Evidence map: topics, trends, and policy in the energy transitions literature

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Abstract

We develop an evidence map of the academic research on energy transitions (ETs) with a focus on what that literature says about public policy for addressing climate change. In this article, the questions we ask are: What trends do we see in the topics that occur in journal articles on the energy transition? And to what extent has public policy been a focus? Where do we need or see energy transitions happening?

Our approach involves: (1) using two literature databases to identify 4875 relevant ET articles over the period 1970–2018; (2) identifying important topics within ET using topic modeling via latent Dirichlet allocation on the abstracts of the articles; and (3) conducting a robustness check on the topics and analysis on the policy-relevant topics. This study contributes to the ETs research by providing the first systematic overview of peer-reviewed articles on ETs. We find that the number of academic articles covering ETs has increased by nearly a factor of 50 since 2008, 67% of them are policy related. Research on governance is pervasive in the literature and contains multiple topics differentiated by substantive foci. Some topics on the social-technical, social-behavioral, and political aspects of transition governance are becoming increasingly popular. Network analysis shows transition governance, energy economics and climate implications, and energy technologies comprise the three largest clusters of topics, but we observe a lack of connectedness between governance topics and technology topics. In the policy-relevant literature, we see a growing number of articles on technological and institutional innovation, and examples from leader countries, especially in Europe. We find only a quarter of articles discussed ETs in developing countries, which is not aligned with a recurring theme, their importance to the global ET.

1. Introduction

In the 2015 Paris Agreement, nearly 200 countries committed to limit global temperature increase to well below two degrees and pursue efforts to limit the rise to 1.5 degrees (UNFCCC 2015). Achieving this goal would require a transformation of today’s global energy system from one that is overwhelmingly fossil fuel-based to a nearly fossil free system by mid-century (Rogelj et al 2018). Although international climate governance has encountered setbacks since 2016, a strong cadre of leaders around the globe recognize the urgent need for sound policies that facilitate a rapid and cost-effective energy transition (ET) to near-zero carbon system. European countries have led the way in recent emissions reductions (Le Quéré et al 2019). India is committed to its ambitious goals for renewable energy installation. China remains a strong supporter of the climate agreement and is the largest investor in clean energy, which helps set the track of its carbon emissions on a plateau and bound to decline in around 2025 (Qi et al 2020). Despite the Trump Administration’s withdrawal of support for the Paris Agreement, policymakers from state and local governments in the United States have led efforts to carry out bottom-up action plans.
However, accelerating the speed of ETs is essential because the pace of transition actions to date is far too slow to meet the Paris Agreement’s goals (Victor et al 2017). The importance and complexity of ETs have attracted scholars from diverse disciplines, including natural science, engineering, economics, political science, sociology, communication, and public policy. In particular, social sciences are crucial for understanding the economic, social, and political aspects of climate change governance. Many major social science disciplines are well-represented within the Intergovernmental Panel on Climate Change (IPCC), especially since the fifth assessment report (Callaghan et al 2020). Considering the diverse and rapidly expanding social science literature, as well as the combined pressures of a narrow window and growing social-economic and political challenges, a comprehensive synthesis of knowledge across multiple fields of social sciences can aid policymaking in the Post-Paris era.

Traditional narrative reviews in summarizing extant studies have synthesized major parts of the scientific literature and yielded important insights. However, as this literature has expanded exponentially, traditional literature reviews face the serious challenge of ‘Big Literature.’ Transparent and subjective full-scale overview of scientific texts becomes impossible when both the number and variety of articles exceeds human’ reading capacity (Nunez-Mir et al 2016, Minx et al 2017, Gurevitch et al 2018). The ‘Big Literature’ challenge is especially salient for literature on ETs because of its interdisciplinary nature. Social scientists who study ETs and climate change often publish on nature science or interdisciplinary journals, such as Science, Energy Policy, Climate Policy, Governance, and other energy and environmental subject specific journals (Bernauer 2013). As a result, social science research on energy and climate governance is scattered across different fields and disciplines, making systematic analysis even more difficult.

This research is motivated by the need to take stock of what we know about policy questions by comprehensively and systematically evaluating topics in the literature on ETs. Following strict methodological procedures, we identify and summarize evidence in a transparent, objective, replicable and updatable manner. It avoids bias in selecting and interpreting literature, allows us to cover 1000s of articles and provides quantitative insights that traditional literature review misses.

In the following sections, we first discuss the definitions of ET. Second, we then systematically survey a total of 6270 published journal articles (in English) on ETs found in two databases since 1970, as the idea of ET in the defined sense first arose from energy security and conservation concerns. This sampling method allows us to avoid selection bias and produce a new dataset consisting of literature on ETs. Third, we use unsupervised machine learning techniques to systematically analyze the selected corpus. Here, we intend to find: What trends do we see in the topics that occur in journal articles on the energy transition? To what extent has public policy been a focus? Where do we need or see energy transitions happening? Finally, we conclude with a knowledge synthesis and a discussion of remaining gaps.

2. Defining energy transitions

Over the past few decades, a vast literature on ETs and related subjects has accumulated (see Markard et al 2012, Araújo 2014, Sovacool 2014, Child and Breyer 2017, Köhler et al 2019 for comprehensive reviews). Although the term ‘energy transition’ is now widely used, as Sovacool (2014) states in his article, the framing and definition of ETs is ambiguous in the existing literature. Child and Breyer (2017) conducted a comprehensive survey on the definition and usage of the terms ‘transition’ and ‘transformation,’ and suggest that the term ‘transition’ is used more frequently in comprehensive discussions of economic and socio-political aspects of changes. Table 1 lists 11 definitions of ‘energy transition’ we find in the literature, sorted by the citation counts on Google Scholar of the publication in which the definition is found. In addition to scoping ambiguity, identifying multiple definitions provides a rich source of keywords with which to search for relevant literature. As demonstrated in table 1, the most cited articles provide broad definitions and thus are not very different in terms of interpretation. Definitions 1 and 2 are found in an IPCC Special Report on Renewable Energy Sources and in the Global Energy Assessment, respectively. From an analytical perspective, definition 9 (Fouquet 2016) is the most narrowly stated. Although this definition can provide analytical clarity, it excludes a large number of articles on the subject, reducing the scope of analysis.

Figure 1 demonstrates the global trajectory of energy use from 1800 to 2018. From this historical perspective, shifts of primary energy consumption have taken decades, if not longer. Historically, mankind has depended on biomass for tens of thousands of years. Since the industrial revolution, fossil fuels started to replace traditional biomass. It took coal more than a century to become the dominant fuel, and oil more than 150 years to beat the ‘King Coal’. Nuclear and renewables have developed for nearly seven decades, yet their combined share is still less than 4% as of today. This speed is much slower than the proliferation of oil and gas. Therefore, to put the term in the context of modern history, ET is a paradigm shift of primary

4 Public policy, as defined by B. Guy Peters, is “the sum of government activities, whether acting directly or through agents, as it has an influence on the life of citizens (Peters 2018)”.

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Table 1. Existing definitions of ‘energy transition.’

| Definition                                                                 | Reference                      | Times Cited |
|---------------------------------------------------------------------------|-------------------------------|-------------|
| 1. ‘A structural shift toward a world energy system that is mainly based on renewable energy’ | Edenhofer et al (2011, p 199) | 401         |
| 2. ‘Transitions: shifts from one stable sociotechnical regime to another’ | Johansson et al (2012, p 1177) | 303         |
| 3. ‘The time that elapses between the introduction of a new primary energy source, or prime mover, and its rise to claiming a substantial share of the overall market’ | Smil (2010, pp 136–141) | 168         |
| 4. ‘A shift in the nature or pattern of how energy is utilized within a system’ | Araújo (2014, p 112) | 163         |
| 5. ‘The switch from an economic system dependent on one or a series of energy sources and technologies to another’ | Fouquet and Pearson (2012, p 1) | 152         |
| 6. ‘Shifts in the fuel source for energy production and the technologies used to exploit that fuel’ | Miller et al (2015, p 31) | 99          |
| 7. ‘Energy transition: change in the state of an energy system. ‘‘Grand’’ energy transition: pervasive changes in an energy system that affect multiple energy resources, carriers, sectors, and end-use applications, often associated with the diffusion of “general purpose” technologies (e.g. steam engines or electricity).’ | Grubler et al (2016, p 19) | 69          |
| 8. ‘A change in fuels (e.g. from wood to coal or coal to oil) and their associated technologies (e.g. from steam engines to internal combustion engines)’ | Hirsh and Jones (2014, p 110) | 63          |
| 9. ‘A transition was from 5% to 80% (or the peak, if it did not reach 80%) of the energy consumption for a particular service in a specific sector’ | Fouquet (2016, p 7) | 44          |
| 10. ‘A particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services’ | O’connor (2010, p 8) | 32          |
| 11. Energy transition is ‘a new direction that pertains to both the socio-technical landscape and the socio-political-technical regime that maintains it’ | Child and Breyer (2017, p 18) | 21          |

As Child and Breyer (2017) suggest, the concept of ET also refers to a complex development of economic, social and political regimes associated with shifts in technologies. The history of economic development reveals the relationship between ETs and broader social economic changes. The modern economy emerged in the late 18th century when the British began to utilize coal on a massive scale. Fundamentally different from mere combustion for cooking and heating, steam engines transformed chemical energy in coal into mechanical power to enable massive production and mobilization. While the rest of the world depended on biomass, Great Britain gained a critical advantage economically and become the first global superpower. Since the late 1870s, the United States systematically powered its economy with oil and gas and become the dominant superpower after the first World War, surpassing the United Kingdom, which stagnated and depended on coal. After World War II, leading economies began to invest in nuclear power and after the 1970s oil crises renewables. In the process, carbon content per mass of fuel has declined. With this definition in mind, we systematically review peer-reviewed articles on ETs to identify topics, trends and policy implications in the literature.

3. Methodology

In this section, we document the method for identifying, selecting, coding and analysing the literature on ETs. We conduct a full survey of the existing literature on ETs and utilize a machine learning technique to systematically assess research themes, to shed light on our research questions. We use the extant peer-reviewed journal articles to build a dataset of the ET literature, following the evidence mapping methodology developed by James et al (2016) and principles presented by Donnelly et al (2018).
Figure 1. World energy transitions (1800–2018). Data sources: Ritchie and Roser (2014), Smil (2016), BP (2019).

We use this approach to summarize accumulated knowledge, and to systematically ascertain the policy implications contained in this literature. The unsupervised machine learning avoids bias in selecting and interpreting literature, allows us to cover thousands of documents (scalable), and provides quantitative insights that traditional literature review misses.

3.1. Building the corpus

First, we identify all possibly relevant ET articles using the search terms related to ETs and climate change. We use peer-reviewed academic literature indexed by Scopus and Web of Science Core Collection, excluding conference papers, books, book chapters and corrections. This search method and number of articles found are summarized in figure 2 and comprises Step A in figure 3.

Second, (Step B) we develop a set of keywords with which to obtain a sample of articles related to the ET. As a preliminary scoping of this body of literature, we searched for keywords related to ET and climate change in all fields in the search engines for the two databases in between 1970 and the end of 2018, and obtained a total of 6270 articles, with the earliest one published in 1971. Here, we tested the completeness of the search by looking for articles cited in section 2. Indeed the 6270 articles we collected with this search include all articles mentioned above. For the details about the metadata that we extract, please refer to the supplementary information (SI, available online at stacks.iop.org/ERL/15/123003/mmedia).

Third, we code articles for relevance to ETs and climate change (Step C). Before scoping the literature, we reviewed the key literature and the state of knowledge about ETs and climate change. Our search yields literature on energy policy, energy technology, ecology, sustainable development, social and science perspective of climate change, oceanology, meteorology, physics, chemistry, and earth science. We exclude articles on pure sciences, such as chemistry and physics for which ‘energy transition’ has a different meaning. Literature on general sustainable development, although might not be energy specific, is included in the review.

To build the corpus, we take the following steps to effectively eliminate irrelevant articles: (1) We sort the 6270 articles by source and manually remove articles from journals focusing on physics, chemistry, engineering, geology, geography, biology, ecology, meteorology, oceanology, earth and atmospheric science, medical science and other irrelevant subjects focusing primarily on natural sciences; (2) We manually read all titles and abstracts of articles published before 2010 and remove those irrelevant articles. We choose year 2010 to be the cut-off point because the concept of ET is relatively new, and early articles might not use the term the same way we defined it; (3) We search for words that are more likely to appear in un-related subjects in the abstracts, and then manually remove those irrelevant articles; (4) We search for articles that do not include any energy-related words in the abstracts, and then manually remove those irrelevant documents on sustainable development on food, agriculture, and water without much to do with energy. These processes produce a set of 4875 articles relevant to the topic of ETs and climate change, with publication dates from 1982 to 2018. We call this set...
the ‘Corpus.’ (5) To assess validity, we test the corpus relativity by manually reading a random sample of 500 documents, and find the frequency of irrelevant articles is less than 1%. For more details about the scoping and selecting procedure, please refer to the SI.

3.2. LDA and analysis

Fourth, in Step D, we run the latent Dirichlet allocation (LDA) topic model using the abstracts of the 4875 corpus articles to identify latent topics. As an unsupervised machine learning method, topic modeling has been used to identify key topics and themes in various literature (for topic model application using literature on energy and climate change, see Tvinnereim and Flottum 2015, Boussalis and Coan 2016, Farrell 2016, Jiang et al 2016, Sun and Yin 2017, Tvinnereim et al 2017, Benites-lazaro et al 2018, Bickel 2019, Lamb et al 2019, Lesnikowski et al 2019, Bohr 2020, Callaghan et al 2020). LDA modeling requires researchers to make research decisions on the concentration parameter of Dirichlet distribution (alpha) topic-word density (beta) and the number of topics (k). We set alpha, to be k divided by 50, and beta to be 0.03. While a handful of methods are available in the literature to estimate the ‘optimal fit,’ no consensus on the preferred approach has yet been established. It typically comes down to human judgement to determine the ‘optimal’ and ‘manageable’ number of topics or whether the topics make analytical or semantic sense (Chang et al 2009, Grimmer and Stewart 2013). Therefore, we combine the quantitative and qualitative approach to determine the number of valid topics. We use the topic coherence score to determine the a range of ‘optimal’ number of topic for model selection (Röder et al 2015), and then use human judgment to analyze the topics’ validity and usefulness under the optimal model. In particular, we run 21 models using 30–130 topics with 500 iterations each, then calculate the topic coherence scores for each model. It appears that for models with 65 or more topics their coherence scores stay relatively stable, around 0.5 (see figure S1 in SI). The appropriate level of granularity is assessed subjectively by the authors, by compiling a spreadsheet (provided as supplemental data) that listed each modeling result next to each other (Callaghan et al 2020). We also assess model validity by separately reading the top ten highest-scoring documents of each topic to determine whether the model could successfully assign documents on analogous subjects into the same topic (see more details about LDA models in SI). We believe the combination of objective and subjective approach is an appropriate practice for LDA model evaluation.
Fifth, we manually name each topic with a meaningful description that captures the terms and content of the top ten highest-scoring documents for the topic and distinguishes it from the other topics (Step E). Sixth, (Step F) we manually code each topic as relevant to policy or not, based on the count of policy focused articles in the top ten most relevant documents within each topic to identify the extent to which it is policy focused, and yield a policy score scaled from 0 to 10. Since different researchers might have various opinions on the extent in which an article is policy related, for replicability we use authors’ word choice instead of human judgement to identify policy related articles for ensuring the objectivity and replicability of this research. We use the following words for identifying policy related content: political, policy, policy related content.

Finally, in Step G we manually group the topics into Z clusters on similar broad themes and give each theme a meaningful name. The output data contain information about article metadata, policy relevance, topic coverage, and category of each article. Figure 3 summarizes the methodology described above. Table S1 in the SI shows the structure of the output.

Using the topic model, we are able to examine trends and policy relevance of each topic, and their interconnection using network analysis. Throughout the analysis, we discuss the content of important topics by citing the top ten highest-scoring articles within each topic. First, we analyze the trend of individual topic by calculating the distribution of topic probability overtime. The same method is used to examine the timely trend of category as well. Second, this study also evaluates the overall trend of each topic by fitting the topic probability over time period (1994–2018) using linear models. This approach has been adopted by other researchers to analyze ‘hot (trending)’ and ‘cold (declining)’ topics (Griffiths and Steyvers 2004, Jiang et al. 2016, Sun and Yin 2017, Bickel 2019). Third, based on the of the co-occurrence probability of topics within individual documents, we are able to calculate the adjacency matrix for compiling the network of topics. Because LDA assigns all topics over all documents, it results in a skewed distribution of topics within each document, so only co-occurrence values exceeding a 10% threshold are considered. Degree centrality and betweenness centrality are calculated for to identify important and bridge topics within the network. Finally, we would highlight important findings using the policy-relevant topics and policy-relevant articles.

4. Results

4.1. Trends in peer-reviewed publications

Scholarly publications covering ETs have grown exponentially since the 1960s (Araújo 2014). The earliest discussions of an ET from a social science perspective were in response to the oil crises in the 1970s. Wishart (1978) describes a future where oil and gas are still expensive for industrial use under economic and political pressure. Research on ETs in the context of fuel replacement dates back to 1970s and the oil crisis resulting from the Arab Oil Embargo of 1973. The concept of ET referred to fuel replacement in the early 1970s because climate change was not acknowledged as a threat, and the direction of ET was not decarbonization but diversification, driven by energy security concerns. Today, the main justification and driving force for an ET is climate change. Some sporadic research related to energy planning and climate change began in the 1980s, as the earliest peer-reviewed article in the corpus dates back to 1982 (Perry et al. 1982).

Once the UNFCCC entered into force in 1994, researchers began to pay more attention to the subject, and yearly publications ranged from four to 13 in the following decade. Around 2008, the number of publications started to grow exponentially, which consisted of several jumps with more than 50% annual increases in 2009, 2010, 2012, 2014, and 2018, reaching nearly 1600 articles within a decade. Therefore, articles published in the last decade are weighted heavier in the analysis because of this much higher volume.

As expected, the literature focusses primarily on the world’s top emitters, i.e. China, the United States, and Europe, and each of them attract 11%, 12% and 50% of overall scholarly attentions (figure 4). In particular, the share of literature on Europe dominates the discourse and has being increasing overtime, from about 34% from 1994–2009 to 47% in 2010–2015 and to 52% in 2016–2018, while the share of research attention on developing countries (except China) decreased considerably. Research focuses on North America (12%–14%) and China (10%–14%) have stayed about the same overtime.

The ETs literature has been highly policy relevant since the 1990s. A total of 3254 articles, or 67% of the total corpus, contain at least one of the policy keywords, and which we thus categorize as policy relevant. The share of policy-related articles is relatively volatile before 2008. Policy relevance has been particularly stable over the last decade, as the annual total number of publications increases. Figure 5 shows the dramatic growth in the past two decades in ETs publications and the proportion of policy related articles.

Despite the abundance of policy-related publications, the distribution of citations received is not normally distributed, rather it is highly skewed such that most of the citations received are accounted for by a small portion of articles. Specifically, among policy-related articles, only 79 articles, or 2% of 3254 articles, were cited more than 100 times. We address the content of the policy-relevant articles in section 4.4.
Figure 4. Geographic distribution of research foci. Histogram in the upper panel shows the total number of publications focusing on each country/region by year, and the lower panel shows the share of each country/region in each period marked by milestone climate meetings (UNFCCC entered into force in 1994, Copenhagen in 2009, and Paris in 2015).

Figure 5. Annual count of peer-reviewed articles on energy transitions and percentage that are policy relevant 1994–2018.
4.2. Topic modeling analysis

By comparing various model specifications as described above, we find the model with 100 topics could best account for the breadth of subjects with the corpus. That model yields eight non-meaningful topics consisting of terms associated with academic writing that are irrelevant for the analysis (AlSumait et al 2009, Bousalis and Coan 2016). The modeling results offer a great deal of detail and opportunity to assess a diverse set of themes in ETs, demonstrating a convincing level of fit using data driven methods, and revealing deductive consistency with our understanding of the field. A total of 92 topics can well represent a wide range of themes of ETs and climate change, and yet provide a manageable set for clustering and further analysis.

The topics accounted for a wide range of themes related to ETs, including popular topics dominating the field, such as energy security, technology innovation, green electricity, as well as energy and climate governance. For interpretation, we choose a descriptive name for each topic using its components words and the top ten most probable documents (see table S2 in SI for the full list of 100 topics). The labels not only provide effective instructions for topic interpretation, but also offer a robustness check for the model quality with respect to semantic validity. Figure 6 presents the top 20 topics in terms of topic probability.

In addition, topic trends and prevalence over time provide evidence for assessing the change of research directions and deepen our understanding of the dynamic structure of the field (Günther and Quandt 2016, Bickel 2019). Figure 7 below shows the topic probability over time, and the three most popular topics in the corpus are highlighted in yellow, red, and blue respectively. The gray area spans the range of topics’ popularity in each year. Given the small number of articles published before the UNFCCC went into force in 1994, topic modeling yields null result for most of the years in between 1982–1993 when there was no relevant article published. Therefore, we present topic trend analysis on articles published from 1994 to 2018.

Figure 7 shows the propensity of the top three topics in colors: energy security, socio-technology, and electricity cost. It appears the topic energy security (the yellow line), trended downward between 1994–2003 then had a sharp a rise in 2005, and since 2011 has slowly declined but remains the most popular topic. In particular, the term ‘security’ refers to conventional national security (Vivoda 2012, Jonsson et al 2015, Strakos et al 2016), as well as unconventional security, which includes sustainable development and climate factors (Kurian and Vinodan 2013, Azzuni and Breyer 2018). The second most popular topic is socio-technology transitions, which is associated with a list of words about market and transition pathways. This topic became popular in around 2005 and peaked in 2009 at 3.5% of total share. The most well-cited (over 500 times) research articles under this topic are about niche market management (Schot and Geels 2008), innovation systems (Smith et al 2010, Markard et al 2012), and conceptualization of transitions and sustainable development (Loorbach 2010, Coenen et al 2012, Seyfang and Haxeltine 2012).

Research on electricity cost ranks as the third most popular topic, and its share has been increasing steadily since 2008. The most relevant articles highlight the importance of energy storage for achieving 100% renewables (Oei and Mendelevitch 2016, Ashfaq and Iancakiev 2018, Lund 2018), economic feasibility of different technologies, the importance of niche markets, knowledge learning, and economies of scale (Grübler et al 1999, Yevich and Logan 2003, Hoogwijk et al 2005, Mcdowall and Eames 2006, Hiremath et al 2007, Edward et al 2007, Yeh 2007), as well as the cost of solar and energy storage (McConnell et al 2015, Gulagi et al 2018, Lund 2018).

Based on the modeling results, we identify five mutually exclusive categories of topics: energy economics, governance, technologies, climate research, and social-behavior. We assign one category to each topic based on the content of the top ten highest scoring documents and whether its top ten most popular terms contain relevant keywords. To summarize: energy economics involves 25 topics on energy cost, environment and climate impacts, cost-benefit analysis, energy models and their uncertainty, technologies consists of 20 topics on energy technologies; and climate research and social-behavior include 15 and 10 topics each. Table S2 in SI provides a complete list of the estimated topics and their associated labels and categories. Figure 8 presents a relative measure of category prevalence by aggregating the topic proportions for each topic under the same category over 1994–2018.

As shown in figure 8, the distribution of categories across time is consistent with that of the topics. The most popular category is Governance, which includes topics on various aspects of policy, such as interest group politics, mitigation policy, investment and finance. It had become the most popular subject since 2009, and remains a steady share of 25%–27%. Energy economics has been the second-most-discussed topic category, with a share of 25% of all topics in 2018. Topics categorized as Technologies, with a predominant focus on technology innovation and renewable technologies, have had relatively stable attention since 1994, taking up around 20% of all topics, with a peak in 2003 at 23%. Topics on Climate Research, such as emissions level, forecasting, and modeling, have been trending rapidly from 1994–1998, but have been decreasing and remain relatively steady in recent years. An increasing trend for governance topics and a slight upward trend
for social-behavior topics are observed. Continuous attention on these two topic categories may be of interest for future work.

In addition, by calculating the slope of topic trends, we identify 53 ‘hot’ topics, which consist of 15 topics on governance, 13 topics on technologies, 13 on energy economics, eight topics on social-behavior and four on climate research. Table 2 lists the top ten hot topics with their ID, topic label, associated terms, category, and slope rank. Consistent with our expectations, highly policy-relevant topics—socio-technical transition, interest group politics, and cooperation network—are becoming increasingly popular over time. In particular, 80% of topics on social-behavior (8), 68% of topics on governance (15), 60% of topics on technologies (12), 56% on energy economics (14), and 27% on climate research (4), are considered ‘hot’ topics. Notice that although there are only ten topics on social-behavior, eight are considered hot topics, and three of them, including...
community engagement, actions and behavior, are among the top ten fastest growing topics.

We also identify 39 ‘cold’ topics, consisted of 11 topics each on energy economics and climate research, 8 topics on technologies, 7 on governance, and 2 on social-behavior. The top ten cold topics with the strongest negative trends covered mostly energy economics and climate research, such as topics on emissions and rural areas. Climate research is a particularly ‘cold’ subfield in the ETs literature. A total of 11 out of 15 topics on climate research have negative trend. Topics on bioenergy and transportation are also among the ten coldest topics. Table S2 in SI lists all topics and their relevant information.

4.3. Topic network
The probability distribution of terms within each document could also provide an important overview about connections among topics, known as a topic network.
network. Figure 9 shows the network of the topics with a co-occurrence threshold above 0.1. Each node represents one topic (tagged with topic ID), and the size of the node represents their prevalence. The links connecting the nodes demonstrate topic co-appearance. Topics are considered connected when they jointly appear in the same documents, thicker lines indicate higher probability of joint appearance. As a result, topics that address similar issues and relevant areas are likely to appear as clusters.

Here, we manually cluster these topics into three clusters. Cluster 1, located on the left of the space, links primarily policy topics, including socio-technical transitions, energy poverty, technology innovation, governance, and interest groups. This cluster includes the highest portion of hot topics with a positive trend (22 out of 25 topics) in comparison with other clusters. Also, topics in Cluster 1 have the highest degree centrality score on average, and topic #2, #8, #33 scored the highest in the network. They cover socio-technology transitions in general, research agenda and interest group politics. Cluster 2 on the lower right of the space covers topics related to the implications of energy consumption, including energy security, economic growth, and climate implications. Topic #12 on consumption has the highest degree centrality score in the cluster, connecting topics on growth, consumer behavior, emissions, and rural energy. Finally, topics in Cluster 3 are connected to Cluster 1 only through topic #6 and #16. The implication here is that, discourses on grand level transitions might not have adequately engaged with technological details. Clusters 2 and 3 share more connections with each other through analysis of geographic distribution of literature (Mahbub et al., 2017, Liu and Lei 2018, Moya et al. 2018) and different energy resources (Le et al. 2013, Bilgen et al. 2015, Yeh et al. 2016b, Erickson et al. 2017) are more likely to co-appear in the same paper that concerns costs and social-environmental implications.

4.4. Policy topics and policy content

Based on the policy-relevant literature and policy-relevant topics, in this section, we synthesize the existing knowledge about ET policy. The average policy score of the 92 topics is 5.02. There are 55 topics have a policy score of 5 or higher, and 18 of them scored 8–10 (listed in table 3). Topics on energy security, energy poverty, policymakers, policy targets, and interest group have a policy score of 10.

As indicated by the slope rank, the landscape of policy focus has been changing. It appears attention of the literature have been moving away from conventional policy topics such as energy security and energy poverty, focusing instead on themes such as interest groups politics, cooperation network, policymaking, as well as specific institutional context.

Furthermore, we accompany the topic modelling result with an analysis of geographic distribution of policy literature by region or country (figure 10). As shown in figure 10, the natural focus of the policy literature of ETs are major carbon emitters, i.e. China, Europe, United States, India, which together represented 60% of global carbon emissions in 2018. Articles focusing on Europe, North America, China, and India represent, respectively, 47%, 13%, 10% and 5% of all country or region-specific policy-relevant literature.

In addition, the share of literature on the top three major emitters, especially on Europe, has increased overtime, while the share of research attention

| ID | Topic Label | Topic Terms | Category | Slope Rank |
|----|-------------|-------------|----------|------------|
| 2  | Socio-technical transition | Transit, actor, sociotechn | G         | 1          |
| 6  | Scientific change | Transform, scienc, challenge | T         | 2          |
| 31 | Community engagement | Local, communiti, engag | S         | 3          |
| 32 | Interest group | Polit, group, interest | G         | 4          |
| 36 | Actions | Framework, action, theori | S         | 5          |
| 9  | Behavior | Effect, relationship, behavior | S         | 6          |
| 16 | Energy planning | Approach, process, plan | E         | 7          |
| 7  | Research agenda | Research, work, field | R         | 8          |
| 58 | Cooperation network | Network, associ, type | G         | 9          |
| 61 | CCS | Initi, scale, success | T         | 10         |
Table 3. Topic policy relevance.

| ID | Topic Label                     | Top Terms            | Policy | Share   | Slope Rank |
|----|---------------------------------|----------------------|--------|---------|------------|
| 1  | Energy security                 | Energy, secur, prosum| 10     | 2.55%   | 83         |
| 17 | Policymaker                     | Polici, support, maker| 10     | 1.22%   | 41         |
| 21 | Policy targets                  | Require, achiev, promot| 10     | 1.17%   | 58         |
| 32 | Interest group                  | Polit, group, interest| 10     | 1.09%   | 4          |
| 59 | Energy poverty                  | Issu, address, consequ| 10     | 0.94%   | 74         |
| 20 | Technology innovation           | Technolog, innov, deploy| 9      | 1.17%   | 66         |
| 27 | Institutional context           | Explor, within, context| 9     | 1.12%   | 19         |
| 28 | Investment and finance          | Countri, nation, invest| 9     | 1.11%   | 64         |
| 56 | Governance                      | Govern, facil, privat| 9      | 0.95%   | 38         |
| 13 | Mitigation                      | Chang, climat, mitig| 8      | 1.25%   | 56         |
| 19 | Policymaking                    | Studi, examin, place| 8      | 1.17%   | 13         |
| 24 | Public trust                    | Project, factor, public| 8     | 1.14%   | 30         |
| 46 | Nuclear                         | Nuclear, question, German| 8     | 0.99%   | 17         |
| 52 | EU                              | Effici, European, union| 8     | 0.97%   | 57         |
| 58 | Cooperation network             | Network, associ, type| 8      | 0.94%   | 9          |
| 62 | Regional context                | Level, region, time| 8      | 0.92%   | 87         |
| 67 | Learning                        | Perspect, longterm, learn| 8     | 0.87%   | 21         |
| 88 | India                           | Particip, India, space| 8     | 0.79%   | 35         |

Figure 10. Geographic distribution of policy research foci. Histogram in the upper panel shows the total number of policy relevant publications focusing on each country/region by year, and the lower panel shows the share of each country/region in each period marked by milestone climate meetings (UNFCCC entered into force in 1994, Copenhagen in 2009, and Paris in 2015).
on developing countries (except China) decreased considerably. Recall the previous discussion about topic categories in section 4.2, which shows topics categorized as Governance has an upward trend since 2003 while Energy Economics is declining. The Governance category contains many topics on governance experience of developed countries, while the Energy Economics category address cost, energy poverty and injustice that mostly concerns developing countries. As such, this pattern is consistent with that of the topic model. Comparing to the geographic focus of the entire corpus (figure 4), the policy-relevant literature follows a similar pattern: policy research on Europe grew from 34% in the post-Rio period to 49% in the post-Paris era, while the share of research on developing countries (except China) shrunk by around one-third, and the share of China and North America remain mostly the same.

Although Europe only ranked the third, after China and the United States, in terms of emissions, it was covered in nearly half of the publications. This is partly due to early exploration of clean energy policies and experience accumulated over the past few decades. Energy policies in European countries, such as niche market development and electricity sector deregulation in Denmark (Laak et al 2007, Verbong and Geels 2007), community engagement in Finland (Ruggiero et al 2018), feed-in-tariff of Germany (Nordensvård and Urban 2015, Akizu et al 2018), green technology innovations in Norway (Normann 2017, Nykamp 2017), generate abundant and important lessons for follower states to initiate more effective strategies based on each specific context. In addition, the highly integrated energy, climate and environmental policies among the European countries on the platform of the European Union not only complemented each other for managing individual shortfalls of energy security (Sencar et al 2014, Bouzarovski et al 2015, Strambo et al 2015), renewable integration (Fragkos et al 2017, Pereira et al 2018, Winfield et al 2018) and technology innovation (Kang and Hwang 2016), but also give them strong political incentive to engage in prolong international climate negotiations as a powerful group (Espa and Holzer 2018, Kurze and Lenschow 2018).

Policy literature on North America are mainly from the United States (85%). Although articles on United States or Canada do not stand out as a unique topic, discussion about them disperses across different topics. In particular, topic #94 on natural gas includes many articles on the United States among its high-scoring documents. Thanks to renewable development and the so called ‘Shale Gas Revolution’, natural gas has become more competitive than coal-power plants (Yeh et al 2016a, Muratori et al 2017), accelerating the retirement of coal power plants, which has been the major driver of emissions reductions in the United States (Schivley et al 2018). However, such ET could be delayed and impeded by interest groups (Downie 2018, Stokes and Breetz 2018). Climate change as the core incentive for deep ETs is particularly vulnerable to political shocks (Akin 2018), casting doubt on the progress of transition beyond natural gas. Moreover, as the largest economy and the second largest carbon emitter, US domestic energy and climate politics has serious implications for global climate governance. Political setbacks and short-sightedness of the US could hinder international cooperation, especially in raising climate finance (Upatelainen and Van de Graaf 2018).

Rapid economic growth and urbanization over the last few decades had made China the largest carbon emitter in the world, however, it received only 10% of scholar attention. Energy and climate governance in China is a state centric approach marked by its effectiveness in producing policy output. But the shortage of public participation and fragmented state actors significantly limits the efficiency of its energy and climate policies, delaying China's ETs (Gilley 2012, Liu et al 2017). This paradox is illustrated by the dynamics between coal and renewables in its energy system. While the statist approach successfully facilitated a strong wind and solar industry and made China the front runner in renewable installations and generation (Liu and Shiroyama 2013, Dai and Xue 2015, Chen and Lees 2016), such development is crippled by the lack of systematic integration and across governmental cooperation, causing significant issues in terms of investment efficiency and quality (Xu et al 2017).

India and other fast-growing economies, similar to China in the early 2000s, have a great potential for rapid economic expansion, as well as for carbon emissions. Given limited carbon budget and high climate vulnerability, the success of India’s ET is critical for managing climate change. International climate community and domestic policymakers have to be more innovative in finding the balance between development and decarbonization (Jaeger and Michaelowa 2016, Busby and Shidore 2017, Parikh et al 2018).

5. Discussion

Given that previous ETs have taken several decades (figure 1), whether the next ET will occur faster than those in the past is a crucial question on which scholars of ETs disagree and is of crucial import to policy decisions. Although researchers propose different recommendations for acceleration from diverse perspectives, most of them can be classified into two themes: technological and institutional innovations. While technological innovation could reduce the cost of low-carbon energy, social-institutional innovation could play a role for incentivising technology innovation and guide individual consumers to choose cleaner fuels. This section summarizes the pattern in the ETs literature and describe several knowledge...
gaps. We also provide some insights about the methodology and direction for future studies.

The topic modelling results reveal the diversity and magnitude of the literature on ETs, however, there are some knowledge gaps worth noticing. First, there is a shortage of scholarly attention on developing countries (except for China). Among the 92 topics, only two can be attributed specifically to rapidly growing economies, i.e. China and India. Other countries with significant growth potential (both in terms of economy and carbon emissions), such as Brazil, Russia, and fast-growing economies in the Southeast Asia, including Vietnam and Indonesia, attract considerably less scholarly attention. Providing realistic alternatives for these economies to pursue development without relying on the traditional fossil-fuel development path is crucial to stabilizing the climate. Figures 4 and 10 on the geographic distribution of literature foci confirm this pattern. We find that literature on ETs in general and on policy-relevant studies in particular come primarily from Europe, a share which has increased over time, while the share of developing world (except China) has been decreasing. Articles on those countries still focus primarily on development and energy poverty. This is a worrisome sign. Given the emissions of Europe and United States have been decreasing, scholars should pay more attention to fast growing economies, exploring country specific institutional contexts and finding them a fair development path that is fundamentally different from the fossil-fuel intensive ones.

Second, as discussed in the network analysis section, several topics have high betweenness centrality, which indicate the connections between different clusters are limited. In particular, Cluster 1 and 2 are linked only through four topics (topic #31 & 24 and topic #56 & 17), and Cluster 1 and 3 are connected only through two (topic #6 & 16). In addition, in cluster 3, topics about specific technologies have a strong connection with electricity cost, but rather have no connection with topics about finance and market condition (topics #28 & 63), i.e. these topics are likely to co-occur with cost in the same document, but rarely discuss finance and market conditions. This might indicate the lack of systematic engagement between the technology subfield and research emphasis on market and finance. Such disconnection could potentially lead to isolated technology research, over or underestimating the economic feasibility of ETs. Although cost analysis for individual technologies is a promising theme in the field, aggregated bottom-up system-wide cost modelling is still immature because of various uncertainties and assumptions, as well as difficulty in modelling social-political factors (Trutnevyte 2016).

Third, although energy politics, especially interest group politics, is a major focus, energy studies fall short on ideological challenges and governance capacity, which could affect countries’ political willingness to speed ETs and their ability to do so. For instance, although many treat natural gas as a bridge fuel (Wu et al. 2016, Dodge and Metze 2017), where does the bridge lead, how long would the bridge exist and to what extent it competes and delays the expansion of renewables remain unanswered. As recent political developments around the world have indicated, anti-globalization, nationalist movements, and identity politics play important roles in global climate change governance and ETs. Even if countries are fully committed, low government capacity could cripple their efforts, especially for developing countries. To close the gap between forward-looking institutional analysis and backward-looking techno-economic analysis, an intensive discussion of government capacity is necessary; that is currently a glaring absence in the ETs literature.

Reflecting on the methodology we have used, systematic methods allow us to overcome the selection bias of traditional literature reviews, drawing insights from an extensive literature comprehensively. It offers reliability, transparency and replicability. We collect literature in a transparent manner, and analyze the data using a replicable unsupervised machine learning technique. However, this approach also has several limitations. First, the corpus used in this research consists only of English-language journals. Second, in terms of topic modeling, there are various approaches for model selection and topic validation, yet scholars have no consensus on the methodology. Third, the network clustering analysis is not driven from a formal quantitative cluster analysis, and the result is sensitive to the thresholds chosen. Fourth, we found that treating all papers equally creates considerable difficulty for synthesizing high-quality insights, as some important and influential researches could be buried in the set of several thousand articles and tens of millions of words. Our experience shows that the evidence map is an informative compliment for traditional literature reviews as well as methodology with ample room for further development.

An extension of this work could pursue the following directions. First, research could explore articles on ETs written in other languages. This effort could consider whether, and if so how, non-peer-reviewed content should be included. Second, future studies could adopt other Structural Topic Model, and other machine learning techniques, to study other important aspects of ET and evaluate topics distribution by incorporating covariates, such as authors’ affiliations and demographics. Third, scholars could apply formal computer-based clustering and network analysis method, utilizing the meta-data to investigate the epistemic communities and geographic connectivity associated with topic clusters, and also cooperation networks around each topic. Fourth, for identifying articles that have important contributions than others, a possible approach is to weight those articles using the number of citations.
received, although care would need to be taken to account for the influence of time available for citation, citation propensity by field, and the size of each sub-field.

6. Conclusion

Adopting a net-zero emission goal within an international climate treaty was a substantial political success not to be taken for granted. But to realize a carbon-free future, countries need to implement robust policies to direct and accelerate ETs and to enhance cooperation within and outside the Paris framework. Insights on the process of ETs is this a crucial necessity. Scientific synthesis of existing knowledge about ETs serves more robust domestic policy-making and international energy and climate cooperation. Here we adopt a broad definition of ETs: a paradigm shift of primary energy from carbon intensive sources to low-carbon ones. Drawing evidence from history, ETs have tendency toward decarbonization of per unit energy use although that process has been slow. Given the urgent need for energy decarbonization, the energy system needs to shift toward a cleaner one more quickly than in past transitions. The results of this research characterize the landscape of the extant ETs literature and thus shed light on future transitions.

This article provides the first evidence map of research on ETs using machine learning for identifying and synthesizing latent topics in the existing literature, and thus directly contributes to our understanding of what have been the focus of academia from 1994 to 2018. We build the corpus by collecting all articles on ETs and climate change in SCOPUS and WoS Core Collection in between 1970 and 2018, and then systematically removing irrelevant articles. This corpus in itself is a contribution to the field. Researchers can find this data online, use or update it for further analysis. LDA modeling allows us to avoid drawbacks of traditional literature review, minimizing human judgment and prevent selecting on the dependent variable. The LDA model shows that 92 out of 100 topics have substantive content; energy security, socio-technological transition, and electricity cost are the three most popular topics in the literature. It reveals that literature on ETs covers a wide range of important topics in the field, covering macro-level ET strategy, micro-level management, and consumer behavior. Scholars are increasingly paying more attention to policy-relevant topics such as interest group politics and institutional context, as well as topics on social-behavior. Our network analysis indicates that further exploring the intersection between politics and technologies, such as implications of anti-globalization movements, nationalism, identity politics, and international relations, could deepen our understanding of recent political obstacles and in order to develop way to overcome the challenges facing global ETs. Finally, the analysis of geographic distribution of research foci suggest that fast-growing developing countries deserve more scholarly attention.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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