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BIOENERGY WITH CARBON CAPTURE AND STORAGE: ARE SHORT-TERM ISSUES SET ASIDE?

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Abstract

Negative emission technologies (NETs) are a set of technologies that could retrieve greenhouse gases from the atmosphere. NETs could dramatically contribute to maintaining the temperature increase to within the limit of 2°C or even 1.5°C. Bioenergy with carbon capture and storage (BECCS) is one of the most studied NETs. BECCS captures CO₂ emissions coming from a bioenergy plant—e.g., electricity, biofuels, and hydrogen—and stores those emissions in a geologic reservoir, typically a saline aquifer. The purpose of this article is to investigate whether a research community exists on BECCS, and whether it is aligned with research priorities. To do so, a bibliometric analysis is conducted based on author collaborations on BECCS in academic journals between 2001 and 2017. The co-authorship network shows that BECCS research is largely based on the integrated assessment model (IAM) research community. These models analyse how power and transportation systems evolve under a climate constraint in the long run, e.g., until 2100. Such a focus has advantages and drawbacks. On the one hand, it helps to build a common vision of the technology and possible roadmaps. On the other hand, I highlight that the implementation features of BECCS in the near future are insufficiently assessed, e.g., techno-economic analyses, business models, local scale assessments, comparison with other NETs. These issues are marginal in the network whereas long-term analyses are at its core. Future research programmes should better include them to avoid a considerable disappointment about the real potential of BECCS.

Keywords: bioenergy with carbon capture and storage; BECCS; negative emissions technologies; bioenergy; co-authorship network

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1 Introduction

Climate change requires considerable efforts to limit temperature increases to below 2°C, or even 1.5°C, as prescribed by the Paris Agreement at the Conference of Parties 21. Actually, an overshoot of the CO_{2eq} concentration in the atmosphere is very likely, meaning there is a need for technologies that allow the absorption of greenhouse gases (GHG) in surplus, as highlighted by the IPCC (IPCC 2014). Such mitigation tools are known as negative emission technologies (NETs) and include afforestation, biochar, and bioenergy with carbon capture and storage (BECCS). BECCS refers to carbon capture and storage (CCS) technologies implemented in bioenergy production, mainly biofuels, electricity production (including cogeneration with coal or natural gas), and paper mills. After its capture, the CO₂ emitted by an industrial site is transported—generally by pipelines—and stored in a geologic reservoir, e.g., a saline aquifer, (Faaij 2006; Obersteiner et al. 2001; Möllersten et al. 2003). Because BECCS and afforestation are the only two NETs included in most integrated assessment models (IAMs) - a type of modelling widely used by the IPCC to assess climate change - one of the main findings of the Assessment Report (AR5) is that the use of BECCS is likely to be necessary (IPCC 2014).

Given the importance attached to BECCS, assessing its potential and adverse effects—on biodiversity and food production—are high research priorities, see Vaughan and Gough (2016) and Fuss et al. (2016). Another crucial concern is how to develop BECCS, since CCS struggles to build large-scale projects in comparison to international roadmap forecasts (Herzog 2016; IEA 2016).

The present article provides a bibliometric analysis of BECCS research to understand the research field structure and whether it fits with the research priorities described above. Scientific knowledge expansion is an ongoing challenge for scientists whatever the research field. However, this issue is particularly sensitive for climate change research, with more than 222 000 articles published since 2014 (Haunschild et al. 2016). Bibliometric tools can be applied to obtain a global picture of the climate change knowledge and its evolution (Haunschild et al. 2016; Li et al. 2011; Stanhill 2001). Some previous studies focused on issues relative climate change as a whole, e.g., climate change controversies (Anderegg et al. 2010; Jankó et al. 2014) or global research distribution among countries (Pasgaard and Strange 2013).

Bibliometric analysis has also been applied to subfields of climate change research. In particular, some articles address climate engineering, also called geoengineering (Bellamy et al. 2012; Belter and Seidel 2013; Linnér and Wibeck, 2015; Oldham et al. 2014). The definition of climate engineering is not well established (Boucher et al.

2014). This concept typically embeds two types of technologies: solar radiation management (SRM) and carbon dioxide removal (CDR). Even if BECCS fits within the latter category, it is explicitly excluded by Oldham et al. (2014) and Belter and Seidel (2013). Bellamy et al. (2012) estimate that BECCS appears in approximately 6% of all geoengineering appraisals.

Minx et al. (2017) analyse the bibliometric data on NETs, including BECCS. Through their discourse analysis, they show that the NET literature is split into three clusters: energy systems, forestry, and other land-based methods. BECCS is embedded in the energy systems cluster. To our knowledge, no bibliometric analysis has yet been published on BECCS.

For this purpose, academic articles on BECCS have been collected and a co-authorship network formed. Key actors (institutions and authors) are identified. It helps then to evaluate whether a research community truly exists on this topic and whether it is well adapted. Indeed, IAM research is shown to have a high-structuring effect on BECCS research. BECCS could benefit from the small world effect detected, which is useful to forward information, promote innovation, and build a common vision of the technology. However, the IAM community tends to focus on the long-term technological pathway rather than short-term implementation issues, which could hinder BECCS development. A cluster analysis is conducted to explore more deeply the topics studied by research teams.

The remainder of this article is organized as follows: Section 2 presents how the articles have been collected and the method used to build and analyse the co-authorship network (including clusters detection and analysis, evolution of the main component between 2010 and 2017, and eventually small-world effect). Section 3 describes general features of the dataset and analyses the co-authorship network, as indicated in Section 3. Section 4 discusses previous results and whether BECCS scientific community exists and whether it is fitted to research priorities. Concluding remarks and recommendations are provided in Section 5.

2 Methodology

2.1 Selection of articles: Queries and sorting

BECCS is an emergent technology whose name is not well settled. Even if the acronym BECCS is prevalent, numerous other terms exist, such as bio-energy with carbon storage (BECS), bioenergy carbon capture and storage (BE-CCS), biomass and carbon capture and storage (Bio-CCS), biomass and carbon capture and storage (BCCS), and

biotic CCS. This profusion of terms provides a first indication that the research field is not yet mature. In addition, some articles do not use a specific word and discuss “bioenergy and CCS”, “bioenergy-CCS”, or “biomass and CCS”. This approach is notably the case for engineering articles describing the features of a carbon capture technology as a suitable solution for bioenergy plants. The word “storage” is lacking. Another case is when the authors do not make reference to the general concept of BECCS when describing a particular application. For example, Uddin and Barreto (2007) detailed a biomass-fired cogeneration plant with CO₂ storage that they call CHP-BIGCC.

For these reasons, several queries are necessary. Documents using these acronyms are collected first; then, the dataset is extended with the query “bioenergy and CCS”. Data are derived from *Scopus* in 2017. However, the query “bioenergy and CCS” is duplicated in *Google Scholar* to identify additional documents. Only articles published in academic journals are retained in the dataset. Sorting is then required to avoid duplication and to select only relevant documents. Many papers do not deal solely with BECCS and compare its benefits (or drawbacks) with other technologies. These articles are maintained; however, those that only mention BECCS as a mitigation tool, without discussing its features, are deleted.

2.2 A co-authorship network analysis: Clusters detection and small-world effect

The collected articles are used to analyse the relationships between scientists working on BECCS through a co-authorship network. A co-authorship happens when a document has more than one other author; it is a record of collaborations between scientists that leads to a research output, here an article. Co-authorship is therefore a meaningful proxy for research collaborations, even though it is not the only one and even if all co-authors do not contribute to the same extent, as Melin and Persson (1996) note. Co-authorship networks are a kind of social network whose mathematical properties help to investigate the structure of a scientific community and its evolution. These properties can be assessed at the macro-level or micro-level. The macro-level regards the features of the overall network, and the micro-level investigates the role of specific scientists, e.g., the most productive or influential. A recent literature review concerning the co-authorship network can be found in Kumar (2015).

Following the small-world phenomenon described by Milgram (1967), Watts and Strogatz (1998) suggest that it may be common for many self-organizing systems (e.g., neural network, power grid), including social networks. These networks have small path lengths and are highly clustered. Compared to a completely regular network, a small-world network presents shortcuts. Data and knowledge can spread knowledge more quickly into the network. The

small-world effect is a common property of well-established co-authorship networks (Newman 2004). To this end, it is assumed that a network exhibits small-world properties (Goyal et al. 2006) if:

1. The number of nodes is very large compared to the average number of links,
2. The giant component exists and covers a large share of the population,
3. The average distance between nodes is short (the average path is of the same magnitude of the logarithm of the number of nodes), and
4. Clustering is high (largely superior to the number of links divided by the number of nodes).

The co-authorship network is built with the software *Science of Science* (Sci2) Tool and uses *Gephi* for the clustering and visualization. The network is represented as a graph, where the nodes are the authors and the links are collaborations on the articles. The width of the node is proportional to the number of articles published by the author.

Community detection is based on the algorithm of Blondel et al. (2008). The dataset of authors' names is cleaned to avoid duplicates and misidentification. Each cluster (or community) is studied to identify possible links between authors. This process is done qualitatively by reviewing authors' features, such as organizational affiliation and nationality, and also the common research issues between authors and research project funding.

3 Results

3.1 Publication trends on BECCS, main journals and articles

Our dataset of articles contains 465 documents—all academic articles published between January 2001 and June 2017. This research field is recent and still small. By contrast, the NET research field includes approximately 2900 articles (Minx et al. 2017), meaning 1.32% of articles published about climate change (Haunschild et al. 2016). Nevertheless, BECCS is a growing research area. After a period of relative stagnation in the yearly publication numbers, a dramatic increase is noted after 2012. Between 2012 and 2015, there is a doubling in publications each year (see Figure 1). The year 2010 corresponds to approximately 10% of all the articles published.

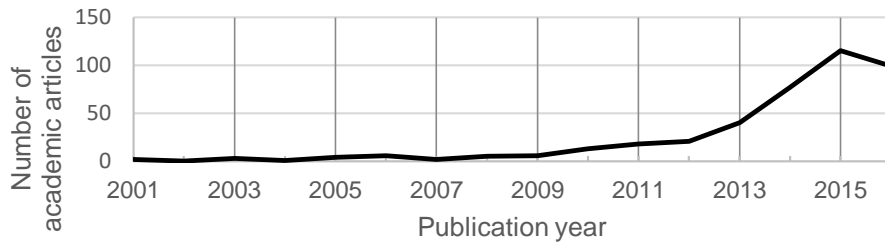


Fig 1 Evolution of academic articles on BECCS (January 2001-June 2017). Since 2017 is uncompleted, the number of articles is not added on this chart.

Table 1 presents the five academic journals publishing the most in the BECCS research field. The first journal is *Climatic Change*, an interdisciplinary journal publishing on BECCS since 2006. This journal has contributed to structuring the research field through several “Special Issues”, including the following examples:

- In 2013: "*Carbon Dioxide Removal from the Atmosphere: Complementary Insights from Science and Modeling*", edited by Massimo Tavoni, Robert Socolow, and Carlo; "*The Impact of Economic Growth and Fossil Fuel Availability on Climate Protection*", with Guest Editors Elmar Kriegler, Ottmar Edenhofer, Ioanna Mouratiadou, Gunnar Luderer, "*Geoengineering Research and its Limitations*", edited by Robert Wood, Stephen Gardiner, and Lauren Hartzell-Nichols.
- In 2014: "*The EMF27 Study on Global Technology and Climate Policy Strategies*", edited by John Weyant, Elmar Kriegler, Geoffrey Blanford, Volker Krey, Jae Edmonds, Keywan Riahi, Richard Richels, and Massimo Tavoni.
- In 2016: "*The Impact of Economic Growth and Fossil Fuel Availability on Climate Protection: Introduction to the RoSE Special Issue*", with Guest Editors Elmar Kriegler, Ottmar Edenhofer, Ioanna Mouratiadou, Gunnar Luderer, and Jae Edmonds.

Table 1 Five top journals publishing on BECCS.

Review	Number of articles
Climatic Change	53
Applied Energy	28
International Journal of Greenhouse Gas Control	27
Energy Procedia	24
Environmental Research Letters	21

The special issues in 2014 and 2016 focus on the comparison and improvement of IAMs that seek to assess climate mitigation scenarios. The Energy Modeling Forum Study 27 or EMF 27 (Kriegler et al. 2014), and Roadmaps toward Sustainable Energy futures or RoSE (Kriegler et al. 2016), are two modelling studies. EMF 27 aims notably at enlarging the technologies embedded in models, and RoSE explores the issue of mitigation pathways sensitivity. Nevertheless, IAM modelling was already present in 2013. For instance, there are five articles about IAM in the special issue on carbon-negative technologies.

The journal publishing the second most articles on BECCS is *Applied Energy*, which has had articles on BECCS since 2010 according to our dataset. Most articles have a strong focus on technology descriptions, e.g., life cycle analysis, innovative process, cost analysis, and review of technologies. However, five articles use IAM. These articles (technological or IAM-oriented articles) were published after 2012. *International Journal of Greenhouse Gas Control* is an academic journal interested in CCS issues, including the technological, political and economic aspects. The IAM is a more marginal issue there (three articles only), and most articles are technology oriented. Nevertheless, other topics appear, e.g., regional assessments (Akgul et al. 2014) and social acceptability (Wallquist et al. 2012).

Energy Procedia publishes conference proceedings, including most greenhouse gas control technologies (GHGT) conferences. The GHGT conferences are interested specifically in CCS. Conferences are held every two years, notably by the International Energy Agency (IEA). The IEA has been established within the framework of the OECD for energy issues and has produced roadmaps about CCS and BECCS (IEA 2013). The first articles about BECCS in *Energy Procedia* started in 2009. Most articles are dedicated to techno-economic assessments (15 articles), and only four use IAM.

The scope of *Environmental Research Letters* is wide since it is interested in all aspects of environmental science. The first related article was published in 2011; however, most are related to a special collection of articles entitled “*Focus on Negative Emissions Scenarios and Technologies*”, with guest editors Robert Jackson, Pep Canadell, Sabine Fuss, Jennifer Milne, Nebojsa Nakicenovic, and Massimo Tavoni; see Jackson et al. (2017). Techno-economic analyses are scarce (only two recorded); however, modelling through IAM is more common (8 recorded). There is also a set of letters, reviews, and comments about NET or BECCS, e.g., Fuss et al. (2016).

The top 10 publications about BECCS also show an over-representation of long-term modelling exercises (articles n° 1, 2, 3, 4, 9 and 10) or analysis stemming from their results (article 6), see Table 2. Most of the articles are not dedicated to BECCS but mention it or use it as a part of a portfolio of mitigation technologies.

Table 2 Top 10 publications on BECCS.

	Authors	Number of citations	Title
1	van Vuuren et al. (2011a)	2461	The representative concentration pathways: an overview
2	van Vuuren et al. (2011b)	454	RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C
3	Azar et al. (2006)	326	Carbon capture and storage from fossil fuels and biomass – Costs and potential role in stabilizing the atmosphere
4	Azar et al. (2003)	323	Global energy scenarios meeting stringent CO ₂ constraints — cost-effective fuel choices in the transportation sector
5	Faaij (2006)	286	Modern biomass conversion technologies
6	Fuss et al. (2014)	284	Betting on negative emissions
7	Yue et al. (2014)	264	Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges
8	Mathews (2008)	225	Carbon-Negative Biofuels
9	Kriegler et al. (2014)	222	The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies
10	Azar et al. (2010)	206	The feasibility of low CO ₂ concentration targets and the role of bio-energy with carbon capture and storage (BECCS)

3.2 BECCS co-authorship network: Main countries and institutions

There are 1118 authors who have contributed to the BECCS research field. As noted above, this paper is focused on the co-authorship network. Interestingly, 51.7% of the authors are connected to a giant component, meaning that they are linked together through their co-authors. A total of 84.77% of the links between the authors are within this component. This giant component is shown in Figure 2. Outside the giant component, authors work alone or in a small group. The second largest group contains only 17 authors with 6 corresponding articles.

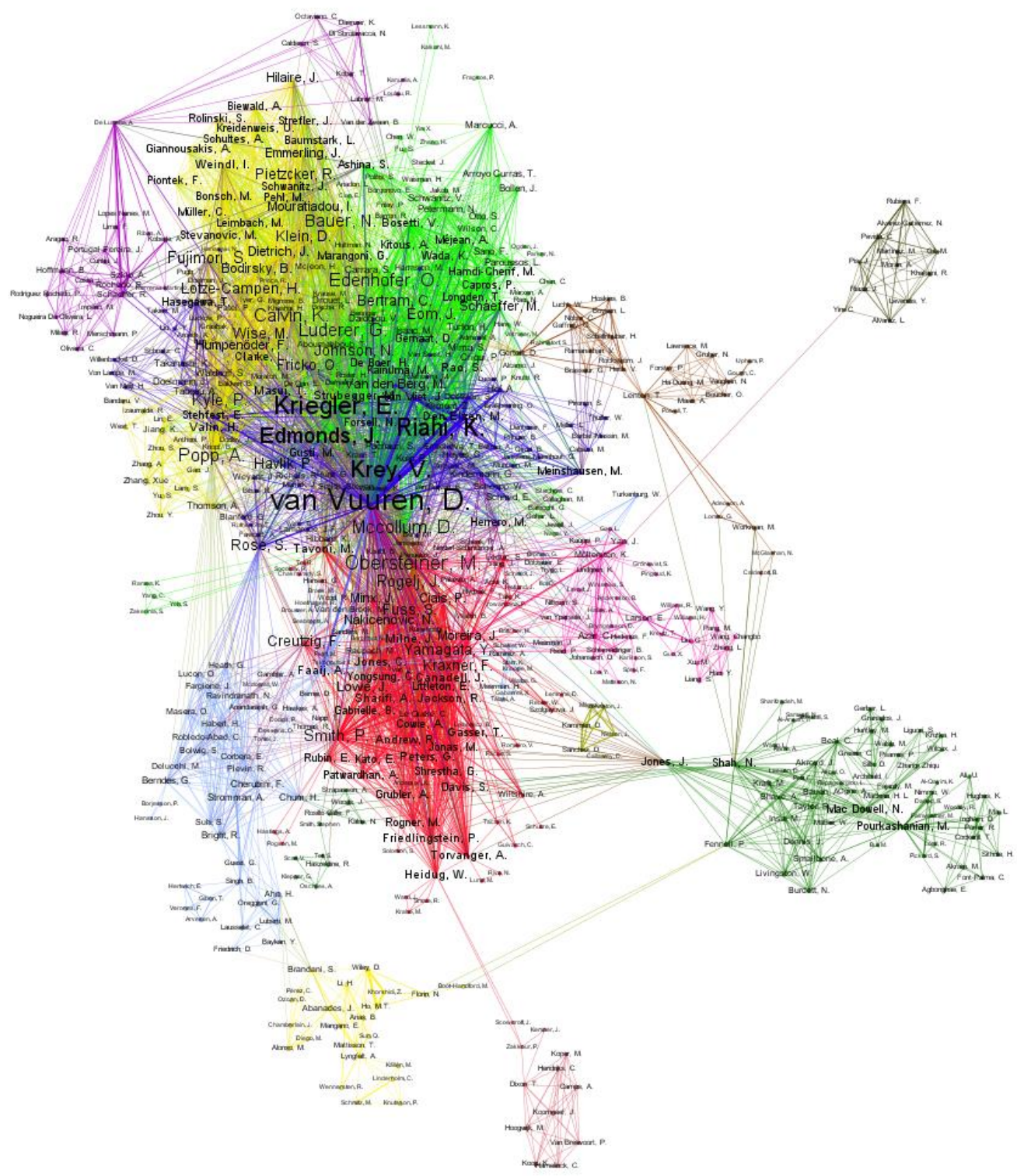


Fig. 2 Giant component of co-authorship network on BECCS. Nodes represent authors, and links represent co-authorship on an academic article. The size of the nodes is proportional to the number of co-authors.

The authors of the giant component come from 32 countries, see Figure 3. More precisely, it is the nationality of their institutional affiliation which is taken into account. More than two-thirds (67%) of the researchers are European. In the European Union, the most highly represented nation is the United Kingdom (17.74%), followed by Germany (11.83%), the Netherlands (9.39%), and Austria (7.83%). The country publishing the second most articles is the United States (17.04%). Most Latin American researchers come from Brazil (4.17%). Asia is less prevalent, although there are Chinese authors (3.30%) as well as Japanese (2.96%). Researchers from Oceania are marginal (less than 2%), and there are even fewer from Africa and the Middle East.

This Western tropism does not match well with the BECCS potential, which is assumed to be greater in emergent countries. Nevertheless, such a tropism is not specific to BECCS. Climate change research as a whole is biased towards developed countries and towards mitigation aspects rather than adaptation (Pasgaard and Strange 2013).

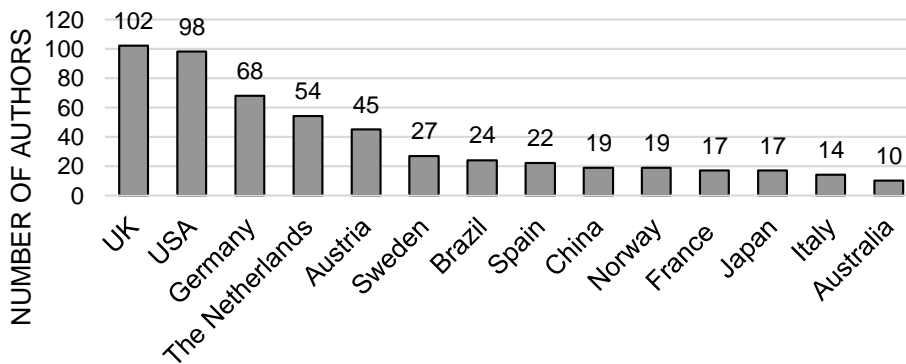


Fig. 3 Main nationalities of researchers in the main component (more than 10 authors).

Another way to investigate the origin of authors is to look at their institutional affiliation (see Table 3). The most prominent organization is the Potsdam Institute for Climate Impact Research (PIK) in Germany, followed by the International Institute for Applied Systems Analysis (IIASA) in Austria. Other organizations include less than 5% of authors.

Some of these organizations are explicitly involved in the IAM research community. More precisely, PIK develops the model REMIND; for IIASA, the model is MESSAGE; for PNNL, it is GCAM; for PBL, it is IMAGE; and NIES uses AIM. Some of the oldest articles about BECCS had authors hosted by Chalmers University and IIASA.

Table 3 Top 10 institutional affiliations of authors in the giant component

% of authors	Institutional affiliation of authors	Country
8.48	Potsdam Institute for Climate Impact Research (PIK)	Germany
7.61	International Institute for Applied Systems Analysis (IIASA)	Austria
4.67	Imperial College London	United Kingdom
3.98	Pacific Northwest National Laboratory (PNNL)	USA
3.98	PBL Netherlands Environment Assessment Agency	The Netherlands
3.81	Utrecht University	The Netherlands
2.94	Chalmers University of Technology	Sweden
2.77	Universidade Federal do Rio de Janeiro	Brazil
2.42	University of California	USA
1.90	National Institute for Environmental Studies (NIES)	Japan

3.3 Cluster analysis of the co-authorship network

A clustering algorithm (following Blondel et al. 2008, see section 2.2) is used to identify clusters of researchers (Figure 1). Each colour refers to a different cluster. This subsection describes the main clusters of the giant component. Clusters of less than 2% of the authors are not investigated here.

3.3.1 Hyper-central cluster

With almost 13% of the authors, this cluster is the second in number in the database but is, above all, the most central (in dark blue; see Figure 2). The authors in this cluster are very connected within the cluster and with adjacent clusters, as described below. At the core, there is the most prolific author of the database—Detlef P. Van Vuuren—who also has the most co-authors and the highest score of betweenness closeness. The most common institutional affiliation is PBL (the Netherlands), with 13.33% of authors, followed by IIASA (Austria) with 9.33%. Not surprisingly, the Netherlands is the first country found (15.33%) with Austria the second, on equal terms with the USA.

The topics of the related articles are very diverse. This diversity is amplified by the high number of contributions considered outside the cluster because an article can have authors in several clusters. Nevertheless, the

articles use IAMs (mainly IMAGE-TIMER, developed by PBL, which is often compared with other IAMs), in common. The risk of delay in climate policy is the main issue here, especially for a stringent target such as the RCP2.6 (van Vuuren et al. 2013). Furthermore, the threat of biomass overuse is stressed, with consequences on food production, e.g., in Lotze-Campen et al. (2014). In most of the papers, BECCS is not the main subject but the technology is included in the mitigation tool portfolio. It seems relevant that central researchers are interested in the most stringent scenario.

3.3.2 North clusters

North clusters are respectively named: northwest central clusters (in yellow), northwest peripheral cluster (in purple), and northeastern central cluster (in light green).

The northwest central cluster is the third cluster in number of authors (in yellow). Katherine Calvin has the most articles (19 articles) and the highest number of co-authors, but Alexander Popp has a higher score of betweenness because of the cluster's role as a broker towards other clusters. PIK (Germany) and PNNL (USA) embedded 28.35% and 20.54% of authors, respectively. As noted above, PNNL has built GCAM and is devoted to the RCP4.5 W/m², a less stringent scenario than RCP2.6 W/m². These factors might explain the slightly more peripheral location of these authors. Articles with authors from PIK generally combined the model REMIND with MAgPIE (a global land-use optimization model) and PLJmL (a global vegetation and hydrology model), see Popp et al. (2011).

With only 5.02% of authors, the Northwest Peripheral is the 8th cluster (in purple). There is no clear leading author in this cluster. A subset of 55.17% of the authors is hosted at the Universidade Federal do Rio de Janeiro (Brazil), and 67.74% come from Latin America. This small cluster is primarily interested in the energy potential of Latin America under climate constraints. Studies are often made at the national level, e.g., assessing, for instance, CCS development in Brazil (Rochedo et al. 2016). Some articles do not rely on IAM but are funded through research projects that aim to develop this type of analysis. Two main research projects have been identified (through the acknowledgements sections of articles). The first one is named the European Brazilian Network on Energy Planning (NETEP) and is part of the 7th European Union Framework Programme (2014-2017). The second project is the Integrated Climate Modelling and Capacity Building Project in Latin America (CLIMACAP), which also benefits from European Union funding. This project was coordinated by PNNL see van der Zwaan et al. (2014).

A subset of 12.11% of the authors belong to the northeastern central cluster which is the 4th largest (light green). The most prolific author is Elmar Kriegler. He also has the largest number of co-authors. Most authors are European (78.57%), of whom 30% are German. The main institution is PIK, with 18.57% of the scientists. This cluster is focused on IAM harmonization and comparison. This strategy is achieved through modelling exercises, in some cases with several models that give an indication of uncertainties and diversities of viewpoints, e.g., EMF 22 and EMF 27. Some other modelling exercises compared only a few models to go into further detail (see RECIPE). Two research projects structure this cluster: AMPERE and RoSE. The most common IAMs are GCAM, REMIND and WITCH, followed by MESSAGE, IMAGE, TIAM, and IMACLIM. This diversity of models could explain the proximity of this cluster with the hyper-central and Northern central clusters.

3.3.3 South clusters

There are four clusters referred as south clusters here: the central south cluster (in red), the peripheral southeast cluster (in forest green), the peripheral southwest cluster (in blue) and the peripheral south cluster (in yellow).

Central south cluster is the main group that contains 13.10% of the authors. The most published scientist is Michael Obersteiner, followed by Sabine Fuss and Florian Kraxner. Nevertheless, the score of betweenness of Pete Smith is high, which indicates his role as a broker in the network. The IIASA is predominant here, with 22.07% of authors. The next institution is CICERO, with 7.89%. This cluster contains some of the oldest articles, e.g., Obersteiner et al. (2001), using the IAM model MESSAGE. Although IIASA developed an IAM, other methods are also used here to assess the potential of BECCS, notably for South Korea and Japan (Kraxner et al. 2014a, b). Recently, viewpoints and literature reviews have appeared that highlight BECCS limitations (Fuss et al. 2014, 2016). These authors evaluate whether NET expansion could occur sufficiently fast and worry about its repercussions on biodiversity. The IAM results are then used as a benchmark for their discussion.

The peripheral southeast cluster is the 4th largest, with 11.07% of authors (coloured in forest green). The most prolific author is Nilay Shah (ten articles collected), who also has the most co-authors. Nevertheless, Jenny Jones has the most important betweenness score of the whole network, followed by Detlef P. Van Vuuren. Jenny Jones links this cluster with the southern, hyper-central and north-eastern clusters. A large part of authors work in British

institutions (72%), some of them in the Imperial College (26.56%) and Sheffield University (14.06%). These articles are rather recent, typically after 2013. They provide techno-economic insights regarding the cogeneration of coal and biomass and related subjects, e.g., impurities in exhaust streams (Porter et al. 2015) or biorefineries (Sharifzadeh et al. 2015). Furthermore, there are articles about microalgae (Greene et al. 2017) and national-scale assessments for countries such as Qatar (Al-Ansari et al. 2014) and the United Kingdom (Sithole et al. 2016).

The peripheral southwest cluster is in 6th position, with 9.34% of the authors. André Faaij has published the most articles about BECCS. Utrecht University is the first affiliation (25.93%) and NTNU the second (20.37%). The Netherlands and Norway are the two main countries in this cluster. Although André Faaij has published about BECCS since 2006 (Faaij, 2006), most of the articles are recent (after 2013). A recurring theme is the life-cycle analysis of industrial processes, e.g., Oreggioni et al. (2017). More generally, there is a strong interest in environmental impacts other than climate change, such as human health (Gibon et al. 2017). IAMs are not yet forgotten and are sometimes adapted to fit the national scale, e.g., in the Netherlands (Tsiropoulos et al. 2017).

The peripheral south cluster is the smallest cluster with 3.98% of authors. The most prolific authors are Dianne Wiley and Minh T. Ho. Chalmers University is the most represented institution. The main nationalities are Sweden and Spain. Articles in this cluster are specialized in techno-economic analyses, especially carbon capture systems and co-firing systems, e.g., Khorshidi et al. (2015).

3.3.4 East and peripheral clusters

This subsection is interested in the last two clusters : the peripheral eastern cluster (in brown) and the slightly peripheral eastern cluster (in pink).

The peripheral eastern cluster is the 9th largest cluster, with only 4.65% of authors (in brown). This cluster is linked to the rest of the network by only a few authors. Timothy Lenton holds a central position in this cluster and is the main author. The cluster is dominated by British (44.44%) and German (29.63%) scientists. There is no clear leading institution here. The Imperial College of London, Humboldt-Universität zu Berlin, and PIK are roughly equal. Unlike previous clusters, this one does not rely on IAM. The focus is on NETs, and BECCS is a part of this portfolio

tool (Lomax et al. 2015). BECCS is also perceived as a geoengineering process (Boucher et al. 2014), which is the issue with the two research programmes REAGIR (in France) and EuTRACE (UE FP7).

At the 7th position, the slightly peripheral eastern cluster includes 6.21% of authors (in pink). The leading institutions are Chalmers University of Technology (27.78%) and Princeton University (16.67%). Kenneth Möllersten and Christian Azar are the main authors in terms of publications and number of co-authors. These authors are some of the pioneers of BECCS (Azar et al. 2003; Obersteiner et al. 2001). Eric Larson has a higher betweenness score. He serves as a bridge to a Chinese team (mainly from Beijing Normal University) interested in technical assessments. For instance, Pang et al. (2017) carried out a study concerning the life-cycle analysis of an electric plant fed with spirulina. Some articles utilize the GET model to assess the evolution of transport and energy sectors (Azar et al. 2003). There are also the former techno-economic analyses dedicated to BECCS, for paper and ethanol utilizations (Möllersten and Yan 2001; Möllersten et al. 2003). More recently, some articles deal with the possible synergies between BECCS and shale gas (Hailey et al. 2016; Liu et al. 2011).

3.3.5 Synthesis of cluster analysis

Table 4 sums up the main information given by each cluster detailed previously. The most central clusters are more likely to focus on IAMs and long-term policy analysis. Local studies and techno-economic assessments regards smaller research teams and are located more peripherally in the network.

Table 4. Cluster analysis of the co-authorship network on BECCS. Main institutions, authors, and research interests.

Cluster	Number of authors (%)	Main institution	Main nationality	Most prolific author	Place of IAMs in the cluster	Other features of the cluster
Hyper-Central	12.98	PBL	The Netherlands	Van Vuuren D.	Very high	Strong presence of IMAGE - TIMER
Central Northwest	12.63	PIK (and PNNL)	Germany (and USA)	Calvin K.	Very high	Strong presence of GCAM (PNNL) and MAgPIE (PIK)
Peripheral Northwest	5.02	Universidade Federal do Rio de Janeiro	Brasil	Lucena A., Schaeffer R. et Szlo A.	High	Analyses on Latin America and Brasil
Central Northeast	12.11	PIK	Germany	Kriegler E.	Very high	Articles linked by research projects about IAM comparisons
Peripheral Eastern	4.65	No central institution	United Kingdom	Lenton T.	Marginal	Articles about Negative Emissions and geoengineering Cluster with a lot of approaches.
Central South	13.10	IIASA	Austria	Obersteiner M.	Medium	Presence of seminal authors
Slightly Peripheral East	6.10	Chalmers University of Technology	Sweden	Möllersten K.	Low	Analyses with the GET models and techno-economic analyses. Presence of seminal authors
Peripheral Southeast	11.07	Imperial College of London	United Kingdom	Shah N.	Marginal	Techno-economic analyses, focus on cogeneration and capture technology
Peripheral Southwest	9.34	Utrecht University	The Netherlands	Faaij A.	Medium	IAM at a national scale, Life-cycle analyses
Peripheral South	3.96	Chalmers University of Technology	Sweden	Wiley D.	Marginal	Techno-economic analyses, focus on cogeneration and capture technology (chemical looping combustion)

3.4 Comparison with co-authorship network in 2010

As noted in Section 4.1.1, the number of publications on BECCS has considerably increased in recent years. In 2010, there were only 42 articles published according to our database, accounting for 8.94% of all articles. Obviously, there were also a small number of authors, i.e., 74, of whom 31 authors are included in the main component,

as depicted in Figure 4. The proportion of authors connected to the main component increased from 41.89% to 51.79% in 2017.

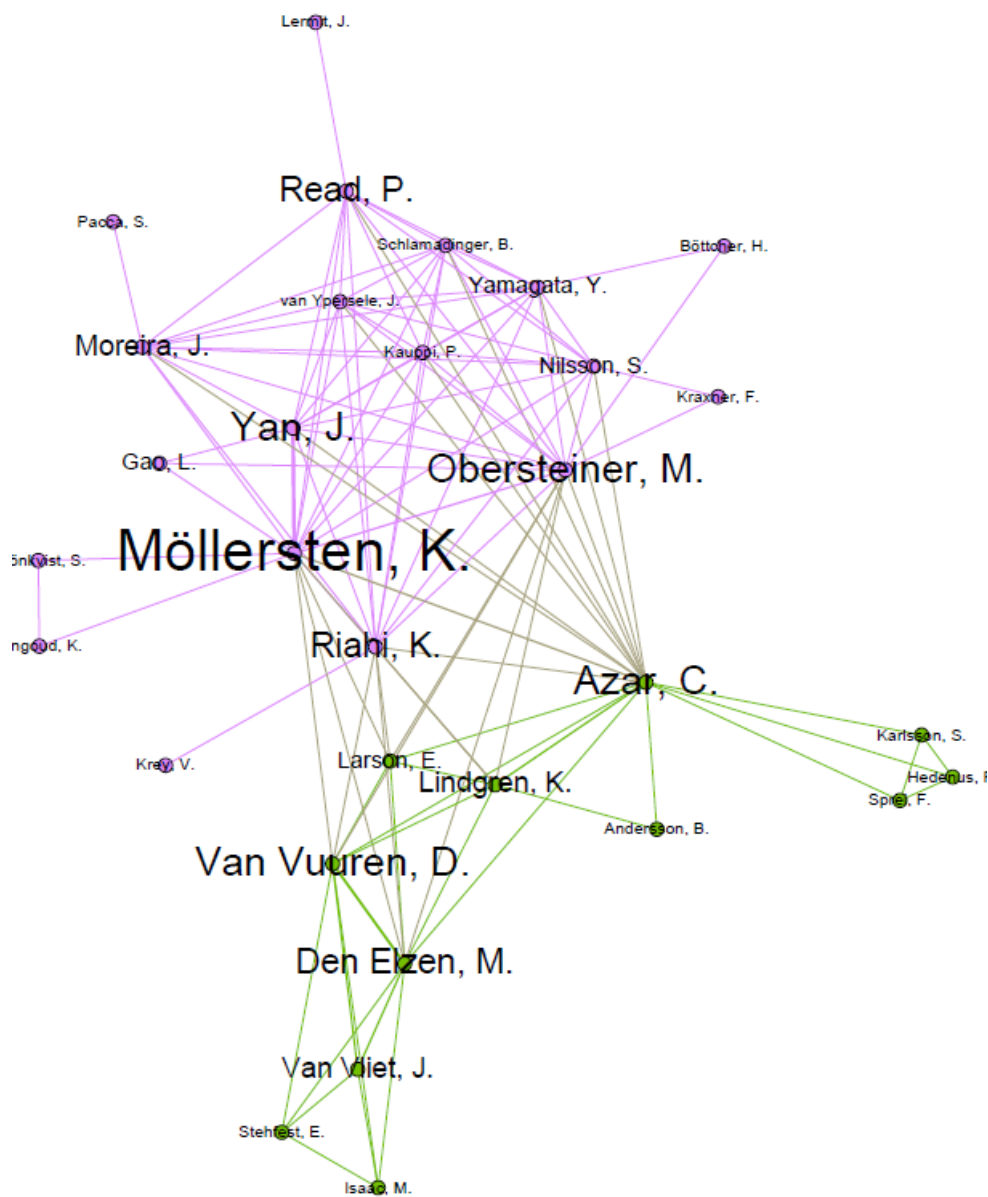


Fig. 4 Co-authorship network on BECCS in 2010 (only the giant component is shown).

The main institutions are Chalmers University and IIASA and, to a lesser extent, PBL. The network appears to be separated into two parts: one dominated by authors affiliated with Chalmers University and the other by authors affiliated with IIASA.

Kenneth Möllersten, Christian Azar, and Michael Obersteiner are the researchers with the most co-authors (more than 18 in 2010). There are seminal authors publishing on BECCS since 2001 (Obersteiner et al. 2001). Kenneth Möllersten was the most prolific author in 2010, and Christian Azar has the highest score of betweenness closeness.

Moreover, the comparison of the 2010 and 2017 networks shows that the current network has been built by an incremental aggregation of authors to this initial main component rather than the linkage of separated clusters of similar size. Among authors in 2010, 34.48% are now linked to the main component. Those who are still not connected published mostly techno-economic analyses. In contrast, authors working with IAM outside the network in 2010 are now integrated, e.g., Luckow et al. (2010) and Tavoni and Tol (2010).

3.5 Small-world effect

Several macrostatistics of the co-authorship network are provided in Table 5. These metrics are used to assess the possibility of a small-world effect in 2010 and in 2017.

The four properties of Goyal et al. (2006) needed to assume small-world properties are respected in 2010 and in 2017 (see Section 2.2). In 2010, the average number of links—meaning the average number of co-authors—is 4.405, which is far lower than the number of authors (74 authors). A main component has already emerged. This largest group of interconnected authors comprises 41.89% of authors, and there is no other large group; the second largest consists of only seven authors. Third, the average path length is approximately 1.93, which is almost half the logarithm of the number of authors (4.30). The clustering property is high since the average clustering coefficient is 0.931 compared to 0.009. In 2017, the average number of co-authors increased, reaching approximately 10.35; however, it is still very low with respect to the 1118 authors in the network. The main component is also larger in number (578 authors) and in proportion (51.7% of the authors are in the main component). The other groups of authors are extremely small in comparison. The average path length has risen steadily (3.63) but remains contained ($\ln(n)$ equals 7.12), and the clustering is still larger. The average clustering coefficient is 0.903 compared to 0.009. There is a small-world effect for academics working on BECCS, despite the facts that the average distance grows and the clustering coefficient slightly diminishes. The small-world features provide evidence for the emergence of a scientific community. This finding suggests that information can move rapidly across the network.

Table 5. Macroeconomic statistics of the co-authorship network

Statistics	2010		2017	
	Total	Main Component	Total	Main Component
Nodes	74	31 (41.89%)	1118	578 (51.7%)
Links	163	118 (72.39%)	5784	4899 (84.7%)
Degree	4.41	7.61	10.35	16.95
Diameter	4	4	10	10
Density	0.06	0.254	0.009	0.029
Modularity	0.53	0.28	0.64	0.56
Number of Communities	20	4	167	18
Average Clustering Coefficient	0.93	0.87	0.90	0.85
Average Path Length	1.93	2.02	3.61	3.62

4 Discussion: Is there a BECCS community?

The co-authorship network presents a main component and the mathematical properties of a small-world effect. In addition, the network is strongly increasing, as is the number of publications. These features seem to indicate an emerging academic network dedicated to BECCS.

Given that the acronym BECCS is the association of a sector (bioenergy) and a technology (CCS), one can imagine that the academic network would mirror this dual origin. However, the cluster analysis shows that BECCS is not an overlap between a research community working on bioenergy and another research community working on CCS. Similarly, it might be assumed that BECCS would be a subpart of a larger network on negative emissions. Nevertheless, most articles do not refer to another NET, with the exception of afforestation. Rather, articles dealing with negative emissions (or geoengineering) occur on the edge of the network.

As shown in the previous section, the BECCS academic network has been based on IAM academic literature since its infancy. The first article of the dataset refers to IAM (Obersteiner et al. 2001). This cluster analysis reveals that several clusters are explicitly specialized in IAM (a high or very high presence). Highly connected to each other, these clusters have a central location or a northern location (namely, the hyper-central, northwestern, peripheral northwestern, and northeastern clusters). Furthermore, the other clusters involve IAM or cite them even more marginally.

In other words, BECCS is mainly thought about and designed by scientists who work on the mutation of the energy system under a climate constraint, primarily at a global scale and until 2100, through economic models based

on partial or general equilibriums. In such models, BECCS is not the only type of technology investigated. No technology could solely solve the climate constraint; thus, BECCS is part of a technological portfolio. Paradoxically, most articles about BECCS are not entirely dedicated to it. Thus, the BECCS community could be perceived as a subfield of the IAM community.

The IAM community is structured institutionally by the IAM Consortium (IAMC). Indeed, in 2007, the IPCC promoted the establishment of the Assessment Modeling Consortium (IAMC) that seeks to coordinate IAM modellers and to become an interlocutor for other institutions, including the IPCC. The IAMC includes more than fifty organizations today. As a consequence, the IAM community is largely aligned with the need for climate scenarios. Notably, this community provides a set of scenarios - named representative concentration pathways (RCPs) - that span the range of radiative forcing values, from 2.6 W/m² to 8.5 W/m² in 2100 see Van Vuuren et al. (2011a). The RCPs served as the basis for climate change projections assessed in the IPCC Fifth Assessment Report. Different organizations were in charge of each scenario.

The footprint of this research programme is clear in the co-authorship network: all of these organizations and models are present, and above all, the RCP 2.6 scenario appears to be central in the network. Authors in the hyper-central cluster are often affiliated with PBL, and the corresponding articles deal with the RCP 2.6. More recently, new socioeconomic scenarios, named shared scenarios pathways (SSPs), have been designed to replace the scenarios from the Special Report on Emission Scenarios (SRES), see Riahi et al. (2017). The SSPs are combined with RCPs into a new scenario framework in a scenario matrix architecture. There are 16 articles that mentioned the SSPs in our dataset.

Thus, it is clear that the BECCS community is based on the IAM community to a large extent. This relation probably explains the small-world effect despite the fact that BECCS is still a young research issue. Moreover, techno-economic analyses are somewhat in a minority, although some were published earlier. Nevertheless, it seems that the BECCS notoriety increases and consecutively enhances new topics and/or new methods. For example, there are more techno-economic analyses on the edge of the network, such as new capture technologies, life-cycle analysis, and implementation issues.

To enhance BECCS research – and notably short-term issues – it is necessary to change the structure deeply of the network. Peripheral topics should become more central to assess the real potential of BECCS in every dimension (technical, economic, and social), and avoid blind spots. To do so, some recommendations can be made, such as : i) developing new research programmes that support techno-economic analyses and research about the implementation

process ; ii) including authors (and institutions) outside the network or very peripheral into these research programmes ; iii) suggesting roadmaps for the next 20 years specific for BECCS (and not as a simple variant of CCS) ; iv) increasing bridges to authors working in bioenergy (and agri-food) as well as negative emissions technologies ; v) including social sciences (e.g. economics, sociology, human geography, law).

5 Conclusion

The dataset includes 465 research articles from January 2001 to June 2017 and allows us to identify overall publication trends, top academic reviews, and the most-cited articles. In this study, a co-authorship network was built and a cluster analysis was carried out. Key actors (institutions and authors) were detected, taking into account their location inside the network. The results show that the research field is largely driven by the IAM research community, which is well structured and provides scenarios for the IPCC. This community can help spread information around the BECCS community and thus to build a common vision of the BECCS potential in the sustainable transition.

However, such a focus on IAM could also have drawbacks. In particular, there are too few techno-economic analyses, especially when considering a short-run implementation. There are also limited studies at the national scale. Concerns about biodiversity impacts and competition with food should also be better investigated.

Improving the integration of researchers outside the network can increase the global knowledge about BECCS. This is especially the case for researchers providing techno-economic assessments or those interested in short-term implementation issues as well as researchers working on other NETs.

A global awareness about the emergency of these research issues is needed. It has to become research priorities - e.g. inside new research programmes – in order to build an efficient innovative BECCS community. Otherwise, there is a risk of a bitter disappointment regarding BECCS potential.

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