Advanced Review

Interdisciplinary research in climate and energy sciences

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Due to the complex nature of climate change, interdisciplinary research approaches involving knowledge and skills from a broad range of disciplines have been adopted for studying changes in the climate system as well as strategies for mitigating climate change (i.e., greenhouse gas emissions reductions) and adapting to its impacts on society and natural systems. Harnessing of renewable energy sources to replace fossil fuels is widely regarded as a long-term mitigation strategy that requires the synthesis of knowledge from engineering, technology, and natural and social sciences. In this study, we examine how the adoption of interdisciplinary approaches has evolved over time and in different geographic regions. We conducted a comprehensive literature survey using an evaluation matrix of keywords, in combination with a word cloud analysis, to evaluate the spatiotemporal dynamics of scholarly discourse about interdisciplinary approaches to climate change and renewable energy research and development (R&D). Publications that discuss interdisciplinary approaches to climate change and renewable energy have substantially increased over the last 60 years; it appears, however, that the nature, timing, and focus of these publications vary across countries and through time. Over the most recent three decades, the country-level contribution to interdisciplinary research for climate change has become more evenly distributed, but this was not true for renewable energy research, which remained dominated by the United Sates and a few other major economies. The research topics have also evolved: Water resource management was emphasized from 1990s to 2000s, policy and adaptation were emphasized from the 2000s to 2010–2013, while vulnerability became prominent during the most recent years (2010–2013). Our analysis indicates that the rate of growth of interdisciplinary research for renewable energy lags behind that for climate change, possibly because knowledge emanating from climate change science has motivated the subsequent upswing in renewable energy R&D.

How to cite this article:
WIREs Energy Environ 2016, 5:49–56. doi: 10.1002/wene.180

INTRODUCTION

As society faces the challenges of anthropogenic changes to local and global environments, national governments must invest in research and development (R&D) to prepare for unprecedented socioenvironmental problems with complex causes and solutions.[1] Among the many problems that confront the international community, climate change is one of the biggest long-term threats to human society;

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Conflict of interest: The authors have declared no conflicts of interest for this article.
Additional Supporting Information may be found in the online version of this article.

it has been deemed a 'wicked problem' in recognition of its complexity and resistance to simple, one-time solutions.[2] A hallmark of such wicked problems is the need to apply research that combines methods from multiple disciplines.[2]

Climate change research requires improved knowledge, methodology, and collaboration across disciplines, such as soil science, marine science, atmospheric sciences, plant physiology, ecosystem science, hydrology, and computer science.[3] Explicit interdisciplinary initiatives have targeted climate change problems ranging from understanding of physical mechanisms to assessing socioecological consequences.[2,4–7] However, there is little systematic understanding of the extent to which the scientific research community has adopted interdisciplinary approaches to understanding and mitigating the magnitude and consequences climate change and how the emphasis of such research has evolved over time and across countries.

Transitioning the global economy from fossil fuels to renewable energy sources has been identified as a key strategy for mitigating climate change.[8–12] Increasing government investments have focused on development and application of renewable energy,[13] and the global investment in renewable energy for both electricity and liquid fuels has been continuously increasing during the past three decades, reaching its peak at $279 billion in 2011.[13] Renewable energy can take many different forms, ranging from solar, wind, and bioenergy to geothermal and hydropower. The generation of energy through these different means carries different complex sets of socioenvironmental risks and benefits.[14] Consequently, successful deployment depends on an interdisciplinary body of knowledge drawing on geophysical and environmental sciences, technology, engineering, business, computer sciences, policy, and economics.[15,16]

As the natural and social sciences are rooted in disciplinary traditions, and interdisciplinary research as a recognized mode of study has evolved over recent decades,[17] we wondered how the young fields of climate change and renewable energy have evolved with respect to interdisciplinary approaches through time and across different regions of the world. Our objectives were: (1) to assess how the adoption of interdisciplinary research for climate change and renewable energy has changed over the past three decades across countries and regions; (2) to explore the shift of the focus area for interdisciplinary research in climate change and renewable energy over the past three decades; and (3) to compare rates of adoption of interdisciplinary research in climate change and renewable energy as an indicator of whether the efforts of the scientific community to mitigate climate change through research on renewable energy tracks closely the progress in climate change understanding.

METHODOLOGY

We used an evaluation matrix of keywords representing climate change and renewable energy and interdisciplinary research in published scientific literature, which are searchable through the *Web of Science* core database. The matrix of keywords included 'climate change', 'climate warming', 'global change', 'global warming', and 'global environmental change' to represent climate change research; *multidisciplinary*, *transdisciplinary*, *crossdisciplinary*, and *interdisciplinary* to represent interdisciplinary research; and 'renewable energy', 'alternative energy', 'biofuel', 'hydropower', 'solar energy' 'wind energy', and 'wave energy' to represent renewable energy research in the *Web of Science* database. Our method resulted in a database of publications that self-identified as either using or discussing interdisciplinary research associated with climate change or renewable energy. This methodology of using keywords as representative of research domain/product has been used previously by various investigators.[18–20]

To explore the evolution of research that self-identifies with one or more of the keywords from the evaluation matrix, we searched for each of these keywords in the *Web of Science* citation database, targeting title, abstract, and keyword. The results obtained were further analyzed to investigate the temporal and international variations of interdisciplinary research in climate change and/or renewable energy. Abstracts for all publications were used for word cloud analysis that was carried out with 'tm', 'wordcloud', and 'RColorBrewer' packages in the *R program* (Version 3.0.2) to elucidate research topics and how they changed over time and across countries. Although not quantitative, the results of a word cloud analysis can be useful for quickly identifying broad topics of interest in a defined population of documents.[21,22] The word cloud analysis is similar to the citation cluster analysis, which has been successfully used for tracking emerging technologies in energy research.[23]

RESULTS AND DISCUSSION

Research on Climate Change and Renewable Energy

The search in the *Web of Science* database returned the number of publications for research on climate change and renewable energy in general and those that

self-identified as discussing or using interdisciplinary perspectives over time and at country level. As measured by the number of published papers, overall scientific productivity of climate change and renewable energy have increased dramatically since the 1940s (very small numbers before the 1980s) (Figure 1). Over that same time frame, publications with an explicitly interdisciplinary perspective have increased at a higher rate than total publications for both climate change and renewable energy, implying that the scientific community is increasingly and consciously adopting approaches that employ multiple disciplines in both areas. The percentage of publications calling out an interdisciplinary approach for climate change research has increased steadily in recent decades (Figure 1(a)). In contrast, the percentage of publications calling out an interdisciplinary perspective for renewable energy research has increased at a much slower rate (Figure 1(b)). The lag of interdisciplinary discourse for renewable energy research compared to climate change research could reflect that interdisciplinary research in renewable energy is either not required at the same level as for climate change, or that it is currently lacking. One could argue that some areas of science are compartmentalized more than others and thus can exist without a strong interdisciplinary perspective. However, this seems unlikely for renewable energy. Lund and Byrne[24] commented that 'The field of energy and environment is defined by its cross-disciplinary basis'; we would tend to agree with this assessment. Therefore, we expect that a perceived lack of interdisciplinary discourse for renewable energy is an artifact, or more broadly a problem with our ability to extract such information from the published literature. Pirotta[25] arrives at a similar conclusion in her analysis of the alternative energy landscape by stating that traditional methods cannot adequately measure multidisciplinary research output. This will likely remain a problem for the foreseeable future.

The growing discussion or use of interdisciplinary approaches for addressing both climate change and renewable energy slowed slightly after 2008, corresponding with the global economic downturn and subsequent stagnation of research funding in the United States[26] and Europe[27] (Figures S1 and S2). However, total publications did not slow, suggesting that interdisciplinary research, notwithstanding obvious lags in the system, might be more vulnerable to funding shortfalls than strictly disciplinary research.

Geographical Contributions to Interdisciplinary Research for Climate Change and Renewable Energy

To understand the geographical evolution of interdisciplinary research on climate change, we performed further analyses of self-identified interdisciplinary publications from different countries (Figure 2 and

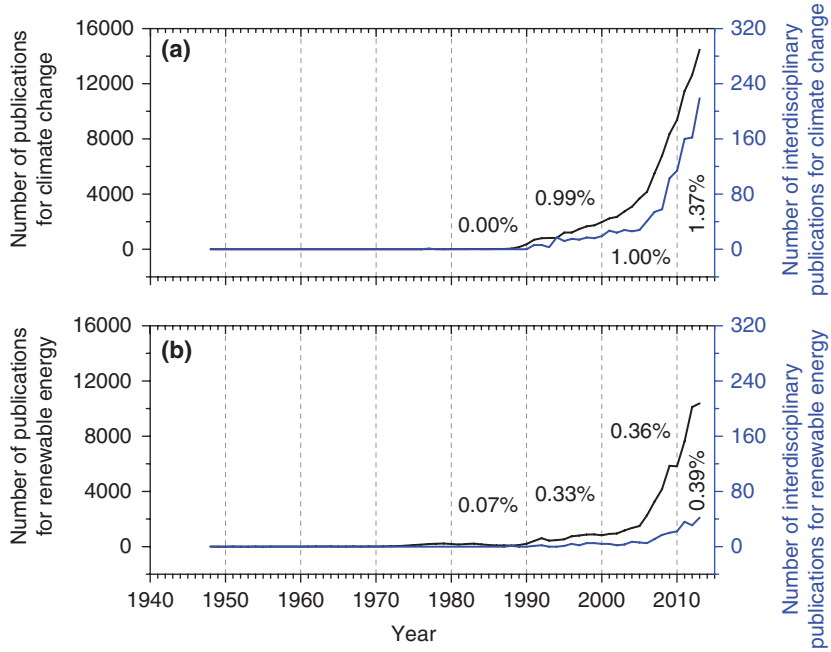

FIGURE 1 | Historical trends of climate change research and renewable energy R&D as general and as interdisciplinary shown as the number of publications in *Web of Science* (a: climate change research; b: renewable energy research).

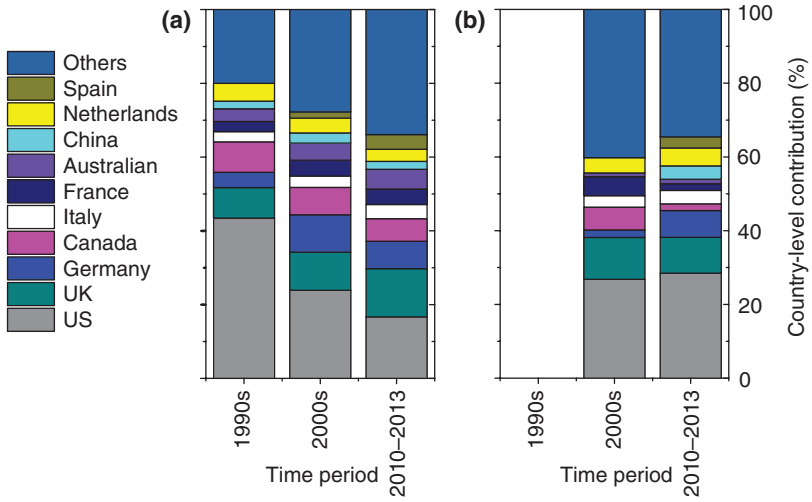

FIGURE 2 | Country-level contribution to interdisciplinary R&D on (a) climate change and (b) renewable energy research (source of information: *Web of Science*, June 29, 2014; the number of publication for renewable energy with interdisciplinary approach in the 1990s is too few for robust country-level analysis).

Figure S3). Although the United States, Canada, and a few European countries have consistently dominated the discussion of interdisciplinary research in publications, the combined output of the rest of the world has increased rapidly as a proportion of total output (Figure 2(a)). For instance, the percentage of annual production of publications from China to that from the United States increased from 5% in the 1990s, to 25% in the 2000s, and to 51% in 2010–2013, even though the annual production of the United States grew by 52% from the 1990s to 2010–2013 (Figure S3). This leveling trend is possibly due to the economic emergence of developing countries, such as China, Brazil, and India, with a corresponding increase in research spending.[28,29] For example, China's annual research and development spending grew on average by more than 20% for nine straight years from 2004 to 2012 (Figure S2). Fittingly, while China's contribution to papers discussing interdisciplinary research was imperceptible in the 1980s (data not shown), it has grown to rival the contribution of Western European countries during the most recent decade (Figure 2(a)).

Globally, interdisciplinary publications on renewable energy were negligible in the 1990s but began to emerge in the 2000s with continuous growth since then (Figure 1(b)) In contrast to interdisciplinary climate change research, a few western economies, principally the United States, the United Kingdom, and Germany, continue to dominate interdisciplinary research on renewable energy (Figure 2(b)). Continued dominance by the United States is well aligned with large investments in renewable energy by the US government in recent years.[13] Similarly, the lack of growth of the share of publications by countries outside of the top 10 contributors is consistent with recent research showing that renewable energy research has not been an area of emphasis among developing economies, except for China and a few other emerging economies.[19]

We further examined the continental-level contribution to interdisciplinary climate change research (Figure 3). The leading continent contributing to the global interdisciplinary research on climate change is Europe, followed by North America, Asia, Australia, Africa, and South America. The overall growth of interdisciplinary research in climate change is highest for Asia, with a 7.2-fold increase, and lowest for North America, with a 3.7-fold increase. Interdisciplinary discourse on climate change increased at relatively uniform rates (5.3- to 5.9-fold) in South America, Europe, Africa, and Australia from the 2000s to 2010–2013. This uneven change suggests a leveling of scientific contributions across the six continents.

There was also an increasing focus on interdisciplinary approaches in renewable energy research. The leading continent contributing to the global interdisciplinary research on renewable energy is Europe, followed by North America, Asia, South America, Australia, and Africa. The increase was highest for Asia, featuring a 6-fold increase, compared with a 4-fold increase for North America, a 2.5-fold increase for South America, a 4.3-fold increase for Europe, a 7.5-fold increase for Australia, while a slight decrease in Africa was observed from 2000s to the 2010–2013.

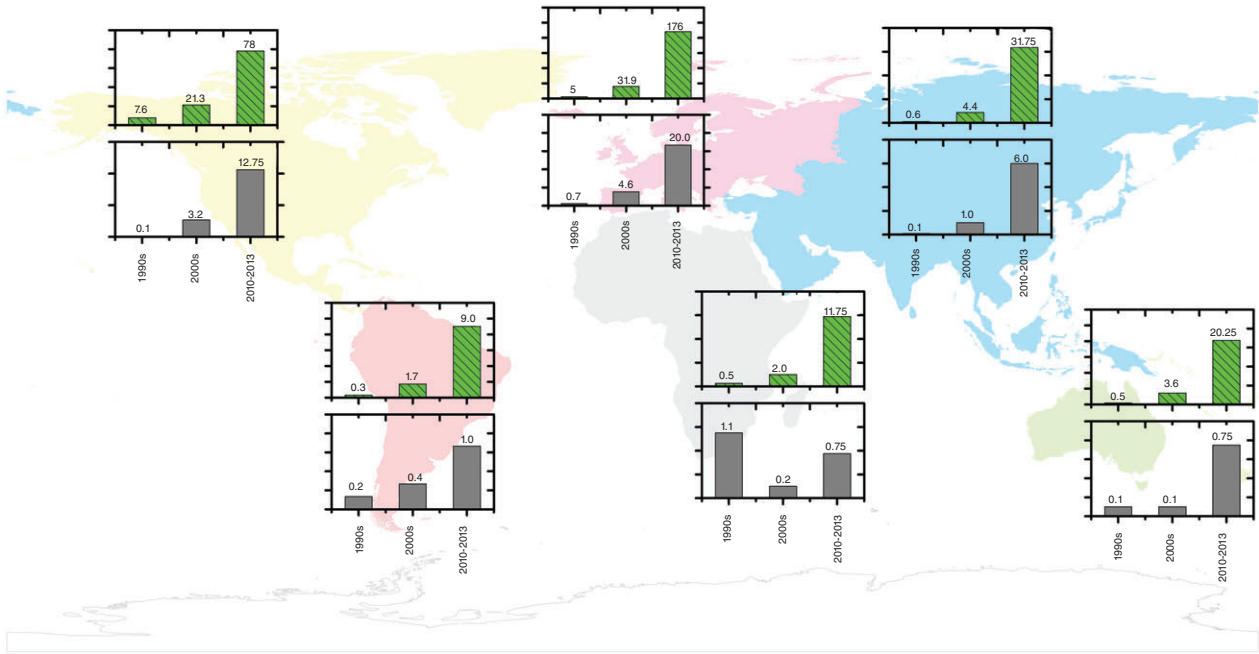

FIGURE 3 | Continental-level contributions to international research in climate change (green bars represent the number of publications for climate change research, while the gray bars represents renewable energy research in the 1990s, 2000s, and 2010–2013, respectively; the unit of the insets is number of publications per year; the values above the bar charts represent number of publications per year in one decade).

Emerging Topics in Interdisciplinary Research for Climate Change and Renewable Energy

We further conducted a word cloud analysis to explore how the dominant subjects of interdisciplinary research have evolved over time in the field of climate change science. The primary focus evolved from data (e.g., field observational data and climate data) during the 1990s to management and water systems (e.g., water quality and availability for a variety of uses) in the 2000s and 2010–2013[30,31] (Figure 4(a)–(c)). Meanwhile, 'models' began to emerge as a major focus of interdisciplinary discussion in the 2000s (Figure 4 (b)), and 'vulnerability' is now becoming popular during the period of 2010–2013 (Figure 4(c)).

A word cloud analysis was also carried out to explore how the dominant subjects of interdisciplinary research have evolved over time in the field of renewable energy. The primary focus evolved from 'solar' and 'water' in the 2000s to 'technology' in the 2010–2013 (Figure 4(d)–(f)). Meanwhile, 'international' became more and more popular in interdisciplinary publications on renewable energy, which concurs with new reports that renewable energy requires international collaboration and has international implications.[32–35]

The increasing focus on interdisciplinary research and the shifting topical focus in climate change and renewable energy R&D reflect the historical trajectory of global economic development. Over the past three decades, more and more countries have become important players in the global scientific community,[36] which is reflected in the declining proportional contributions of the United States and Europe and increasing proportional contributions of other countries to interdisciplinary research (Figure 2). On the other hand, a few developed and emerging economies continue to dominate renewable energy research.

SUMMARY

This study identified a marked increase in scientific literature targeting climate change and renewable energy research over the past three decades, with an increasing emphasis on interdisciplinary research through time and internationally. Moreover, the contributions from different countries have evolved to be more even across the globe, more so for climate change than for renewable energy. The research topics have also evolved: Water resource management was emphasized from 1990s to 2000s, policy and adaptation were emphasized from the 2000s to 2010–2013, while vulnerability became prominent during the current decade (2010–2013).

Interdisciplinary research for renewable energy lags behind that for climate change, possibly implying that interdisciplinary research in renewable energy is either not required at the same level as for climate

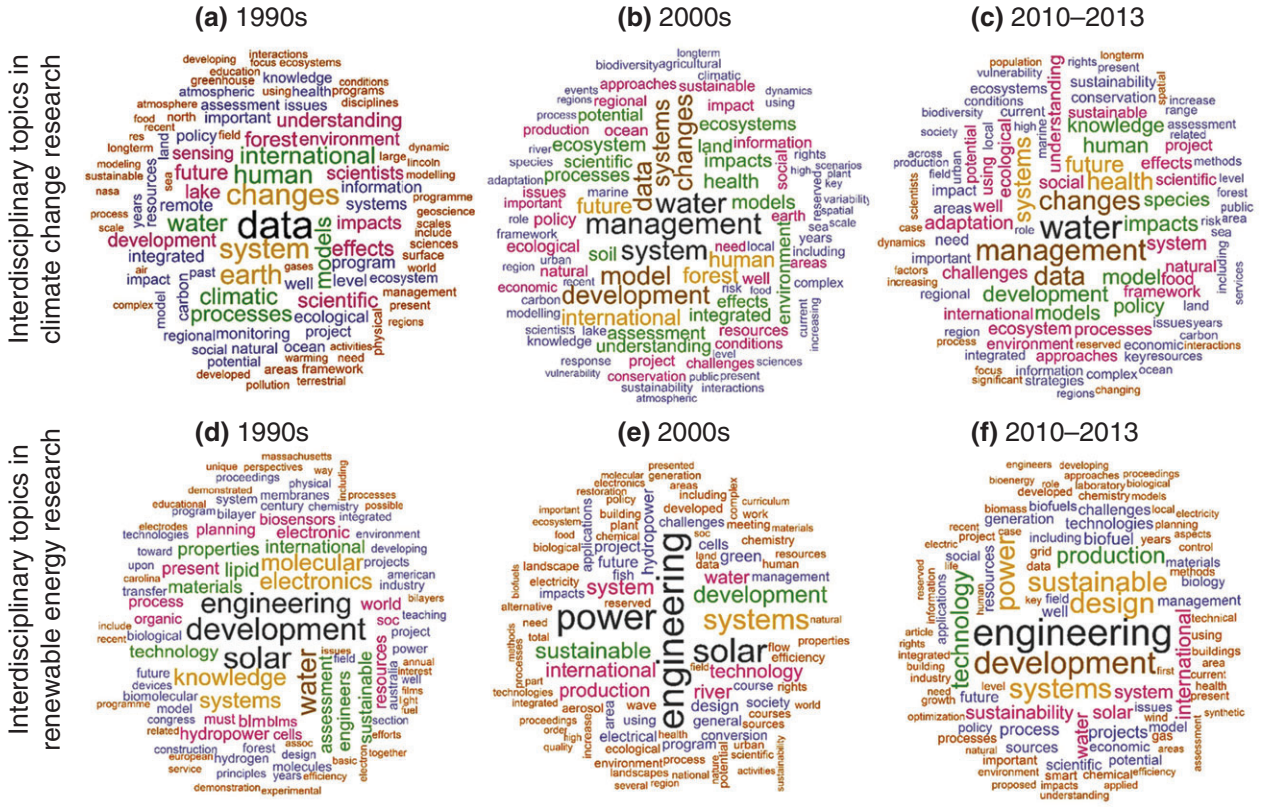

FIGURE 4 | Word cloud analysis showing changes in the focus of interdisciplinary R&D in climate change from (a) the 1990s, (b) the 2000s, to (c) 2000–2013, and in renewable energy research from (d) the 1990s (e), the 2000s, to (f) 2000–2013. The top 100 words are shown for each analysis; the same color indicates same frequency.

change, or that it is currently lacking. Alternatively, our methods may be inadequate to capture the degree of synthesis and integration that actually occurs in renewable energy R&D. Our approach likely omits a large fraction of interdisciplinary studies as many interdisciplinary studies likely do not use one of these search terms in the title, abstract, or keyword. Similarly, proprietary research on development of renewable energy technology is unlikely to be published in the open scientific literature.[37] However, the search results likely represent a subset of the literature that actively discusses the need and frameworks for applying interdisciplinary research to climate change and/or renewable energy. Insomuch as this portion of the literature reflects or presages the mindset of a larger research community, it might also mirror how research across disciplinary boundaries may have evolved over the years. Hence, our data may offer a proxy for the rates at which interdisciplinary approaches have been adopted over time and in different countries for climate change and renewable energy R&D.

Note Added in Proof

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ACKNOWLEDGMENTS

We thank Drs Virginia Dale, Rebecca A. Efroymson, Yetta Jager, and Bruce Tonn at Oak Ridge National Laboratory for their constructive comments and Ms Amy Harkey at Oak Ridge National Laboratory for editing the language. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725.

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