Technology, policy and management for carbon reduction: A critical and global review with insights on the role played by the Chinese Academy

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The development of new technologies and techniques for industrial carbon reduction has risen to prominence in contemporary engineering and economics studies, a trend triggered by rising levels of concern regarding climate change. Within this context, the scientific literature puts emphasis on energy topics and energy policy. Studies from the social science, economics and management science perspectives would benefit from a coherent and recognized taxonomy of the subthemes, a taxonomy that spans disciplines and guides studies of the carbon reduction and technology (CRT) debate in the various industrial sectors. This paper identifies and analyses the existing body of literature; it systematically reviews a set of 3310 scholarly contributions. The study also conducts a semantic social network analysis from that dataset's keywords, identifying promising core themes. Findings include the need for more management research in this field, the need for an interdisciplinary research agenda. We also observe a growing contribution of the Chinese academy to this complex and diversified debate.

Keywords: Carbon reduction; Technology; China; Industrial sustainability.

1 Introduction

Over the last decade, climate change and thus carbon emissions have become a major concern of society. Academics and policy makers alike assume that traditional patterns of growth and consumption cause negative external effects on the environment as well as on human living conditions (e.g., Beccherle and Tirole, 2011; Brahic, 2014; Georgakellos, 2012; Hughes et al., 2010; Krause, 1996; McCartney et al., 2008; Musso and Rothengatter, 2013; Rosen and Guenther, 2015). These effects respectively the climate change implications are severe (Boxall, 2014; Bray, 2010; Desjardins, 2013; Lacressonnière, 2014; Ratter et al., 2012). Consequently, recent policy research reveals an increasing number of carbon emissions assessment initiatives and national policies around the globe (Auld et al., 2014; Chou and Liou, 2012; Hübler et al., 2014; Ishii and Langhelle, 2011; Khanna et al., 2014; Mackay and Probert, 1995; Moore et al., 2014; Prasad and Munch, 2012; Roelfsema et al., 2014; Saveyn et al., 2012; Tang et al., 2012; Yuan et al., 2012). Previous research has amassed a diverse body of knowledge concerning the characteristics of that challenge as well as regarding the instrumental role of technology for its mitigation. Our paper pursues to develop a coherent and recognized taxonomy of the many subthemes that spans disciplines and guides studies of the carbon reduction and technology (CRT) debate. Specifically, we identify the distinct subthemes of carbon reduction in industry and therefore future research directions for management science and industrial management studies.

The management science and economics literatures in their turn contain a rich body of knowledge concerning various perspectives of climate change mitigation. One stream of research discusses the development and role of new low-carbon technology, sustainability indicators for decision-making and new techniques for industrial sustainability (Garniati et al., 2014; Hansson, 2010; Ion and Gheorghe, 2014; Janeiro and Patel, 2014; Kuehr, 2007; Markusson, 2011; Montalvo, 2008; Sabadie, J., 2014; Shi and Lai, 2013; Van der Gaast et. al, 2009). A growing number of studies provide functional insights to managing for sustainability. Such perspectives include ‘green’ marketing (Ko et al., 2013; Rex and Baumann, 2007), sustainability accounting and reporting (Hahn and Kühnen, 2013) or ‘green’ logistics (Colicchia et al., 2013; Demir et al., 2014). Other scholars from across scientific disciplines call for new consumption patterns, a circular economy and downscaling. Those patterns are to acknowledge the limits to growth, in particular, a scarcity of energy resources (Kalimeris et al., 2014; MacKenzie, 2012; Sekulova et al., 2013; Sorman and Giampietro, 2013). This paper explicitly focuses on research into the role of new technology for carbon reduction and emissions mitigation. We analyze the structure and features of the debate, including the range of new technologies, scientific disciplines and affected industry sectors.

Research into *carbon reduction and technology* (hereafter referred to as ‘CRT’) is highly dispersed in terms of disciplines and frequently case specific (i.e. Fu et al., 2014; Napp et al., 2014; Rai et al., 2014; Shi et al., 2012; Szolgayová et al., 2014; Xiao et al., 2014; Xu et al., 2013). Thus, the principal contribution of our study is to provide a guide to the current body of knowledge for the full CRT debate. First, it informs future research by clustering promising topics and setting them into the context of industrial sustainability. While previous research has developed a number of terminologies for environmentally sound technology and cleaner production, the scholarly contributions lack a coherent metadiscipline. There is in particular no systematic literature review providing clarification and organization on the prominence of different technologies considered in the CRT debate. Second, we investigate the contribution of the Chinese Academy to all the identified themes in the CRT debate. Although over time a number of studies have looked at technology transfer to emerging economies such as China (e.g., Saikawa and Urpelainen, 2014; Ang, 2009; Liu and Jiang, 2001), and into intellectual property concerns (Lee et al. 2009), only few articles, e.g. De la Tour et al. (2011), Liu and Goldstein (2013) or Gosens and Lu (2014), vice versa have addressed the role of the Chinese academy’s and economy’s own contribution to the global development of green and clean technology.

This paper is also distinctive in terms of its methodology, which combines social network analysis of keywords co-citation data with bibliometric rankings of authorship, journal source titles and citation data. Previous literature reviews do not process an equally rich dataset or methodology. The findings from our study open up new directions for the economic and business study of CRT in an industrial context.

The structure of the paper is as follows. Section 2 reflects on current definitions and terminologies of technology in the context of carbon reduction. It sets the context of management and economics studies before moving to the quantitative analysis in the following sections. Section 3 then explains the research methodology: dataset sampling and analysis. Sections 4–5 systematically analyze academic contributions relating to CRT. Section 4 applies bibliographic methods, while section 5 conducts a social network analysis of the dataset articles’ keywords. Thereafter section 6 discusses the implications of our findings for future studies. Specifically, we create a coherent classification spanning an interdisciplinary and heterodox literature. Technology management and economics scholars will find a state-of-the-art framework guiding empirical research in technology development and techniques for carbon reduction. Across sections, we put emphasis on investigating the role of Chinese researchers within the CRT debate. Finally, section 7 summarizes the conclusions.

2 Theoretical Framing

2.1 Justification of research

A growing number of studies in industrial economics and economic policy refer to the concept of a ‘clean’ industry. This includes reference to the use of ‘clean technology’ (some authors excluding nuclear power technology), ‘clean production’, and modified industrial processes that avoid greenhouse gas emissions as well as limit the consumption of fossil fuels (Pérez-Martínez et al., 2014; Markusson, 2011). Furthermore, Zhang et al. (2013a) define carbon capture, utilization and storage as technology that realizes low-carbon for fossil fuels or energy consumption. Their definition then covers storage, production & manufacturing technology utilization that is more efficient and transport of CO_2. Furthermore, Okagawa et al. (2012) distinguish different types of clean and green innovation; they differentiate between the ones that improve carbon intensity (renewable energies, bioenergy) and those that increase autonomous energy efficiency.

Likewise, policy scholars, technology development and commercialization-related academics have introduced a category named ‘environmentally sound technology’. It represents a listing of process and product technologies, which policy makers and counselling economists believe to facilitate the reduction of carbon emissions in both traditional and new manufacturing industries. More precisely, Muchie (2000, pp. 203f.) refers to technologies ‘generating little or no waste’, ‘integrated technological systems’ of knowledge experience and routines, goods & services and related equipment, or technological paradigms. Those are ‘environmentally sound’ if they prevent pollution or treat pollution after it has been generated (UNEP, 1992, ch. 34 §§1–2; Muchie, 2000). Therefore, technology in this context is instrumental to policy targets. Specifically, new technologies are expected to contribute to the ‘maintenance of natural resources used for production’, promoting an industry which becomes less environmental degrading to the atmosphere (CO_2 emissions), biosphere or geosphere. ‘Clean’ is also not a fixed term but a dynamic one: today’s clean technology may appear dirty in the light of future technological progress (Hale, 1995). Additionally, some product and process innovation studies refer to ‘low carbon technology’. That terminology again embodies technological innovations for an economy emitting lower quantities of greenhouse gases (Shi and Lai, 2013) while practitioners put emphasis on the energy sector as well as aspects of energy efficiency (e.g., House of Commons, 2010). Equally, practitioners, policy-makers (Appleton, 2006; Ernst & Young, 2011; Kennet et al., 2009; Lacy et al., 2010; critical cf. Károly, 2011) and academics address the challenge of industry transformation for environmental sustainability (Kumar et al., 2012; Markard et al., 2012; White and Noble, 2013).

Within this paper, we shall define the CRT debate as follows. It shall cover any reflection or evaluation of product or process technology or techniques, where academics assume that technology/technique will reduce carbon emissions in an industry or across the different industrial sectors.

There are few bibliographic literature reviews related to CRT: They are not interdisciplinary and somewhat biased toward a specific scientific discipline or technology group. Previous review papers usually also process a much smaller dataset than is addressed here. For instance, Shi and Lai (2013) provide a review of ‘green and low carbon technology innovation’. They find that authors of highly cited papers are usually from developed countries and that renewable energy, including energy efficiency initiatives, takes an instrumental role in the mitigation of climate change (pp. 842ff.). Shi and Lai identify a number of ‘green and low carbon technology innovation’ themes, namely, regulation/policy innovation; adaption and diffusion; technology transfer; technology innovation management and capability; research and development; and entrepreneurship innovation. Likewise, the concept of environmentally sound technology has nurtured an own field of technology and innovation studies. The WIPO IPC Green Inventory including related Y-patent classes categorizes the many environmentally sound technologies and it has become a common classification for comparative international patent analyses (Costantini et al., 2013; Shapira et al., 2014; Veefkind et al., 2012; WIPO, 2010). Among others, these examples illustrate how scholars have developed a number of disciplinary perspectives upon carbon reduction but lack a coherent mental map of the various options of CRT across the different industry sectors.

The aim here, therefore is to develop a consistent meaning for the term ‘carbon reduction’ *and* ‘technology’, equivalent to the ‘triple-bottom-line’ (Elkington, 2001), a well-acknowledged theory framework for sustainability in industry or society, balancing an economic perspective, environmental responsibility and social responsibility. This review aims, in similar vein, to cluster the various current opportunities of technology use for carbon reduction and for the various industries. This study explores a unique large dataset representing the CRT debate; and it promotes a consistent terminology for the area of carbon reduction in industry, which we label as ‘(environmental) industrial sustainability’. For instance, Shi and Lai’s (2013) search term ‘innovation’ already embeds a number of assumptions such as novelty, whereas this paper detaches the debate upon ‘technology’ from any such pre-assumptions. The use of different terminologies in different scientific disciplines impedes the cross-fertilization of findings upon industrial sustainability. This study provides a tangible agenda for future empirical research and it critically appraises the topicality of Chinese academy’s research development in CRT.

2.2 Selected framework for the proposed analysis

Within this section, we critically review contemporary terminologies of technology in the context of carbon reduction. The terminology frameworks illustrate the state of the art challenges under discussion, and at the same time, clarify the object of study.

Kuehr (2007) divides ‘environmentally [sound] technology (EST)’ into zero impact, clean technologies; cleaner technologies that minimize industrial processes’ harmful effects to the natural environment; cleansing technologies at the end-of-pipe / product life; and techniques measuring on the environment. He emphasizes that green technology, clean technology and clean production each pursue the mitigation of pollution and carbon emissions reduction. The term ‘clean’ represents a problem-centric analysis whereas the term ‘green’ indicates a product-centric perspective. Policy-related research specifically also refers to EST in the context of technology transfer to emerging growth markets (Forsyth, 2007; Ramanathan, 2002; Thiruchelvam et al., 2003).

Some technologies for carbon reduction qualify as ‘green’. However, Dangelico and Pontrandolfo (2010) find that the meaning of ‘green technology’ is itself manifold. They derive a classification of ‘green options’ from clustering a sample of firms listed in the Dow Jones Sustainability World Index (DJSWI). Interestingly, they suggest classifying technologies by a matrix of generic product foci (materials, energy and pollution) and environmental impact (less negative, null, positive). Dangelico and Pontrandolfo further distinguishing between companies producing technologically based goods (technology sector), companies selling consumer goods, the industrial sector of manufacturing and distribution, and companies specialized in basic materials.

A number of engineering and social science scholars expanded the concept of environmentally sound technology toward a circular economy. Such economy is characterized by a more sustainable design of products and product lifecycles. That is, the vendor shall 'close the loop' at the end of product life (e.g., Krikke, 2011; Hellström, 2007; Slowak and Regenfelder, 2013). Closing the loop implies the recovery of materials, recycling and approaches incentivizing the second use of technological products. Complementing such approaches, the term 'eco-design' characterizes novel conceptions how to deploy natural resources in a manner that is either more efficient or less exploitative of natural ecosystems. This includes more ecological friendly design of products, services and processes (OECD, 2011, pp. 29f.). The concept of a circular economy enables debate as to how new consumption patterns, societal values and business models, rather than new technology alone, can reduce carbon emissions, and thus mitigate climate change (Lorek and Spangenberg, 2014; Mylan, 2014; Dryzek et al., 2011; Southerton et al., 2004; Lafferty and Meadowcroft, 2000). That said, technology for carbon reduction need not necessarily be a product, it can also be a new technique introduced in traditional industries. As such, it would not necessarily qualify for technology management scholar's common listing of 'environmentally sound technologies'.

More recently, Tseng et al. (2013) refer to design for remanufacturing, for disassembly or for recycling, and to green supply chain strategies. Green supply chain strategies in that context are sustainable practices of a firm's operations, therefore ranging 'from product design, raw material sourcing and manufacturing, to storage, transportation, usability and end of product life management'. Tonn et al. (2014) distinguish indefinite reuse, recyclability and renewability (IR_3). These IR_3-approaches characterize industrial ecosystems, which facilitate a resource saving economy – that implies, using fewer original materials in production, reduced production volumes, and energy emissions. Tonn et al.'s terminology of infinite reuse, recyclability and renewability identifies the future requirements of a circular economy, taking a systems view. It is thus not best suited for static analysis, such as, identifying certain industry or manufacturing sectors of most relevance or certain technologies for carbon reduction. We have already referred to the stream of literature relating to limits to growth, or 'de-growth' (Kalimeris et al., 2014), which itself encompasses a rich debate and reaches beyond the scope of this study.

This paper will apply Dangelico and Pontrandolfo's (2010) matrix of 'green options' to structure the debate. The focus of our analysis lies on identifying and clustering the future research topics and related industry sectors of the CRT debate. Dangelico and Pontrandolfo's framework is instrumental because it is able to embody all previously recaptured definitions of technology in the context of the CRT debate. Namely, each specific new product technology can be assigned to a certain matrix field. For instance, photovoltaic panels would belong to 'energy & positive impact'. We specifically look at the variety of green options in the sectors 'technology' and 'industrial' application. This includes carbon reduction in industrial process, new techniques and the commercialization of new product technology. The green options matrix also facilitates a structured discussion of this paper's multi-disciplinary findings.

The strength of our paper is to combine advancing terminology and representing the full structure of the CRT debate from a rich dataset. More specifically, this paper will apply the green options matrix for clustering the conventional technology sectors within our subsequent keywords social network analysis of carbon reduction & carbon reduction and technology.

3 Research methodology

3.1 Dataset creation

The articles for the subsequent bibliographic literature review were retrieved from the ISI Web of Knowledge repository, using the terms '(low-)carbon, reduction and technologies/technology' in the title, abstract or keywords of articles available. The repository represents a well-acknowledged database of rigorous journal articles. It is thus well suited to form a representative subset of scholarly contributions. Using a keyword search, we retrieved 3310 articles published from 1990 to the end of February 2014.

The choice of keywords applied to the full ISI Web of Science dataset allows the identification of all relevant contributions to the CRT debate, that is, from the various disciplines and industries. The selection includes not only social sciences but also engineering disciplines. We deliberately excluded medical and health sciences related works. It is important to note that this paper focuses exclusively on the CRT debate. – By using only the combination of '(low-)carbon, reduction' *and* 'technologies/technology', works that might refer to specific aspects of carbon reduction or technology separately are not included.

As previously mentioned, the literature on carbon reduction is linked to the widely acknowledged climate change challenge. Disciplinary studies, such as those by environmental economists, would associate climate change mitigation with a number of specific keywords such as carbon emissions or policy. However, our review aims to be non-disciplinary, systematically covering the entire CRT debate. Our choice of keywords reflected that aim. In a qualitative screening of relevant studies, we identified that relevant articles usually referred to 'low-carbon' or 'carbon reduction'. Likewise, if authors discussed technology, the term 'technology' was to be found at least in the abstract of the paper. Therefore, we applied the combination of these keywords to retrieve the dataset. The resulting dataset includes international journal articles published and in press.

3.2 Analysis techniques

In order to decompose the CRT debate, our paper makes use of three different methods. Firstly, we run a quantitative, bibliometric analysis, which allows us to understand the structure of the CRT body of knowledge. This study makes use of classic bibliometric techniques for analyzing this body. Such bibliometric techniques have been applied in a number of literature reviews, for both management studies (e.g., Gingras, 2010; Taticchi et al., 2010; Pilkington and Meredith, 2009; Neely, 2005) and technology studies (e.g. Choe et al., 2013; Ho et al., 2014). In our study, SITKIS software (Schildt, 2006) is used to perform the necessary analyses. This also includes evaluating the received citations of prominent papers and journals in our dataset. We assume that authors frequently cite papers they regard the most relevant or influential for the respective debate (Culnan, 1986; Sharplin and Mabry, 1985). More specifically, this paper ranks the importance of different research streams and disciplines according to the bibliometric findings. For instance, given the competitive acceptance rate of highly prestigious journals, any single published article is likely to demonstrate some degree of authority within the debate. The rank of received citations of a journal source or an author indicates the relevance of the topic; it technically means that other authors refer to this journal source/author.

Secondly, our study then uses keyword co-citation information to reconstruct the different promising topics in the CRT debate. More specifically, if several papers use the same keyword, they form a related theme within a social network analysis. Additionally, our paper requires the measure of betweeness centrality to identify the most centric keywords of our large dataset. Betweenness centrality measures the probability for a node i that pairs of other nodes require i in order to interconnect indirectly. Therefore, high betweeness centrality indicates the control of information flows (Freeman, 1979, p. 222f.). As our study compares centrality measures for nodes within a social network graph and not across different social networks, betweeness centrality is valid measure of power for any keyword (White and Borgatti, 1994).

Thirdly, we use metrics from this social network analysis to isolate keywords with high 'authority' over the network. To simplify; authority means that the keyword best represents a specific subtheme of the network. Social network analysis has become a well-accepted method of management scholars to measure relative importance or power in social structures among firms (Borrett, 2013; Rost, 2011; Bonacich, 2007; Granovetter, 1983). The social network co-citation analysis allows us to isolate topics, to compare the relative importance of the different article keywords and to make a meaning of their co-location in the social network. We follow well-established studies (e.g., Van Duijn and Huisman, 2011; Scott, 2000; Kleinberg, 1998) in placing particular emphasis on the centrality and authority concepts of network metrics.

Social network studies initially developed the authority measure for a systematic analysis of hyperlinked contents. Authority nodes are characterized by a large in-degree, which means, many nodes point to what is then termed an 'authority'. The nodes referring to different authorities must furthermore overlap. The algorithm thus aims to find the different most representative nodes behind a common topic. The overlapping nodes, those from which references emanate, become hubs of the network, while the nodes that are the subject of such references become acknowledged as authorities. The assumption of a common topic is justified by the fact that a hyperlinked contents analysis constructs the social network from a keywords search so that the network does represent a subset of a larger data pool (Kleinberg, 1998).

In summary, it is the purpose of network authority metrics (node authority, flow authority) to 'assimilate' the information of a full network through a small subset of terms. This assimilation needs to best pick representative nodes for the full network's subthemes, that is, effectively and robust against different network sizes. We can thus not pick central themes of a network manually from graphical illustration, if the full network is hyperlinked rather than splitting up naturally into different network components (Aggarwal et al., 2011; Kleinberg, 1998, 1999). Kleinberg (1998) furthermore suggests the measurement of authority as a method to cluster link structures into distinct cohesive subsets. Similarly, we will use the measure of node authority in this study when we discuss distinct key subthemes for further research. The network graphs are drawn and the metrics are calculated using the SNA software Gephi (cf. Bastian et al., 2009). Combined, the bibliographic and social network analysis allows us a judgment upon what are the central subthemes of the CRT debate and how they interrelate to each other.

4 Findings from bibliographic analysis

4.1 Publications

We observe an increase in attention to the CRT debate. The number of publications grows exponentially over time (Figure 1).

This increase in publications does not begin until the early 90's, with no publications matching our search terms in the years before 1990. This is consistent with the arrival of the term 'environmentally sound technologies', along with emerging its political prominence (UNEP, 1992). Our use of non-disciplinary and technology-neutral search terms makes us confident that Figure 1 represents the full CRT debate across all major disciplines and policy-driven viewpoints. This coverage and the non-political, non-disciplinary view makes this study unique to the further development of the field.

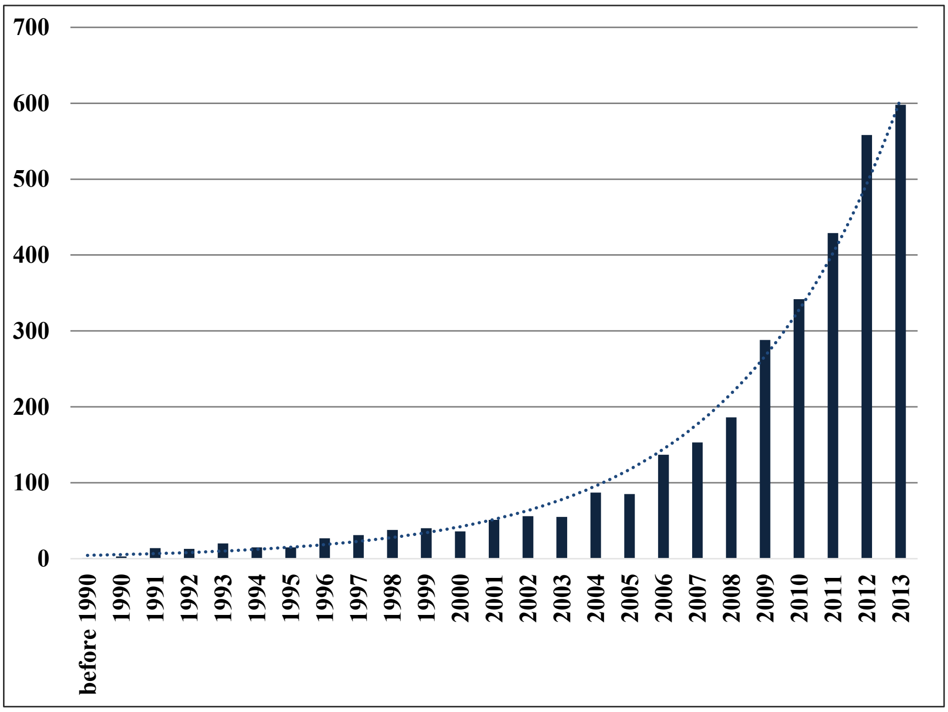

Fig. 1. Publications per year.

Table 1 provides a ranking of the top 20 journals by number of publications. They account for only 33% of the publications in our sample, so that we overall find a fragmented field of journals. This finding supports the quality of our sample in several ways. The full list of journal source titles for our paper's dataset is non-disciplinary, and technology neutral in its focus. It does also not refer to a specific industry sector. However, the ranking of research areas by the ISI Web of Knowledge suggests a high importance of the 'energy' topic. Table 2 lays out the applied areas of research.

Table 1. Top 20 ranking of journals by number of publications.

Rank	Journal title	Publications
1	Energy Policy	297
2	Environmental Science & Technology	103
3	Applied Energy	54
3	Energy	54
5	International Journal of Hydrogen Energy	51
6	Energy Fuels	43
7	Fuel	42
8	Energy Economics	41
9	Industrial & Engineering Chemistry Research	36
9	International Journal of Greenhouse Gas Control	36
11	Climate Policy	33
11	Journal of Hazardous Materials	33
13	Chemical Engineering Journal	30
13	Journal of Cleaner Production	30
15	ISIJ (Iron and Steel Institute of Japan) International	29
16	Water Research	28
17	Climatic Change	27
18	Bioresource Technology	24
18	Renewable Energy	24
20	Electrochimica Acta	23
20	Journal of Power Sources	23
20	Metallurgist	23
	N	**1084**
	% of dataset	**33%**

Whereas the term ‘energy’ appears in about 50% of the journal source titles (Table 1), only one research area explicitly relates to ‘energy’ (Table 2). The later social network analysis of our paper clarifies on the meaning of the term ‘energy’ (compare sections 5.1 and 6.2.1). It does not merely embody the power generation industry but rather stands for technology suppliers and new clean energy technologies. Nonetheless, the bibliographic analysis already reveals that energy studies scholars dominate the CRT debate. Literature finds similar results for the Chinese academy. Shi and Lai (2013) present a transnational dataset dominated by technical or engineering disciplines (72.6%), with the major share of Chinese contributions coming from economics (79.3%) (calculated from ibid., Fig. 7 and 10). The topic of energy policy is a consistent concern in CRT studies.

Table 2. Top 20 research areas in our sample.
For a detailed description of the applied areas of research refer to (Thomson Reuters, 2014).

Applied area of research	Publications
Environmental Sciences	1126
Engineering	1120
Energy Fuels	918
Chemistry	407
Materials Science	307
Metallurgy & Metallurgical Engineering	262
Electrochemistry	171
Physics	163
Business Economics	160
‘Science & Technology (other topics)’	130
Agriculture	112
Thermodynamics	111
Water Resources	108
Meteorology & Atmospheric Sciences	102
Biotechnology & Applied Microbiology	100
Public Administration	62
Construction & Building Technology	51
Transportation	45
Mechanics	43
Food Science & Technology	39

In order to help investigate the technological and managerial issues behind the CRT debate, Table 3 ranks the keywords most frequently used by authors. The keywords predominantly point to the issue of carbon dioxide in the context of climate change. A cluster of keywords around climate change prevails, followed by the term ‘policy’, which both indicate works in the area of economics. There are also, many keywords referring to engineering disciplines. However, the topics ‘renewables’, ‘costs’, ‘behavior’, ‘efficiency’, ‘sustainability’, ‘innovation’ and ‘industry’ could also derive from management science papers. It is interesting to note that our keyword search did not explicitly address ‘climate change’, ‘energy’ or ‘policy’. Despite that, energy policy and the energy sector are predominant in the bibliographic rankings. The highly ranked keywords for the energy sector include ‘storage’ and a number of technology categories such as ‘biomass’ or ‘renewables’. We furthermore observe themes indirectly linked to manufacturing industries, e.g. carbon nanotubes. Other noteworthy themes are energy efficiency and [waste] water. It is interesting to note that the nature of the keywords suggests an emphasis on the production side of energy issues, with limited focus on the consumption side.

Table 3. Top 50 keywords used by authors.
Explicit carbon reduction issues as emphasized by authors (underlined).

Keyword	**Publications**
CCS / Carbon Capture / CO_2 Capture / Capture / Carbon Capture and Storage	280
CO_2 / Carbon Dioxide	270
Energy	226
Climate[-]Change	187
System[s]	181
Emissions	159
Performance	156
Carbon [Dioxide] Emission[s] / CO_2 Emissions	136
Policy/ies	125
Biomass	124
Model	116
Renewable Energy/ies / Renewable Energy Technology/ies / Renewables	99
Kinetics	97
Oxidation	95
Activated Carbon	94
Hydrogen	87
Cost[s]	84
Storage	83
Waste[-]water[s]	81
Adsorption	80
China	79
Removal	77
Behavior[s], Behaviour	72
Temperature[s]	72
Coal	70
Greenhouse Gases / Greenhouse Gas	69
Nanoparticles	69
Water	68
Mechanical[-]Property/ies	65
Microstructure	65
Greenhouse[-]Gas Emission[s]	64
Methane	64
Energy Efficiency	63
Sustainability	60
Degradation	57
Carbon Nanotubes	56
Climate Policy	56
Combustion	56
Power	56
Innovation	55
Growth	54
Industry	53
Design	52

Electricity	52
Generation	52
Mechanism[s]	52
Particles	51
Efficiency	50
Gas	48
Scenarios	48
Simulation[s]	48

The reader would note that China is the only country enlisted among the top 50 keywords. It likewise ranks 2nd regarding geography of scholars (also see Table 5). This reflects the effort of Chinese scientists to disseminate their research, but of course does not provide any evidence concerning quality and impact of the same, be it for the academic or the industrial community.

4.2 Prolific authors and citations

This section looks at the authorships, their geography and the disciplinary character of the CRT debate literature.

The ranking of the most prolific authors is plotted in Table 4; it presents data related to the geography of both authors and co-authors who receive the same weight when counting. Note that the geography of scholars refers respectively to the country of the employing institution where the researcher is currently situated (Table 4) or, when the article was published (Table 5). Given that our keyword search was for a *combination* of technology, carbon and reduction, we might have expected a dominant group of lead authors. However, the main finding here is a scattered field of contributions with no dominant clique of authors or institutions. Table 4 accounts for 112 out of 3310 articles, 598 publications just for the year 2013. This demonstrates the diversity of the CRT debate, spanning a vast number of journals and authors. While a German scholar leads the list of most prolific authors, we also find two Chinese authors at Chinese institutions among the most prolific authors.

The most prolific authors include an economist, an energy policy specialist, a metallurgist and a climate change modeler. The most prolific author in the sample, Ottmar Edenhofer, is an economist. The journal Nature has called Edenhofer the ‘Climate Chairman’ (Schiermeier, 2013), referring to his leading role in the European research community on climate change and beyond (i.e. Edenhofer et al., 2013). Timothy Foxon works on the co-evolution of energy policy, institutions and technology for the transition toward a low carbon economy. Yonglin Kang serves the Chinese State Key Laboratory for Advanced Metals and Materials where the emphasis lies on developing new generations of steel materials. Detlef van Vuuren models the assessment of climate change. Daniel Kammen leads the Renewable and Appropriate Energy Laboratory, and the Transportation Sustainability Research Center, both at Berkeley. He also holds professorships in Energy Studies and Public Policy.

Table 4. Ranking of the 10 most prolific authors.

Author	Publi-cations	Research institution	Geography of scholars
EDENHOFER, Ottmar	13	Potsdam Institute for Climate Impact Research	Germany
FOXON, Timothy J	12	School of Earth and Environment, University of Leeds	UK
KANG, Yonglin	10	School of Materials Science and Engineering, University of Science & Technology Beijing	China
VAN VUUREN, Detlef P	10	Copernicus Institute of Sustainable Development, Department of Geosciences, Utrecht University	Netherlands
KAMMEN, Daniel M	9	Renewable and Appropriate Energy Laboratory, University of California Berkeley	USA
KEITH, David W	9	School of Engineering and Applied Sciences and Harvard Kennedy School, Harvard University	USA
VAN DER ZWAAN, Bob	9	Energy research Centre of the Netherlands, and Columbia University's Lenfest Center for Sustainable Energy (Earth Institute)	Netherlands
KAINUMA, Mikiko	8	Social and Environmental Systems Research, National Institute for Environmental Studies	Japan
RUBIN, Edward S	8	Department of Engineering and Public Policy, Carnegie Mellon University	USA
SHIMIZU, Masakata	8	Department of Materials Science and Engineering, Faculty of Engineering, Kyushu University	Japan
YEO, Yee-Chia	8	Electrical and Computer Engineering, National University of Singapore	Singapore
YU, Hao	8	School of Material Science and Engineering, University of Science & Technology Beijing	China

Country wise, the geography of scholars is led by the United States and China, followed by England, Japan and Germany (Table 5). Other highly ranked countries from Asia are South Korea and India. Note that only one country from South America is included in the top 25: Brazil.

Table 5. Geography of scholars: Top 25.
Dataset retrieved in February 2014, reflects all publications that match our keywords up to that date.

Country	Publications
USA	843
China	518
England	379
Japan	215
Germany	213
Canada	158
Australia	131
Netherlands	110
South Korea	110
France	108
India	107
Spain	103
Italy	99
Sweden	78
Poland	59
Austria	55
Taiwan	55
Switzerland	49
Brazil	47
Scotland	45
Norway	43
Russia	42
Portugal	40
Belgium	34
Greece	32

In Figure 2, we illustrate the number of citations per year. The trend in citations is consistent with the previously observed exponential growth in publications. Next, in Table 6, this study ranks the top journal source titles. There is some degree of congruence between a journal's rankings by citations received by number of publications. Specifically, Energy Policy heads both rankings.

'Energy' topics and 'energy policy' in particular, followed by topics of environmental science, chemistry and fuel studies lead the citation ranking as illustrated in Table 6. Some differences in high citation but low publication numbers derive from extraordinary high journal impact factors. The median of the Eigenfactor Article Influence score (AIS) for the top 20 cited journals as to Table 6 is 1.01. However, the journals Nature, Nature Materials, Science, the Proceedings of the National Academy of Sciences of The United States of America and Energy & Environmental Science score much higher.

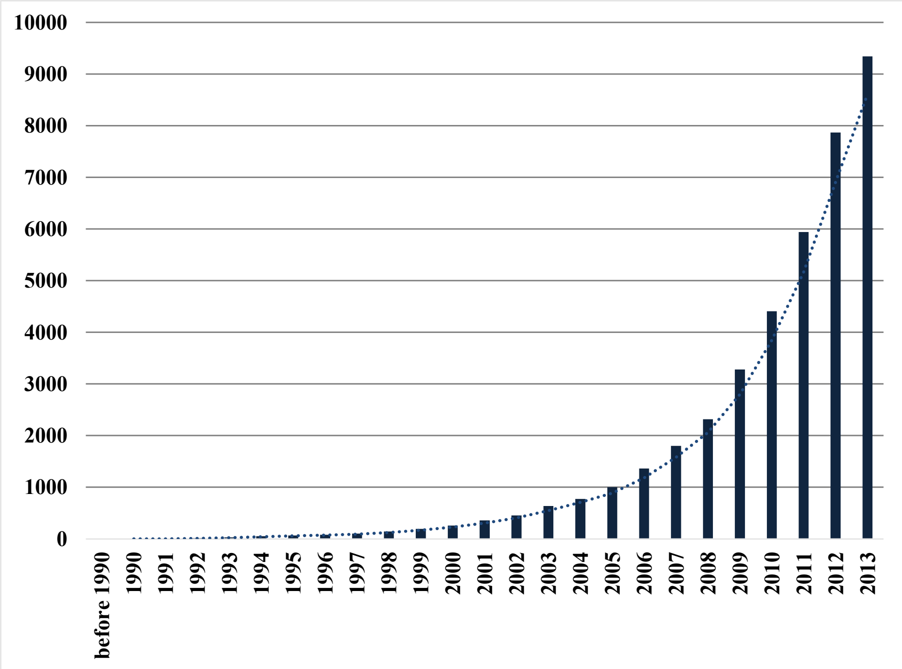

Fig. 2. Citations per year.

Table 6. The 20 top cited journals.

AIS retrieved from the University of Washington Eigenfactor project (2014). The Eigenfactor Article Influence score (AIS) derives from a page-rank algorithm applied to the well-established Thomson-Reuters citations 5-year-impact-factor. Emphasis in bold numbers added by the authors.

Rank by no. of citations received	**Rank among top 20 by no. of publications**	**Journal source title**	**Authority (AIS)**	**Citations received**
1	**1**	Energy Policy	0.75	3580
2	-	Nature	**20.37**	3359
3	2	Environmental Science & Technology	1.60	3070
4	-	Nature Materials	**17.92**	1048
5	**16**	Water Research	1.30	845
6	-	Atmospheric Environment	1.03	739
7	3	Energy	0.79	683
8	-	Applied Catalysis A-General	0.93	626
9	5	International Journal of Hydrogen Energy	0.72	625
10	-	Science	**17.52**	608
11	9	Industrial & Engineering Chemistry Research	0.64	569
12	8	Energy Economics	1.14	551
13	-	Energy & Fuels	0.73	544
14	20	Electrochimica Acta	0.98	519
15	7	Fuel	0.98	511
16	11	Journal of Hazardous Materials	0.92	487
17	-	Energy & Environmental Science	2.70	473
18	-	Proceedings of The National Academy of Sciences of The United States of America	4.90	468
19	3	Applied Energy	0.87	462
20	17	Climatic Change	1.84	440

Noteworthy are the journals Water Research (AI 1.30) and the fuels cluster, namely Energy & Fuels (AI 0.73) and Fuel (AI 0.98). Their impact factor is close to the median of the top 20 although their ranking by citations and by publication numbers differ. In combination, the received high numbers of citations, the average prestige (impact factor) but the relatively low numbers of publications indicate a gap for future research.

The received citations are concentrated on a few prolific articles. If we look at the most frequently cited studies over time (Figure 3), we observe a pattern of overlapping article life cycles. Although we observe few works dominating the dataset in numbers of cumulative citations received (Table 7), there is, however, no indication of any star author within the CRT debate. The number of citations received is rather low, if measured in terms of arithmetic mean over the full dataset (12.4 citations). This again reinforces our finding of a dispersed debate.

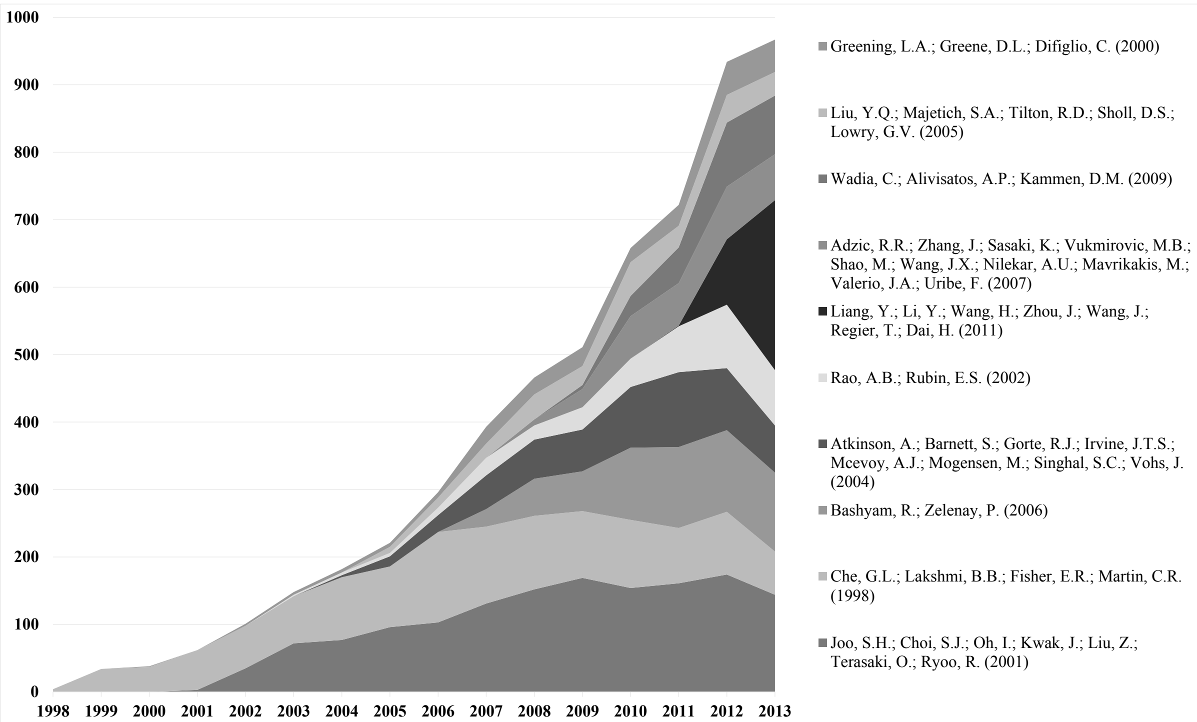

Fig. 3. Citation frequency of the 10 most cited works over time.

A few works stand out in the debate (Table 7). Several of them are published in the journal Nature. We find a clear focus on science and technical development whereas two papers are related to economics, namely, to economies of scale in PV and energy efficiency in consumption. Arguably, the articles could mark specific technical breakthroughs or have been the first contributions to a disciplinary debate at their times, thereafter taken up by subsequent studies. It is nonetheless beyond our data to explain the concentration. Although the Chinese academy comes out as relevant in our dataset, the geography of the most cited studies is still dominated by US institutions. Arguably, articles require a few years for raising their citations and the contemporary role of the Chinese academy in the debate might be just emerging, with evidence to follow. The results of Table 7 are also ambiguous. The most cited authors work at US institutions but a number of them are Chinese scholars. Furthermore, our article sample includes 102 papers with 'China' in the title as compared to 50 for 'UK', 47 for 'Europe*'/'EU' and 41 for 'US'/'USA'.

Table 7. The top 10 most cited works (cumulated citations).

Authors	Article title	Year of public-cation	Citations received (cumu-lated all years)	Geography of scholars
Joo, S.H.; Choi, S.J.; Oh, I.; Kwak, J.; Liu, Z.; Terasaki, O.; Ryoo, R.	Ordered nanoporous arrays of carbon supporting high dispersions of platinum nanoparticles	2001	1478	South Korea and Japan
Che, G.L.; Lakshmi, B.B.; Fisher, E.R.; Martin, C.R.	Carbon nanotubule membranes for electrochemical energy storage and production	1998	1252	USA
Bashyam, R.; Zelenay, P.	A class of non-precious metal composite catalysts for fuel cells	2006	615	USA
Atkinson, A.; Barnett, S.; Gorte, R.J.; Irvine, J.T.S.; Mcevoy, A.J.; Mogensen, M.; Singhal, S.C.; Vohs, J.	Advanced anodes for high-temperature fuel cells	2004	589	UK, USA, Switzerland and Denmark
Rao, A.B.; Rubin, E.S.	A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control	2002	392	USA
Liang, Y.; Li, Y.; Wang, H.; Zhou, J.; Wang, J.; Regier, T.; Dai, H.	CO_3O_4 nanocrystals on graphene as a synergistic catalyst for oxygen reduction reaction	2011	362	USA and Canada
Adzic, R.R.; Zhang, J.; Sasaki, K.; Vukmirovic, M.B.; Shao, M.; Wang, J.X.; Nilekar, A.U.; Mavrikakis, M.; Valerio, J.A.; Uribe, F.	Platinum monolayer fuel cell electrocatalysts	2007	312	USA
Wadia, C.; Alivisatos, A.P.; Kammen, D.M.	Materials availability expands the opportunity for large-scale photovoltaics deployment	2009	282	USA
Liu, Y.Q.; Majetich, S.A.; Tilton, R.D.; Sholl, D.S.; Lowry, G.V.	TCE dechlorination rates, pathways, and efficiency of nanoscale iron particles with different properties	2005	271	USA
Greening, L.A.; Greene, D.L.; Difiglio, C.	Energy efficiency and consumption: The rebound effect – A survey	2000	257	USA and France
Citations received, arithmetic mean over full dataset			**12.4**	

4.3 Findings concerning the role of the Chinese academy

Table 8 presents funding figures based on academics' explicit acknowledgement of any funding institutions in their papers. Thus, while the data presented are descriptive of the dataset, the analysis does not necessarily reflect the structure of funding in different countries. Among all institutions and nations, the National Natural Science Foundation of China (NSFC) funds the highest number of publications in our dataset. The NSFC is committed to low-carbon innovation as it has for instance just announced a £20 million joint program with the UK EPSRC in March 2014 (EPSRC, 2014). The State Council as the highest Chinese planning authority issues five years and long-term plans which determine public R&D funding, more specifically, 'The National Medium- and Long-term Program for Science and Technology Development' (2006-2020)' and 'The Five-Year Plan' (12th: 2011-2015). Whereas the National Natural Science Foundation of China (NSFC) directs and supports basic and applied, basic research (cf. NSFC International Evaluation Committee, 2011), the Chinese Academy of Sciences (CAS) represents the national academy and thus serves as the highest Chinese scientific and technological advisory body. Since the 1980s, the academy has intensified its focus on innovation when it issued the Knowledge Innovation Program (Suttmeier et al., 2006, pp. 81ff.). The NSFC expenditures are predominated by the 'General Program' which funds small, PI (principal investigator)-initiated projects. Additionally, the 'Major Program' funds large research projects in areas of national priority (NSFC International Evaluation Committee, 2011, Fig. 11 on p. 30).

Table 8. Geography of public funding
Dataset retrieved in February 2014, reflects all publications that match our keywords up to that date.
a) Jointly by all EU members, i.e. Austria, Belgium, France, UK, Germany, Greece, Italy, Netherlands, Poland, Portugal, Spain or Sweden.

Funding agency	Publications	Country
National Natural Science Foundation of China (NSFC)	161	China
National Science Foundation (NSF)	50	USA
European Commission and European Union (EC/EU)	49	EU members[a)]
Ministry of Education of China (incl. Fundamental Research Funds for the Central Universities)	29	China
US Department of Energy	25	USA
National Basic Research Program of China	24	China
Natural Sciences and Engineering Research Council of Canada (NSERC)	21	Canada
China Postdoctoral Science Foundation	15	China
Engineering and Physical Sciences Research Council UK (EPSRC)	15	UK
Australian Research Council	12	Australia
Chinese Academy of Sciences	12	China
Swedish Energy Agency	12	Sweden
Korean Ministry of Education, Science & Technology	8	South Korea
Ministry of the Environment Japan	7	Japan
Spanish Government	7	Spain

N: 447 (13.5%) out of 3310 papers in our sample are explicitly funded.

China's recent five-year plan 2011–2015 for the NSFC covers a number of basic research frontiers. NSFC environmental science funding encourages themes like 'climate change – impact and adaptation; conservation and utilization of biodiversity; ecosystem service and ecological economy; mechanisms of water/soil/air pollutions and regional environmental processes; urbanization and environmental quality; cleaner production and circular economy; environment and health; natural disaster – risk, prevention and reduction' (NSFC, 2012, ch. 8 on disciplinary development). For chemistry, 'more efforts will be focused on the interdisciplinary research and combination of chemistry with physics, life sciences, material science, energy science, and environmental science'. The plan likewise refers to marine science impact on 'climate' and the 'marine carbon cycle', to 'energy materials', 'eco materials' and various fields of energy science. The latter entails 'energy saving', 'clean coal', 'renewable energy' and 'carbon capture and storage'. Furthermore, Chinese energy science shall research multidisciplinary in collaboration with other natural sciences, information and management science (NSFC, 2012).

5 Findings from social network analysis

5.1 Keywords profiling

As outlined in the methodology section, the following social network graphs and metrics are constructed from co-citation data. The nodes of the graph are keywords stated by the authors. If two articles use the same keyword, we connect all other keywords given in both articles with that one, common keyword. The method sequentially applies to all articles with a minimum citation threshold and to all keywords. The social network graph then illustrates the latter. Figure 4 draws the social network from the full dataset.

Our dataset forms one integrated social network component, dominated by few highly co-cited keywords. These few centric keywords such as energy or performance are statistically likely to co-occur with any keyword in the dataset. Whereas the authorship is highly dispersed (see our bibliographic analysis), topics are somewhat integrated into one core component. Consequently, we find the different themes of the CBT debate must either overlap or share a common context – beyond the excluded search terms technology or carbon reduction. Furthermore, the results of this analysis highlight the complexity and diversification of the CRT debate. In fact, the graph shows a great dispersion of keywords used. It entails a mix of engineering, policy and management keywords and several specific topics forming the debate, although overall, the resulting network structure presents the CRT debate as an integrated field of research.

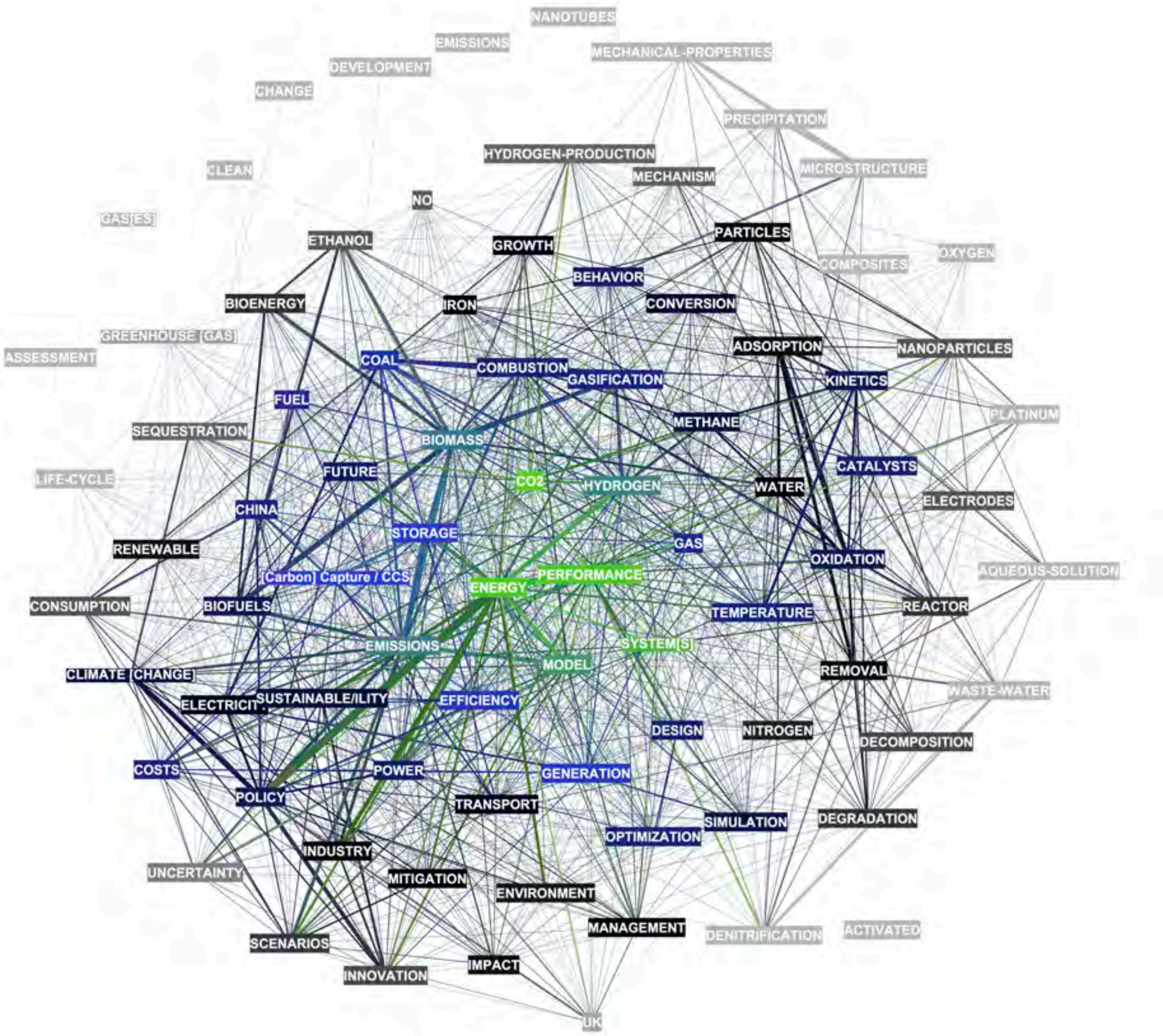

Fig. 4. Keywords' social network analysis.
Minimum citations to citing articles set to 30 (1%). Search terms from dataset creation and their edges removed from the network graph: 'carbon', 'reduction', 'technology', 'technologies'.

The heat map of Figure 4 (from grey, to black, to blue, to green) indicates that 'energy', 'performance' and 'CO_2' are the most meaningful words of the CRT debate. Table 9 measures the centric keywords. We find that a cluster of keywords around the climate change challenge is centric to the social network. This cluster integrates the various and diverse contexts represented by the many other keywords.

Table 9. Top 5 keywords by betweeness centrality
Values calculated from the full network as illustrated in Fig. 4.

Keyword	**Betweeness centrality**
CO_2	177.99
GREENHOUSE [GAS]	100.15
CLIMATE [CHANGE]	98.07
ENERGY	91.30
PERFORMANCE	87.47
Avg	*25.09*

In Figure 5, we explore which associations the term ‘energy’ makes to other keywords. All other keywords are faded in grey color. The energy topics theme primarily refers to ‘policy’ and ‘performance’. That said and reflecting our bibliometric results, the first theme of the CRT debate appears to be energy policy. Moreover, the term ‘shares its central position with interdisciplinary keywords such as CO_2, ‘performance’, ‘sytem[s]’ and ‘model’. Correspondently, keywords scoring high in Table 9 indicate that our dataset’s keywords are most probably associated with ‘energy’ topics (‘energy’, ‘CO_2’, ‘greenhouse gas’, ‘climate change’).

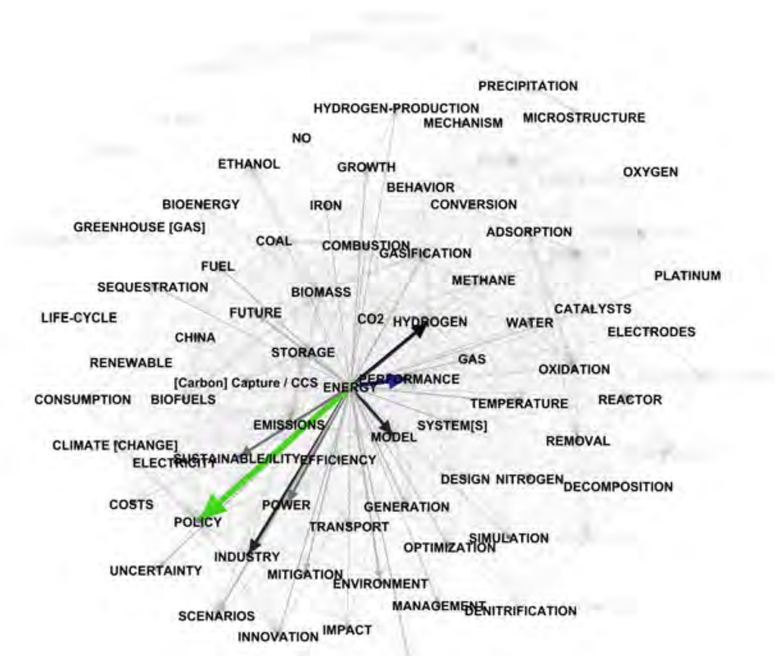

Fig. 5. The energy theme highlighted.

The energy theme dominates the graphical representation of the full keywords set, and the graphical representation of the social network illustrates one integrated component. Its decomposition requires specific social network metrics. Research suggests taking the reference of one keyword to another keyword for the authors’ judgment upon authority (cf. Kleinberg, 1998, 1999). Table 10 ranks the keywords’ authority. It reveals that a number of themes related to industrial sustainability are of high importance to the CRT debate. Likewise, while centrality measures confirm the importance of energy policy as a matter of climate change mitigation, such measures have not ranked the topic ‘energy’ high in authority. ‘Energy’, not shown in Table 10, has an authority value of 0.0154, ‘CO_2’ of 0.0064. We hence argue that the energy cluster’s many edges cloud other still significant clusters of the CRT debate.

Table 10. Top 10 keywords by authority
Values calculated from the full network as illustrated in Fig. 4.

Keyword	Authority
SYSTEM[S]	0.0391
PERFORMANCE	0.0340
STORAGE	0.0282
TEMPERATURE	0.0276
MODEL	0.0256
SUSTAINABLE/ILITY	0.0250
WATER	0.0244
TRANSPORT	0.0231
SIMULATION	0.0224
RENEWABLE	0.0218
Avg	*0.0118*

Regarding technology use, the retrieved high authority keywords cover a number of industries such as, materials, water supply and disposal, transport and fuel, or novel service providers optimizing the carbon footprint. Although 'food' does not come up as an own theme in keywords, agriculture and food science are among the top 20 research areas in our dataset.

5.2 Keywords profiling for industrial sustainability

Previous section has demonstrated that a cluster of keywords around the climate change challenge is centric to the full dataset's social network. The betweeness measures for the energy topicality provide respective evidence. Therefore, if to explore the other directions of industrial sustainability in the data, if present, we next need to isolate our dataset from this climate change keywords cluster. The purpose is to identify significant CRT themes that the many associations of keywords with 'energy' may have hidden. Figure 6 draws the social network from the reduced dataset.

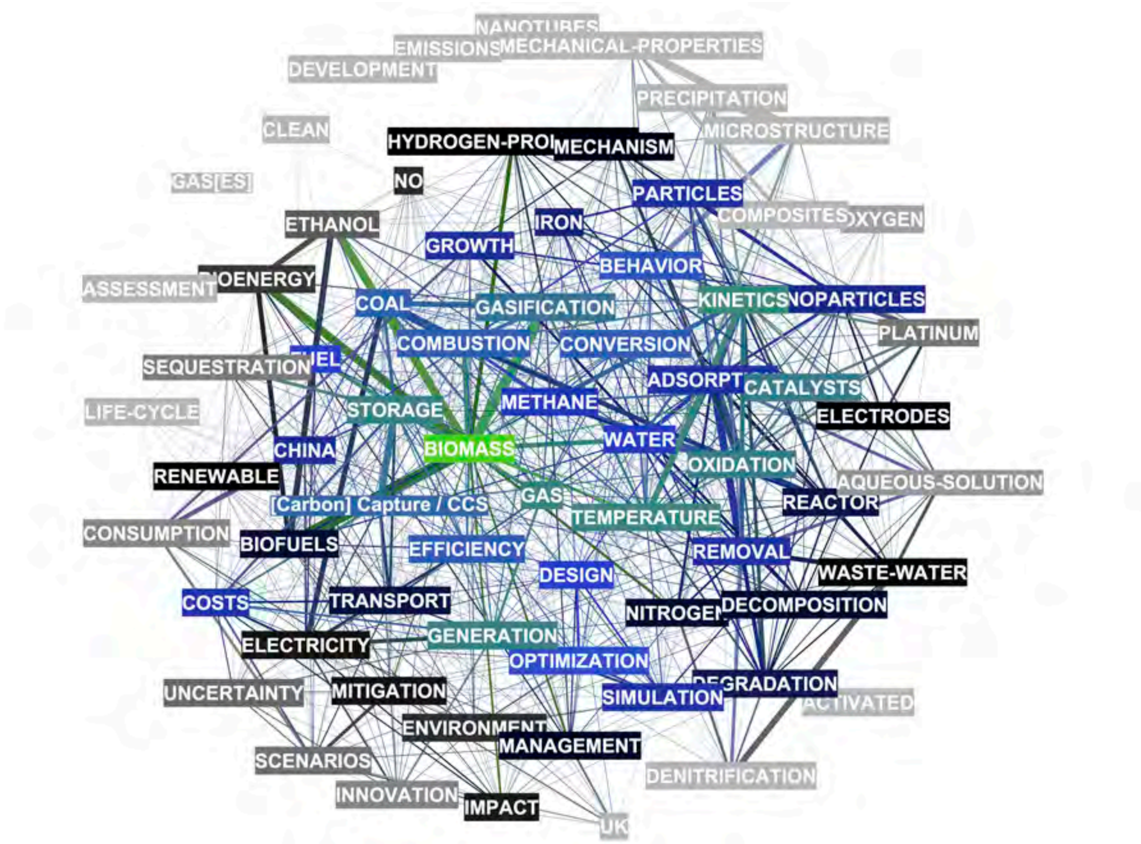

Fig. 6. Keywords' social network analysis, without energy theme.
Equals data from Fig. 4 after having modified as follows. First, we removed the keywords nodes from the energy theme and central political keywords: 'energy', 'CO_2', 'greenhouse [gas]', 'climate [change]', 'emissions', 'sustainable/ility'. Second, we furthermore refer to the strongest edges from the term energy, as highlighted in Fig. 5 and therefore remove the following nodes: 'hydrogen', 'industry', 'model', 'performance', 'policy' and 'power'. Additionally, we exclude the terms 'system[s]' and 'future', as they remain vague without context.

Interestingly, the reduced social network again reinforces the energy theme. However, it points at specific renewable energies and technologies to mitigate carbon emissions in the power sector. Such technologies i.e. cover CCS, bioenergy and biofuels. This also consistent with the International Energy Agency's contemporary focus on the development of storage concepts and techniques for carbon dioxide (cf. IEA, 2013).

Again, we apply the authority measure to identify distinct themes in the CRT debate (Table 11). The full network's authority ranking (Table 10) already reveals a number of industrial themes, which we can reconfirm for the reduced network's authority ranking (Table 11). The high authority keywords are representatives of distinct subthemes in the debate and we will thus use them to discuss the green options in industrial sectors.

Table 11. Top 10 non-energy keywords by authority
Values calculated from the reduced network, as illustrated in Fig. 6.

Keyword	Authority
TEMPERATURE	0.0387
STORAGE	0.0376
WATER	0.0343
OXIDATION	0.0310

REMOVAL	0.0299
SIMULATION	0.0299
TRANSPORT	0.0288
WASTE-WATER	0.0277
OPTIMIZATION	0.0277
PARTICLES	0.0265
Avg	*0.0143*

The reduced network's analysis presents three categories of keywords (Figure 6 and Table 11). Firstly, there is a theme of carbon reduction and zero emissions technologies for the power industry. Secondly, certain areas of industrial activity such as water or transport are exposed and thirdly, the high authority keywords include a number of keywords describing techniques, not necessarily product or process technology. For instance, the term 'simulation' could likewise refer to a product such as software or to smart infrastructure solutions, to counselling such as the modeling of climate change impacts or to optimization technologies for industrial operations.

6 Discussion

6.1 The CRT debate: An agenda for the future

Previous sections outline a rich field of research: the CRT debate attracts an increasing number of authors and spans a large number of disciplines. One of its strengths and at the same time challenges is its diverse structure. We apply and extend Dangelico and Pontrandolfo's (2010) taxonomy of green options in order to structure the many CRT perspectives (Table 12).

Table 12. Mapping the top 10 non-energy keywords with the terminology of 'green options'
Values calculated from the reduced network, as illustrated in Fig. 6.

Keyword	Green options sector	Authority
TEMPERATURE	Industrial	0.0387
STORAGE	Technology	0.0376
WATER	Industrial, Technology	0.0343
OXIDATION	Industrial	0.0310
REMOVAL	Industrial	0.0299
SIMULATION	-	0.0299
TRANSPORT	Industrial	0.0288
WASTE-WATER	Industrial, Technology	0.0277
OPTIMIZATION	Industrial	0.0277
PARTICLES	Technology	0.0265
Avg		*0.0143*

Following that terminology, we find rich keyword evidence for the technology sector as well as the industry sector. On the other hand, keywords on basic materials such as nanoparticles or platinum only represent a periphery of the keywords co-citation network. The green options matrix distinguishes between companies producing technologically based goods (technology sector); companies selling consumer goods; the industrial sector of manufacturing and distribution; and companies specialized in basic materials. Given the importance of 'policy' topics in our sample, we suggest expanding this matrix by a political sector. That is, research induced by governmental stimuli or changing normative frames of society (e.g., the climate change challenge, see Table 9).

This analysis finds that the high authority keywords aggregate to a set of industrial sector options (OPTIMIZATION, OXIDATION, TEMPERATURE, REMOVAL, TRANSPORT, WATER, WASTE-WATER) and technology options (STORAGE, PARTICLES, WATER, WASTE-WATER), see Table 12. Topics of 'consumption' play no major role in the network graphs. Basic materials are less central to the CRT debate: They do not rank high in terms of keyword authority, although the social network graph names few materials, e.g. platinum or nanotubes. Our analysis therefore suggest that the main emphasis of research, apart from energy, is sustainability in industrial processes context – which we may label 'industrial sustainability' or sustainability in industry. This also includes how to scale up the new environmental sound technologies in rapid growth countries such as China (Tan et al., 2010).

Our social network analysis (Figure 4) in combination with the journal citation and publication rankings indicate a set of distinct keywords clusters in the CRT debate. We will hereafter use these clusters to discuss the promising future themes of technology for carbon reduction in industry:

- New directions in clean energy and related energy policy
- Environmental science
- New CRTs for industry (non-energy): industrial sustainability
- Optimization techniques: sustainable operations

6.2 Future CRT core themes

This section discusses the identified core themes of carbon reduction *and* technology, combining the insights from bibliometric and social network analysis. Furthermore, our dataset suggests that the Chinese academy plays a growing role. Our bibliographic review's article sample includes 102 papers with 'China' in title as compared to 50 for 'UK', 47 for 'Europe*'/'EU' and 41 for 'US'/'USA'. Therefore, we proceed as follows. The paper will first characterize each theme, then comment the role of the Chinese academy and finally, in very brief, highlight directions for future research. The social network graphs presented graphically highlight the discussed keyword within the reduced dataset (Figure 6: keywords' social network analysis, without energy theme). That said, we do not present any new data but rather critically draw implications from our findings.

6.2.1 Clean energy

Both the bibliometric and social network analysis confirmed the importance of the energy policy theme within the full CRT debate. The broader debate in that area has been the subject of many review papers and high impact journals (e.g., Energy Policy), so we focus here on the less explored sub-topics that are as well prominent in our data.

The keywords 'storage' and 'biomass' represent strong themes in the area of CRT for the power industry (Figure 7). The term 'storage' holds co-citations with several energy sources and it receives a strong citation from the term 'carbon capture [systems]' (for comparative studies cf. Román, 2011; Wilson et al., 2011). CCS is not associated with renewable energy sources, probably because those do just not emit carbon dioxide that needs to be stored.

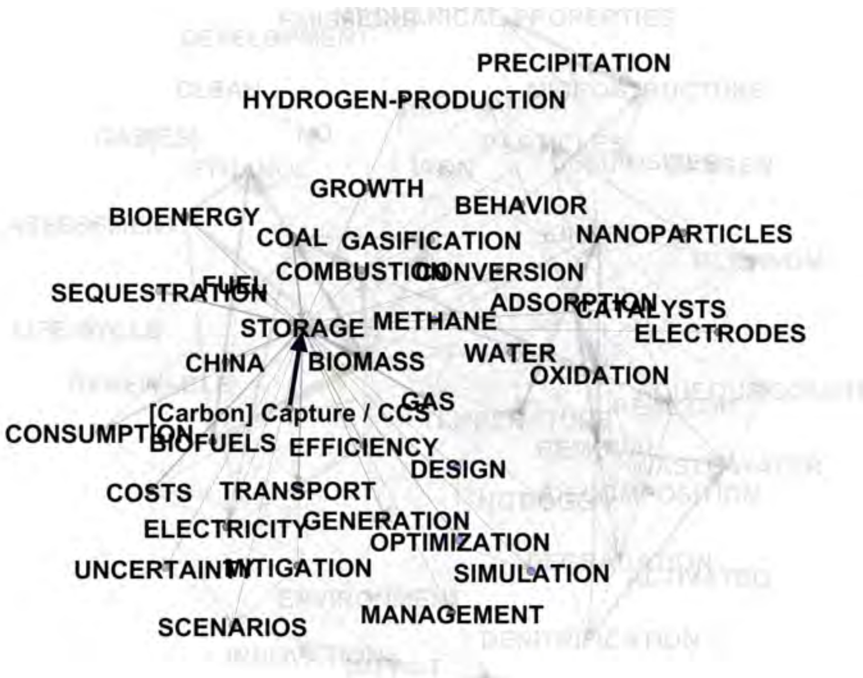

Fig. 7. Keywords co-citation with storage

In the energy-reduced network, the keyword ‘biomass’ retrieves high centrality scores. The technology serves a variety of uses across industries, among them, electricity and heat (domestic or industrial), or biofuels. The keywords biofuels and bioenergy in our sample strongly reference the keyword biomass; implicitly, this sub-theme is about cleaner energy provision and cleaner transport.

Opposite, Figure 8 does not include the keyword ‘China’. The finding is consistent with literature claiming that the portfolio of emphasizes renewable energies is different among regions and countries. The Chinese academy for instance rather puts high emphasis on photovoltaic energy generation. Nonetheless, among the top 20 cited papers in our sample, we find a study estimating China’s black carbon emissions particularly from the use of coal for cooking and heating. Its discussion also refers to biofuels (Streets et al, 2001). We can conclude that the CRT debate findings for clean energy do not clearly favor a particular technology but highlight the importance of the ‘renewable energy’ category.

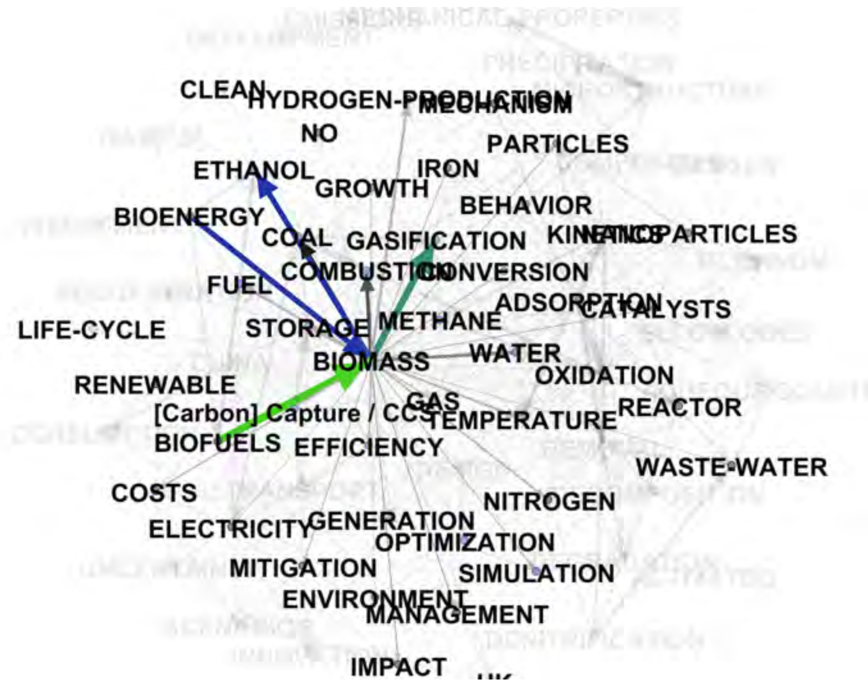

Fig. 8. Keywords co-citation with biomass

The strong clean technology theme aligns with the focus of policy makers in the CRT debate. For instance, OECD promotes a ‘Clean Energy Infrastructure’. ‘[Clean energy] includes the following sectors: solar, wind, hydro, geothermal, marine, biomass and waste-to-energy, biofuels and energy smart technologies (such as smart grids, energy efficiency and electric vehicles).’ (OECD, 2013, p. 3).

6.2.2 Environmental sciences’ contribution to the CRT debate

‘Environmental sciences covers resources concerning many aspects of the study of the environment, among them environmental contamination and toxicology, environmental health, environmental monitoring, environmental geology, and environmental management. This category also includes soil science and conservation, water resources research and engineering and climate change.’ (Thomson Reuters, 2014).

The high number of publications and the high citation rank of the Environmental Science & Technology journal best represents this topic area in our sample. The most cited articles are: ‘A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control’ (received citations: 392); ‘Materials availability expands the opportunity for large-scale photovoltaics deployment’ (282); ‘TCE dechlorination rates, pathways, and efficiency of nanoscale iron particles with different properties’ (271); ‘Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy’ (149); ‘Reductive precipitation of uranium by zero-valent iron’ (145); or ‘Mineral CO_2 sequestration by steel slag carbonation’ (124). The majority of Environmental Science & Technology articles in our sample discuss a specific domain of technology impact on the natural environment. The economics perspective of retrieved articles inter alia deals with pricing effects, carbon footprint, efficiency and counter fighting climate change (e.g., ‘Reducing greenhouse gas emissions for climate stabilization: Framing regional options’).

There are only few studies in our sample debating the role of water management, water infrastructure or the interaction of technology with the consumer for the purpose of carbon reduction. In consequence, the economics and management science research on water in the broader context of sustainability should be expanded in future scholarly works. Overall, we find that there is a rich engineering community discussing the development of low-carbon technologies. Our extended green options framework could help humanities research to relate to the engineering and science research based on the technology meaning (Table 12) and perceived societal or managerial challenges such as clean air, water or sustainable mobility.

6.2.3 Water and new carbon reduction technologies

'Water' represents a major theme in our sample (see Tables 6 and 11). The journal Water Research ranks 16th in terms of publication numbers but 5th in terms of citations received. Likewise, there is a strong sub-network for water and waste-water (see Figures 9–10). If we compare Figure 10 (waste-water) with Figure 7 (storage), we conclude that the water theme is distinct from the energy theme. Water is however also a topic for specific bioenergy, e.g. biomass. Figure 10 draws a strong edge between water and denitrification. Among other topics, the keywords describe treatment technology for waste-water.

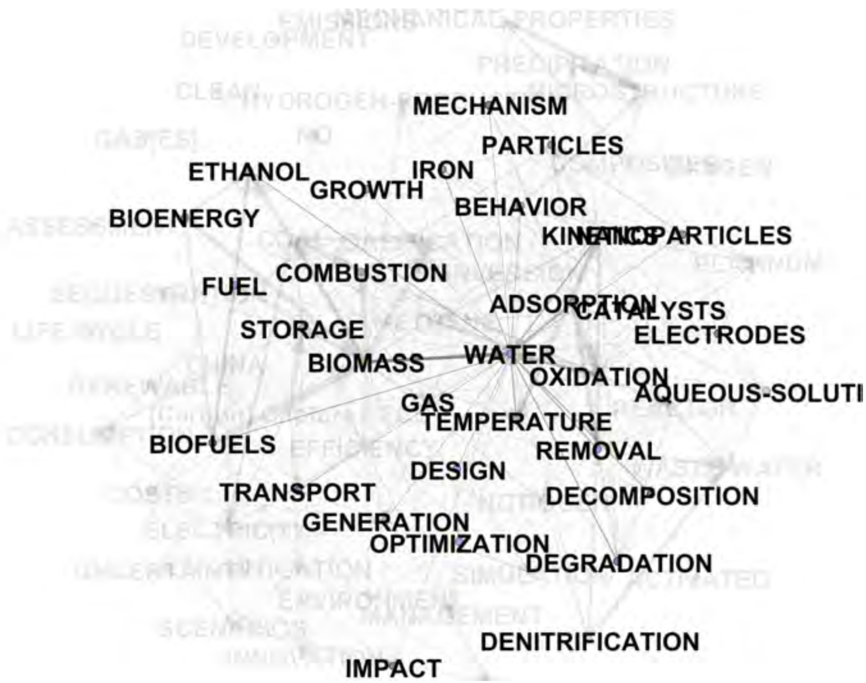

Fig. 9. Keywords co-citation with water

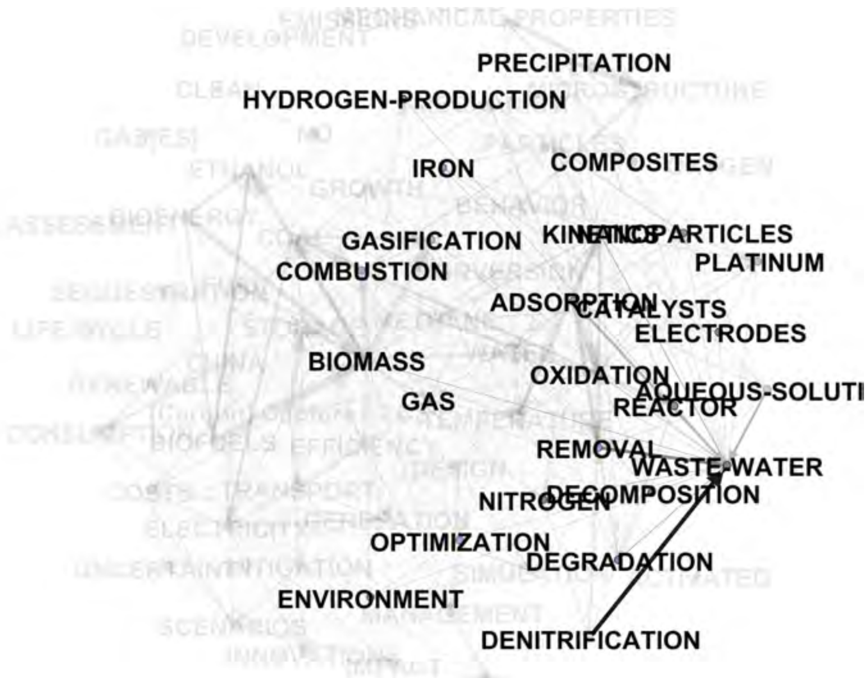

Fig. 10. Keywords co-citation with waste-water

All articles our bibliometric analysis retrieved for the Water Research journal discuss the broader theme of water treatment. More specifically, this includes the removal of substances from drinking or waste-water (nitrogen removal, nutrient removal, denitrification), ‘biodegradability’ (removing pesticides) and other aspects of fluids treatment from contamination. Those studies merely explore technology-use in water treatment process (e.g., ‘Microbial fuel cells for simultaneous carbon and nitrogen removal’ or ‘Greenhouse gas production: A comparison between aerobic and anaerobic wastewater treatment technology‘).

Our dataset includes two water related papers with ‘China’ in title, one about drinking water treatment technology and one related to CO_2 emissions from water consumption (Li et al., 2012; Li et al, 2004).The water topic is an example how future research could expand our knowledge of green infrastructures from and for the Chinese economy.

6.2.4 Transport and new carbon reduction technologies for industry

‘Transport’ is associated with technical terms such as storage (of CO_2), gas or water as well as functional terms such as costs, innovation, management, scenarios or simulation (see Figure 11). Note that despite the current debate on ‘smart’ ‘cities’ and ‘infrastructure’, our sample does not retrieve such keywords. It demonstrates the divide of two disciplines. Whereas environmental science and new sustainability technology for industry studies overlap with the energy & energy policy literature, our keywords social network as well as the highly ranked journal source titles suggest that scholars on system innovation or business ecosystems do not explicitly use the phrase ‘carbon reduction’ combined with ‘technology’ in title or abstract. Our sample contains a number of China related economics studies that discuss the potential effects of CRT, if used in road transportation (e.g., Ou et al., 2010; Wang et al., 2007).

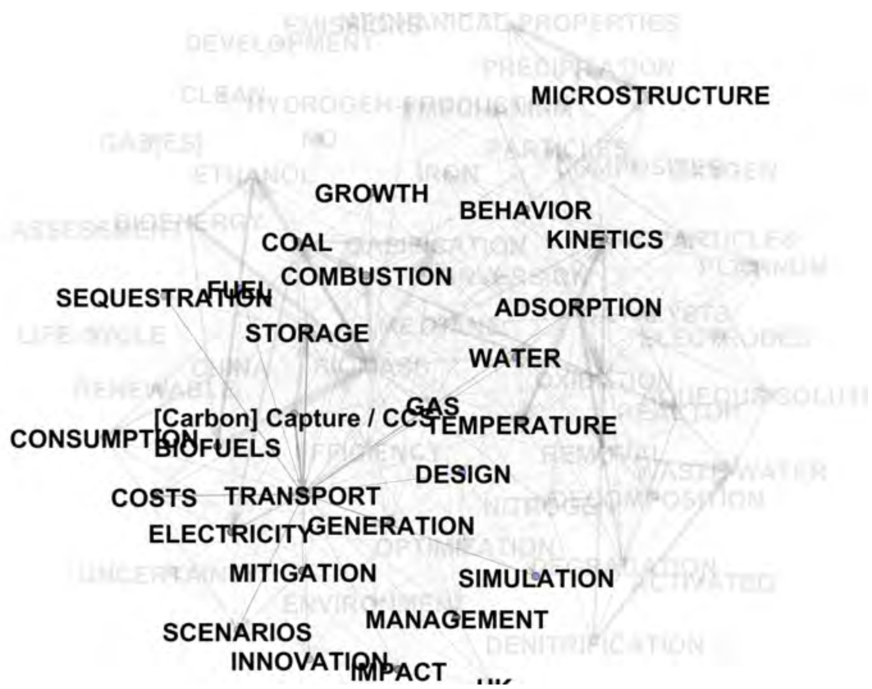

Fig. 11. Keywords co-citation with transport

6.2.5 New materials as carbon reduction technology for industry

'Particles' links to few materials and a number of chemical as well as electrochemical words (Figure 12). It thus indicates a cluster of process technology development. The top cited articles are technology not country specific (see article titles in Table 7).

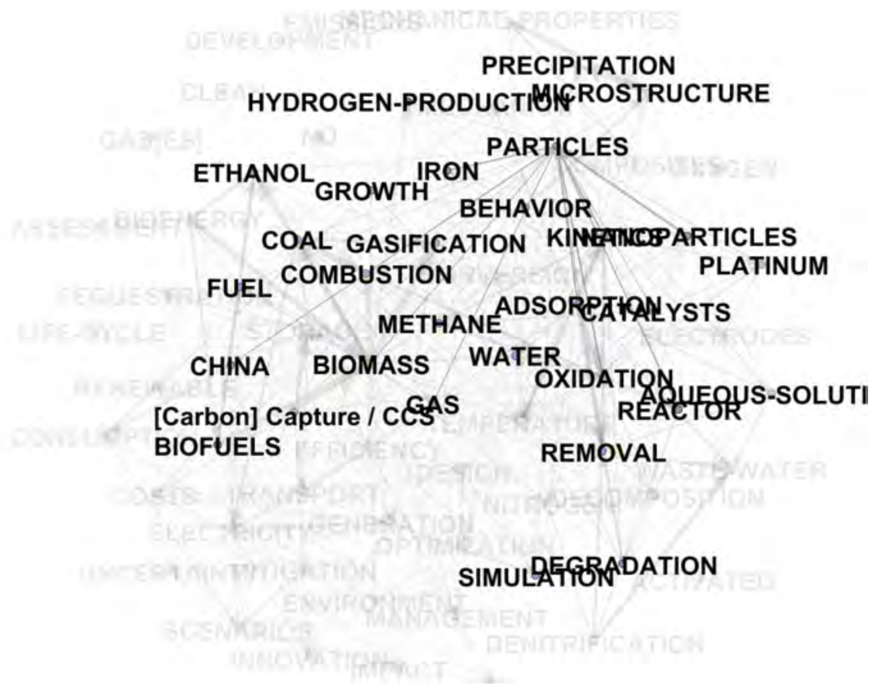

Fig. 12. Keywords co-citation with particles

This paper has previously explored the high authority keywords related to carbon reduction in industrial context. They include the keywords '[waste]-water'; 'transport'; and 'particles' (material sciences). The bibliographic analysis additionally indicates topics related to fuels.

More specifically, within our sample the Fuel journal ranks seventh in terms of publications while, however, 'fuel' is not among the top 50 keywords (Table 3). We conclude it covers technologies of substituting conventional or producing cleaner fuel. For instance, associated keywords from our social network graph are 'bioenergy', 'ethanol', 'methane' or 'combustion [technology]'.

In the subsequent section, we also identify a few sub-networks which are neither attached to an industry nor addressing a specific topicality. They characterize optimization techniques. Likewise, the keywords 'temperature', 'oxidation' and 'removal' characterize technical terms, which we cannot attribute to a specific theme. Therefore, we provide no graphical illustration for them. All these technical terms might be indicators of sustainable operations or sustainable systems innovation studies.

6.2.6 Sustainable operations

The Environmental Science & Technology journal contains few management science studies, for instance, addressing technology life-cycle analysis (alternative automobile fuel, wind power, shale/natural gas/coal) or the assessment of sustainability. Likewise, our keywords social network reveals a cluster of simulation and optimization (Figures 13–14).

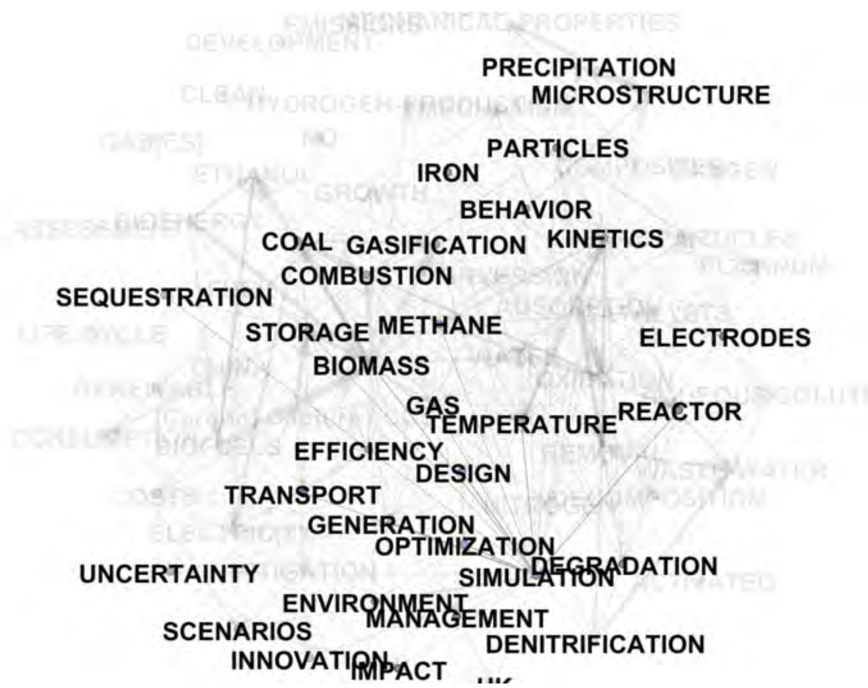

Fig. 13. Keywords co-citation with simulation

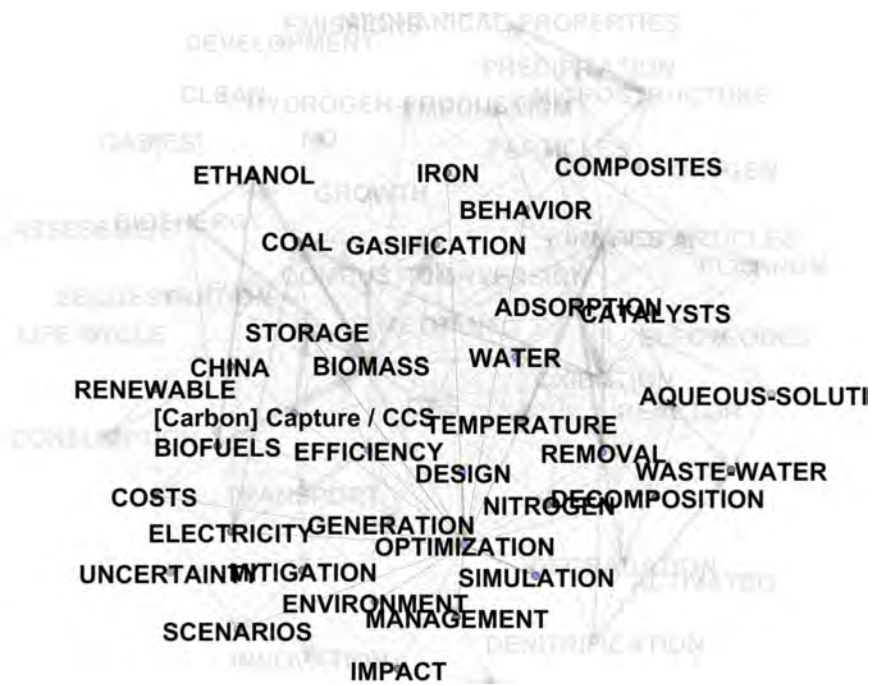

Fig. 14. Keywords co-citation with optimization

The keyword cluster of 'optimization' inter alia refers to major industrial sector keywords such as storage (of CO_2) and water. 'Simulation' refers to the keywords storage (of CO_2), transport and particles. Optimization and simulation techniques specifically may reduce carbon emissions of traditional technology; they facilitate its improvement (design, efficiency) and low-carbon processes in established industries. This also includes the simulation of carbon emission effects by economists. For instance, Kejun et al. (2010) and Qiang et al. (2011) compare carbon emissions for diffusion scenarios of different technologies in China. Saveyn et al. (2012) model the long-term effects of climate targets from different countries' policies. Zhang et al. (2013b) argue that strategy and harmonious inter-sector working mechanisms, and not just technology, are instrumental in achieving a low-carbon economy. They raise the interesting argument that the Chinese economy needs such new inter-sector working mechanisms in order to manage local low-carbon communities.

Furthermore, contemporary studies of sustainability in industry and specifically, of urban living increasingly emphasize an ecosystems and product-service systems perspective (Ceschin, 2013; Liedtke et al., 2014). Namely, that the urban implementation of low-carbon solutions in transportation, water or product delivery requires certain infrastructure (e.g., Bobker, 2006; Bolton and Foxon, 2015; De Haan et al., 2014), society involvement (Rangarajan et al., 2013) and possibly new business models (Boons and Lüdeke-Freund, 2013; Boons et al., 2013). Whereas the term 'systems' has high authority in our social network analysis, surprisingly however, the keywords 'infrastructure', 'institutions', 'business model', 'software' or 'standards' are not present in our sample. That may indicate a gap in management science, that is, research concerning the effective development, and empirical studies of product-service systems for carbon reduction. Equally, future studies might reflect on sustainable operations of these systems so that they develop the full resource- or energy-saving potential.

Overall, we argue that industrial business models need to be re-thought in the light of the CRT debate and of the opportunities arising from more sustainable ways of doing business. It is worthy of note that research in this field is growing, with relevant contributions including the recent work of Bocken et al. (2013), who reviewed emerging business models for industrial sustainability.

6.3 The contribution of the Chinese academy to the CRT debate

The keyword ‘China’ has a large number of co-citations with energy-related topics. It also gives reference to the industrial sector, specifically to the terms ‘particles’/‘mechanical properties’ and ‘removal’ (Figure 15). This demonstrates a strong contribution in clean energy and related energy policy as well as certain new carbon reduction technologies for industry. New energy technology development, energy conservation, environmental protection, and clean energy vehicles are high priority industries of the Chinese overall 12th five-year plan (cf. KPMG, 2011). In our co-citation network, the keywords ‘renewable’, ‘bioenergy’, CCS and ‘energy’ support the argument that China is focusing on renewable energy and carbon storage concepts (Figure 7). Concerning, sustainable operations, results are less clear. The keywords co-citations considered, the contributions of the Chinese academy do not relate to ‘water/waste-water’; ‘transport’; or the terms ‘temperature’, ‘oxidation’ and ‘simulation’.

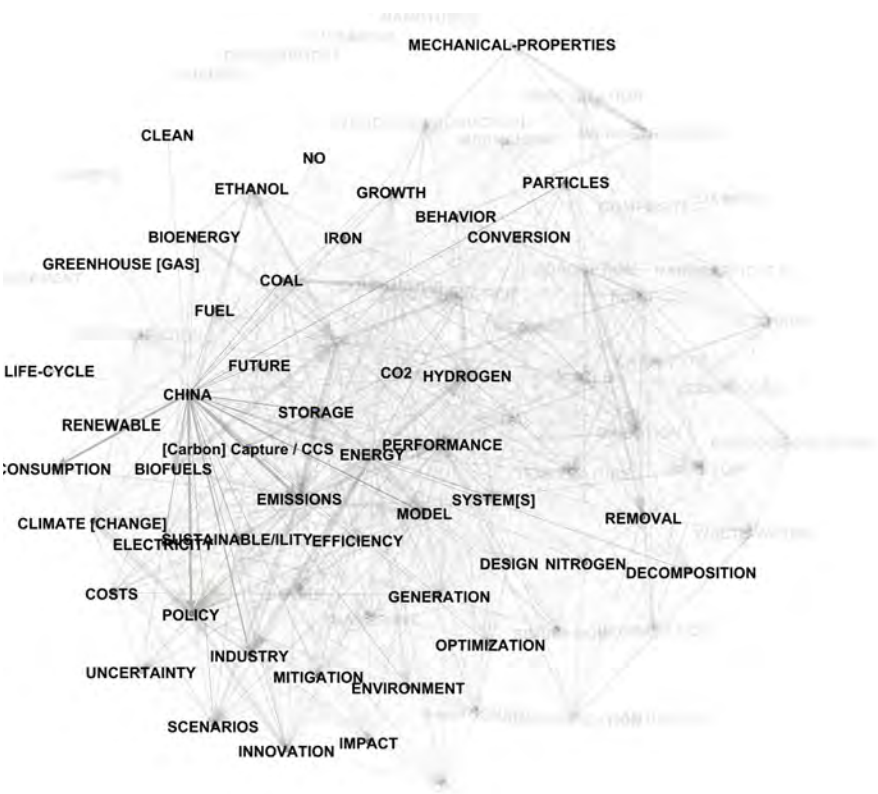

Fig. 15. Keywords social network analysis, highlighting linkages between China and other keywords.
Data and social network algorism drawn from Fig. 4.

Overall, we find the Chinese academy’s contribution to the CRT debate is evident. Namely, the full co-citation network includes only two countries by keyword: China and the UK. This may imply that there are more dedicated carbon capture & technology articles on China / UK or from China / UK as compared to other countries. The analysis of authorship has also revealed prolific authors from Chinese institutions.

6.4 What is missing to develop a strong research agenda

The previous section identified promising themes for future research. Table 13 summarizes these themes and classifies them in their meaning of technology.

Table 13. Technologies, management and society in the context of the CRT themes
a) Adapted and extended from Dangelico and Pontrandolfo (2010).

Technology meaning as green option [a)]	Core topics
Political and societal	• New techniques and consumption patterns which mitigate climate change • Clean energy policy
Creating new technologically based goods (technology sector)	• Renewables • Carbon capture systems / storage • Clean water • Clean fuel
Selling consumer goods	(not subject to the CRT debate)
Manufacturing and distribution (industrial sector)	• New technology from environmental sciences • Clean transport
Specialist in basic materials	• Environmental sciences • New metals (e.g., keyword 'particles')
Sustainable operations	• Optimization • Simulation • Removal

We propose that researchers need to clarify, in terms of management and operations, how technology can be instrumental to achieve climate change mitigation. Such analysis may need to account for industry sector specifics. Furthermore, the term 'technologies' enforces a narrow view. Sustainable operations also demand for new techniques. Adding to the many terminologies is not necessarily beneficial to support the rise of a CRT discipline. Therefore, this paper connects to and adapts the well-suited terminologies already in place, i.e. the term 'green options'. The clean energy policy research is instrumental but only represents a part of the low- carbon economy. For instance, the UK energy incl. indirect services to the national gross value added (GVA) accounts for 2.4% in 2010 (Newton, 2011).

To overcome disciplinary barriers we suggest that researchers make explicit of use the term 'carbon reduction and technology (CRT) debate'. We have stressed the following challenges as future CRT core themes:

- Clean energy,
- Technology development driven by environmental sciences,
- New carbon reduction technologies for the water and the transport sector,
- New materials as carbon reduction technology and
- Sustainable operations.

7 Conclusions

This study has systematically reviewed the research landscape associated with carbon reduction *and* technology. In doing so, we highlighted promising future directions, derived from a large dataset. We present the first large dataset review of the full carbon reduction and technology debate. Furthermore, the underlying dataset selection does not refer to any political concept and does not favor a certain discipline. By combining a bibliometric analysis and a keywords social network analysis, our paper is also exceptionally rich in rigorous data. The bibliographic results indicate a body of knowledge that is highly dispersed, scattered into subthemes from various disciplines. Whereas we retrieve a dominant cluster of energy and energy policy research, the dataset also reveals a number of core themes in industrial sustainability. More surprisingly, keywords of sustainable operations hold co-citations with the various themes of industrial sustainability. At the same time, we cannot identify an explicit discipline of sustainable operations in the dataset. We suggest that the debate should more actively reflect optimization techniques as a core contribution to carbon reduction in conventional industries. Furthermore, we find a large number of studies by the Chinese academy, from Chinese authors and relating to carbon reduction in the Chinese economy. Likewise, we observe, that Chinese academics acknowledge the receipt of significant funding for CRT research. Highly cited papers expose certain technologies, not countries. Therefore, we find the CRT debate overall is more technology centric than reflecting regional or national challenges.

There are also few limitations as follows. Whereas this paper covers the full carbon reduction and technology debate, the large size of the sample (N: 3310) does not allow us to discuss all the contributions for each discipline or industrial sector. It is rather the purpose of this study to guide research by framing the many directions. A bibliometric analysis also cannot capture qualitative trends of the debate. Second, some keywords in our social network analysis remain subject to interpretation, given no explicit context (e.g., ‘temperature’). We also apply a relatively new although rigorous measure when referring to network nodes authority. The set of keywords used cannot cover all contributions to the CRT debate; specifically, it will omit papers where scholars discuss relevant subtopics without spelling out the term carbon reduction in title or abstract. We suggest that future research should also clarify the hidden keywords of the different pre-dominant themes in the CRT debate. This paper contributes an initial outline of those potential themes. We also recognize the limitations of our qualitative analysis of funding institutions. Specifically, we are limited to a description of the evidence emerging from the dataset. We argue that this could be an interesting area for further research so as to highlight how different countries organize funding and how this affects the quantity, quality and visibility of the research produced.

Nonetheless, the rich keywords dataset allows us to isolate clusters of keywords and so reveals the less explored themes of research. This facilitates us to identify the promising directions for CRT research that looks at the industrial sector (e.g., water, sustainable operations). Finally, we put a focus on the Chinese academy whereas, considering studies following up the individual CRT themes (e.g., sustainable operations and carbon reduction), should also select other emerging and rapid growth economies for future comparative CRT literature reviews.

Finally, our paper provides a guiding, unique holistic framework for researchers as well as practitioners on industrial sustainability. For instance, it lays out a structured research agenda and contextualizes the different disciplines of the CRT debate. From a management perspective, further research should target sustainable operations and the commercialization of environmentally sound technology in traditional business sectors as well as the implementation of product-service systems. Economics research in that regard should explore the governance and incentive mechanisms needed to implement large product-service systems for carbon reduction – covering the core challenges such as energy supply, urban congestion, water, fuels, the more sustainable production of food, or sustaining natural ecosystem services.

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