneidensis MR
 1640 biochar; effect; soil; hydrothermal carbonization; characterization
 888 bipolar plate; gas diffusion layer; PEM fuel cell system; phase flow; micro direct methanol fuel cell
 552 perovskite solar cell; stability; perovskite; performance; efficiency
 1854 wave energy converter; array; layer fluid; breakwater; water wave
 331 esterification; combustion; diesel engine; emission characteristic; diesel
 944 ethanol steam; syngas production; methane decomposition; catalytic partial oxidation; dry reforming
 546 proton conductivity; arylene ether sulfone; sulfonated poly; vinyl alcohol; composite membrane
 1709 Turkey; hydrogen production; hydrogen; Algeria; hybrid renewable energy system
 2302 energy; energy analysis; energy evaluation; degrowth; ecological footprint
 2516 molten carbonate fuel cell; MCFC; solid oxide fuel cell system; heat; hybrid system
 752 environmental Kuznets curve; financial development; decomposition analysis; economic growth; energy consumption
 421 coal pyrolysis; underground coal gasification; biomass gasification; coal char; NOx emission
 65 porous silicon; silicon nanocrystal; microcrystalline silicon; H thin film; silicon quantum dot
 1546 solar air heater; PV/T; absorber plate; photovoltaic thermal system; compound parabolic concentrator

898 beta o; oxygen delignification; organosolv lignin; kraft lignin; mechanical pulp
 2561 indoor air pollution; rural electrification; solar home system; exposure; child
 1722 high temperature corrosion; corrosion; wood ash; ash deposition; recovery boiler
 1210 organic food; local food; rurality; alternative food network; farmers market
 1784 photovoltaic module; solar cell; partial shading condition; pv module; degradation
 585 electrochemical property; hydrogen storage alloy; alloy; ni mh battery; microstructure
 439 in ga; cu₂znsn; sse; cu₂znsn₄ thin film; cuinse2
 170 turbulent premixed flame; deflagration; detonation; detonation transition; mild combustion
 2310 butanediol; clostridium acetobutylicum; butanol production; klebsiella pneumoniae; clostridium beijerinckii
 125 dye sensitized solar cell; dssc ;
 2491 proton conductor; hydrogen permeation; bazro3; barium zirconate; proton
 1409 oil spill detection; wind wafe; langmuir circulation; significant wave height; swell
 1262 ammonia borane; hydrogen generation; hydrolysis; sodium borohydride; bh₄
 397 photoelectrochemical water oxidation; solar water splitting; bivo₄; hematite; hematite photoanode
 82 photosystem; reaction center; rhodobacter sphaeroide; electron transfer; light harvesting complex
 2145 ground source heat pump system; borehole heat exchanger; soil; ground; groundwater flow
 168 pile; liquefaction; offshore wind turbine; cpt; geogrid
 573 water oxidation; efficient hydrogen evolution; overall water splitting; oxygen evolution reaction; electrocatalytic water oxidation
 4204 luminescent solar concentrator; luminescent; dye; quantum dot; layer
 2366 electrodialysis; anion exchange membrane; bipolar membrane; diffusion dialysis; electrochemical characterization
 2232 global solar radiation; estimation; solar irradiance; satellite; active radiation
 205 fischer tropesch synthesis; co₂ methanation; methanol synthesis; cinnamaldehyde; cu zno al₂o₃ catalyst
 1755 co₂ capture; co₂ absorption; monoethanolamine; piperazine; co₂
 952 nitrous oxide emission; denitrification; methanotroph; n₂o emission; n₂o
 72 hzsm; sapo; methanol; zeolite membrane; zeolite catalyst
 1378 scheduling; heat exchanger network; uncertainty; global optimization; planning
 2173 electrochemical reduction; carbon dioxide; co₂; co₂ reduction; formate
 1168 phase change material; pcm; thermal energy storage; paraffin; latent heat
 1426 efficient oxygen reduction; fe n c catalyst; zn air battery; efficient metal free electrocatalyst; iron phthalocyanine
 14 zno nanorod array; zno film; zno nanowire; zinc oxide thin film; zinc oxide nanorod
 3640 wind farm; vulture; wind turbine; diclofenac; andean condor
 3740 intermediate band solar cell; hot carrier solar cell; quantum dot solar cell; solar cell; impurity photovoltaic effect
 396 chlorophyll content; photochemical reflectance index; desertification; leaf area index; ndvi
 1340 hydrogen production; hydrogenase; methyl coenzyme m reductase; syngas;
 2201 methanol; ethylene glycol; methanol poisoning; activated charcoal; dog
 455 co₂ capture; co₂ adsorption; carbon dioxide; methane; ch₄
 1130 centrifugal compressor; film; tip clearance; centrifugal fan; tip leakage flow
 1974 hydrogen embrittlement; hydrogen diffusion; hydrogen; high strength steel; hydrogen trapping
 2440 hydrogen production; parabolic trough solar collector; co₂; methane; coal
 1502 lead acid battery; charge estimation; electric vehicle; valve; state
 249 gas sensing property; sno₂ thin film; sno₂ nanostructure; acetone;
 2300 triboelectric nanogenerator; contact electrification; piezo phototronic effect; particle; bed
 1767 organic electrochemical transistor; electrochromic polymer; thermoelectric property; pedotpss film; pedot
 2258 hydrogen storage; molecular hydrogen; storage
 1483 cdte thin film; cds cdte solar cell; cds film