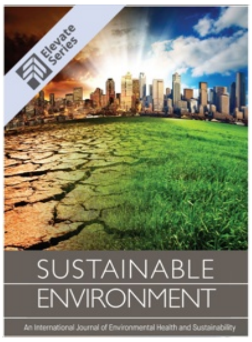

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Leveraging natural language processing to bridge divides in sustainable transitions research

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ABSTRACT

The growing need to address climate change through sustainability governance has amplified the importance of Sustainable Transitions Research (STR). Despite its interdisciplinary scope and methodological variety, STR continues to face divisions between research domains, often exacerbated by its rapid expansion and the methodological tensions between qualitative and quantitative approaches. This study uses natural language processing (NLP) to analyse 448 published articles, initiated from two foundational STR papers, to explore thematic and semantic patterns within the field. The NLP analysis reveals underlying connections and synergies across theoretical, empirical, and conceptual domains in STR, highlighting potential for cross-fertilisation between disparate research areas. The findings map key relationships across the STR community, providing a comprehensive overview of how different domains are interlinked. Recommendations include fostering hybrid approaches and enhancing collaboration between qualitative and quantitative research traditions. By bridging these divides, the STR field can advance in guiding more effective sustainability governance.

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Sustainable transitions research; interdisciplinary research; natural language processing; NLP; automated content analysis; latent Dirichlet allocation

1. Introduction

The Brundtland Report (1987)—which defined sustainability as providing environmental protection whilst maintaining economic growth and equity for present and future generations—instigated a new field of socio-political and socio-economic research wherein researchers have sought to theoretically, analytically, and empirically guide sustainability transitions (Köhler et al., 2019; Markard et al., 2012). Sustainability transitions, moreover, have risen to the top of governance issues in recent years, pressed by the urgency to respond to climate change (Allen et al., 2019; Herman, 2024a). The Sustainability Transition Research (STR)[1] community has contributed extensively to these fields.

On the one hand, STR's research insights have much to offer for policymakers and decision-makers. On the other hand, much remains in siloes (Leach et al., 2007), limiting its full potential to decisively impact sustainability and climate governance (Coen et al., 2020; Hansmeier et al., 2021). Policymakers are, moreover, drawn to research from economics and hard sciences rather than social sciences (Corbera et al., 2016). Indeed, the authors for the IPCC's Summary for Policymakers—which have far-reaching consequences for sustainability governance worldwide—are predominantly economists (Chan et al., 2016; van der Geest & Warner, 2020).

Consequently, notwithstanding major inroads into various research domains, the STR community remains somewhat side-lined with respect to policy influence, due in part to the technocratic nature of sustainability and climate policy guidance (Gupta, 2016). Since some disciplines tend to exert more influence upon sustainability governance and related policies (Corbera et al., 2016), there is a growing urgency to bring qualitative and quantitative disciplines closer together. Indeed, since the STR community has not had much 'interaction with research in environmental economics' (Köhler et al., 2019: 6), it has yet to 'fruitfully mobilize insights from other social science fields to better understand particular processes or dimensions of [sustainability] transitions' (Köhler et al., 2019: 6). Such active engagement and collaboration might otherwise help the STR community to more practically influence policy (Holtz et al., 2015).

Paradoxically, one obstacle which precludes STR from having a greater influence on sustainability governance lies in its rapid growth. Indeed, thousands of articles, books, and conferences have emerged from it in recent years, which might lead to information overload for policymakers with limited time (Coen, 2007). The substantial body of STR literature to some extent exceeds current capacity to find synergistic areas with

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other neighbouring disciplines in its way forward (Geels, 2007; Geels, 2019; Mathis et al., 2022). Even in the most comprehensive review articles (Köhler et al., 2019; Markard et al., 2012; Sovacool, 2014), researchers admit that they are unable to even scratch the surface of the breadth and depth of the research domain.

With such an expansive body of literature, consisting of thousands of case studies, tried and tested theories and much policy guidance and support to offer, the question arises: How might this research domain impart a greater impact on sustainability governance? In relation, drawing on Turnheim et al. (2015), how can STR bridge between quantitative and qualitative disciplines to improve its policy reach? To address these questions, this article demonstrates an important use case for machine-aided text mining and natural language processing (NLP). NLP methods are applied to two seminal articles in STR: Köhler et al. (2019) and Markard et al. (2012). Using latent and semantic techniques, the method then enables digging deeper into the themes, concepts, and theories that form the core of STR. In so doing, hitherto hidden and potential research synergies are uncovered—in particular between innovation systems and technological change, power asymmetries in sustainability transitions, co-evolution and governance—and, more generally, between quantitative and qualitative methodological approaches.

This article is structured as follows. Section 2 provides an essential background to sustainability and climate governance literature. The main themes, concepts, frameworks, and theories are then addressed. Section 3 outlines the published literature corpus and details the methods deployed. Section 4 delivers the results, providing statistics, tables, and figures based on 448 published journal articles. Section 5 discusses the results in connection with related literature, future research trends and needs. The article closes with an outline of how the methods could help to refine the important research stemming from the STR community, strengthening its influence on sustainability governance in the 21st century.

2. Governance of sustainability: Background and concepts

2.1. Scope and background

Policymakers often demand empirical, quantitative-based research and advice (Breuer et al., 2019; Schmidt & Sewerin, 2017). The STR community, indeed, recognises but is yet to sufficiently respond to this need: as Köhler et al. (2019) contend, it is paramount to produce statistics and data on 'rates of change' and 'indicators for measuring transition dynamics'. Yet these are often absent in STR scholarship. The inclusion of such research would effectively help to validate conceptual approaches and extend theoretical developments which, in turn, would lead to practical, and empirically grounded, analyses and policy insights (Garnåsjordet et al., 2012; Herman & Shenk, 2021). Such analyses could, in turn, provide scope to deliver practical guidance for sustainability-driven governance research (Bulkeley, 2016; Gupta, 2016; Geels & Turnheim 2022).

While the STR community might lack quantitative and statistical research output—which are the strengths of the ecological and environmental economics community (Vatn, 2005)—the latter falls short in considering power, political economy, institutions, and other socio-economic subjects that are consequential to sustainability governance, and indeed vital contributions from the STR community (Luukkanen et al., 2012). Furthermore, the quantitative analysis of sustainability policies—and its consequent impacts on technology, innovation, and sociotechnical systems—necessitates greater theoretical underpinning, which is also a fundamental strength of STR (Herman, 2024b).

While each respective research discipline falls on, relatively speaking, opposing sides of the research spectrum—albeit with a handful of related but much lesser-explored themes lying in between—bridging across these multiple disciplines, research domains, empirical approaches, and theories can prove highly consequential (Papachristos, 2018). Ideally, such bridging and cross-domain research fertilisation can improve the efficacy of interdisciplinary research for sustainability governance, spanning multiple salient research domains such as climate policy, green growth, and related socio-technical transitions governance strategies. Machine-aided content analysis is one way to quickly draw out key themes, topics, theories, and methodologies within a literature corpus; it can therefore enhance bridging across disciplines by uncovering potential connections between diverse research domains such as social science, economics, politics, and governance. Below we outline the main themes, concepts, frameworks, and theories in STRN, before returning to a discussion of these methods.

2.2. Overview, themes, and concepts

In the early development of STR, much of the focus was on isolated case studies and discontinuous changes, limiting broader analysis to single transitions (Kanger & Schot, 2019). Even then, scholars advocated for expanding beyond historical case studies to enable more comprehensive comparisons across regions and countries (Berkhout et al., 2004; Loorbach & Rotmans, 2010). Researchers also recognized the need to integrate qualitative and quantitative approaches, highlighting gaps in the field that needed to be addressed (Carlsson et al., 2002; Hekkert et al., 2020; Shove & Walker, 2007).

As the field evolved, the complexity of climate change and environmental degradation—commonly viewed as 'wicked problems'—prompted a shift in focus. These challenges require research to transcend simple causal models and adopt approaches that account for the intricate nature of sustainability transitions (Kreienkamp & Pegram, 2021). Recent studies have responded by exploring complexity governance, which seeks to address the interconnected and multifaceted nature of sustainability issues (Turner & Baker, 2019).

Initially, the STR community's influence on sustainability governance and policy was not immediately apparent (Markard et al., 2015). However, its growing potential to guide transitions has become a key area of focus in recent years. To effectively steer sustainability governance, policymakers and private actors must adopt a dynamic approach—constantly shifting perspectives across different policy levels and timelines (Garud & Gehman, 2012; Geels et al., 2017). This requires a deeper understanding of the underlying structures, regimes, and networks that shape transitions (Geels et al., 2023; Kalt, 2024). While qualitative insights are essential for grasping the complexities, quantitative research remains invaluable for establishing causal links and predictive models (Schmidt & Sewerin, 2017).

2.3. Frameworks and theories

There exist many themes and concepts within the STR community, but four main theoretical frameworks are widely applied (Köhler et al., 2019; Markard et al., 2012; van den Bergh et al., 2011). These frameworks—alternatively defined as constructs or heuristic devices—provide the bulk of investigative research for the sustainable transitions (Sovacool & Hess, 2017) and are as follows:

(1) The Multi-Level Perspective (MLP) (Rip & Kemp, 1998; Geels, 2002; Smith and Stirling, 2010)
(2) Technological Innovation Systems (TIS) (Hekkert et al., 2007; Hekkert & Negro, 2009; Markard et al., 2015)
(3) Strategic Niche Management (SNM) (Rip and Kemp, 1998; Geels and Raven, 2006; Schot and 130 Geels, 2008)
(4) Transition Management (TM) (Loorbach, 2007; Rotmans et al., 2001)

2.3.1. The Multi-Level Perspective (MLP)

The MLP integrates three 'levels' of analysis: (1) niches, where a protective space is developed to cultivate radical innovations (Sengers et al., 2019); (2) socio-technical regimes, which encompass established technologies, institutional structures and incumbent actors that overtime co-evolve into a stable configuration; and (3) socio-technical 'landscapes' which tie in broader elements such as inter-governmental regulations, wide-spread societal norms, and natural environmental conditions—each of which is seen as affecting regime stability, and also providing opportunities for niche technological breakthroughs (R. P. M. Kemp et al., 2001). As such, the MLP can incorporate into its analysis power struggles between regime actors, niche innovators and landscape factors, each of which are critical to sustainable governance analyses (Fuenfschilling & Truffer, 2016; Herman & Sovacool, 2024; Van Sluisveld et al., 2020).

2.3.2. Technological Innovation Systems (TIS)

TIS has strong methodological and empirical ties to approaches in evolutionary economics (Nelson & Winter, 1982; Williams & Edge, 1996). Indeed, TIS builds on key evolutionary economics' themes such as technological innovation, industrial upgrading, and institutional quality (Hansen & Coenen, 2015). While TIS excels in modelling technological innovation and performance, it is critiqued for failing to deliver in policy steering and guidance (Safarzynska et al., 2012; Sovacool, 2014). Whereas earlier TIS research emphasised redirecting 'already existing innovation system configurations, not on understanding generative mechanisms of a specific transition case or a set of cases', more recent TIS research has taken a 'pragmatic' approach to instantiate understand the innerworkings of innovation systems (Hekkert et al., 2020; Schot & Kanger, 2018; Sovacool, Herman, et al., 2024).

2.3.3. Transition Management and Strategic Niche Management (TM and SNM)

TM and SNM are largely aligned with one another, which is the logic for grouping these two frameworks together. These research frameworks can be traced to R. Kemp (1994) and R. Kemp et al. (1998), as well as Geels and Schot (2007). Elzen et al. (2004) and Smith et al. (2005) add to the literature by modelling the emergence of industrial and political regimes germane to TN and SNM—taken up in recent empirical research (Kivimaa, 2014; Kivimaa et al., 2017; Sovacool, Del Rio, et al., 2024). Hence, a concerted focus on actors, power, governance, and politics underlies SNM and TM. One key difference, however, is that TM originated essentially as a transition governance framework and is consequently applied in action-based research, as articulated in a generally accepted definition of TM:

> [It is] a balance between structure and spontaneity, between management and self-organization, between long-term ideals and short-term action and between theory and practice [. . .] a concept of multiple meanings: academic and concrete, new and familiar, top-down and bottom-up [. . .] [it is] a new mode of governance which provides a framework for a generic (scientific) governance approach and an operational policy model to influence long-term societal change [. . .] a new paradigm for research and policy practice.
>
> *(Loorbach, 2007: preface)*

Although newer frameworks are beginning to emerge (Zolfagharian et al., 2019), the four theoretical frameworks remain central to the body of scholarship (Geels et al., 2017). Indeed, this is underscored by the automated content analyses conducted in the Result's section below. These frameworks and themes are, furthermore, revisited in the conclusion section.

Having provided essential background and scope on governance of sustainability and policy, Section 3 elaborates on the automated textual analysis methods which, indeed, can be useful for STR for three main reasons: (1) to uncover instances of bridging across multiple disciplines, which will provide fertile ground for new interdisciplinary research; (2) to discover lesser-known topics and themes that can beneficial for moving STR forward and increasing its impact on transition policy and governance; (3) and to offer a methodological basis for deeper analysis of related textual data, such as climate policy documents, corporate sustainability reports, and other environmental policies.

3. Materials and methods

This section outlines the use of automated content analysis and natural language processing (NLP) methods, offering practical guidance for applying these tools in other research areas.

3.1. Overview: Automated content analysis

Although quantitative methods are often criticized for lacking depth, natural language processing (NLP) efficiently uncovers hidden themes and cross-disciplinary opportunities. NLP quickly processes large datasets, offering a comprehensive view of research domains, making it valuable beyond the STR community. Unlike manual reading and synthesis, which are time-consuming and less replicable (Krippendorff, 2011; Weber, 1990), textual content analysis, prominent since the 1940s (Franzosi & Roberto, 2004), has gained traction with advancements in computing (Duriau et al., 2007; Gaur & Kumar, 2018; Short & Palmer, 2008). NLP reduces high-dimensional textual data to reveal patterns and latent knowledge through keywords, topics, and core research themes (Boyd-Barrett et al., 2002; Mora et al., 2020).

3.2. Machine-aided content analysis methods

Machine-aided content analysis often follows a deductive approach (Drisko & Maschi, 2016), but latent analyses delve deeper by uncovering underlying structures in textual data (Neuendorf, 2017, 2019). This method blends both inductive and deductive approaches, allowing theory and concepts to validate NLP-generated results. Though unfamiliar to some STR scholars, machine-aided techniques are widely applied across disciplines.

For example, Sovacool (2014) analyzed 4444 articles and 90,079 references in social science and energy research, showing that hard sciences dominate over social sciences. Coen et al. (2022) used automated extraction to assess the impact of climate-related discourse on corporate climate performance in the UK. Herman (2023) employed VOSviewer (N. Van Eck & Waltman, 2010) to study green growth literature in developing countries, a technique also applied to analyze the effect of transition research on sustainability policies (Chappin & Ligtvoet, 2014). Additionally, Nesari et al. (2022) performed a scientometric analysis of sustainability research, generating a knowledge map from 1831 articles, while Firoozeh et al. (2020) used automated keyword extraction to enhance their literature review.

Despite the power and replicability of NLP, data curation is essential (Krippendorff, 2011). Researchers must filter out irrelevant results ('noise') and synthesize findings for greater accuracy (Kobayashi et al., 2018). Redundant themes, spurious keywords, and other irrelevant terms must be removed (Duriau et al., 2007; Weber, 1990). A solid understanding of the research domain is critical, as theory guides the coding and refinement of the data (Neuendorf, 2002, 2019).

3.2.1. Procedure: Automated analysis of STR

The first step in automated analysis involves constructing a representative corpus, defined as the collection of documents to be analysed (Weber, 1990). The corpus may consist of various unstructured textual data, such as published literature, policy documents, or corporate reports. This phase is not automated and requires carefully considered research decisions, such as selecting a specific scientific domain (e.g. sustainability governance), policy domain (e.g. private sector climate governance), or a research focus (e.g. corporate sustainability reporting) (Coen et al., 2022; Székely et al., 2017).

For instance, previous studies have utilized automated content analysis to synthesize sustainable energy technology research in key journals (D'Agostino et al., 2011; Sovacool, 2014), analyse newspaper coverage of nuclear power (Gamson & Modigliani, 1989), and examine the intersection of green marketing campaigns with public opinion (Carlson et al., 1996). The automated analysis follows a series of replicable steps, as established by earlier research (Aykol et al., 2013; Weber, 1990), ensuring consistency and rigor in the methodology. These steps are applied systematically to enhance the accuracy and reproducibility of findings across diverse datasets.

Accordingly, the following procedure was undertaken for this article:

(1) *Define the units of the corpus*: this draws on Markard et al. (2012) and Köhler et al. (2019) to build our corpus, obtaining PDFs of each published article in their respective bibliographies. Unpublished articles were removed.
(2) *Define the initial coding scheme*: published articles are labelled by first and second author, followed by publication year. If they happen to have more than two authors, 'et al'. is used.
(3) *Coding the data extraction protocol*: A code was built in Stata® to automatically download, label, and automatically file all articles in the corpus.
(4) *Testing on a random sample to validate the method*: This was conducted using Wordstat by Provalis® and involves testing on a random sample of about 10 percent of the corpus.
(5) *Assessment of accuracy and reliability*: The authors checked the automated output and revised the dictionaries—which automatically remove spurious words—accordingly.
(6) *Check the coding of the sample again to ensure accuracy*: A second check on the entire corpus was conducted, following the previous step.
(7) *Code the output text*: Our results include keywords, phrases, and topics.

The corpus was constructed using two foundational papers: Köhler et al. (2019) and Markard et al. (2012) (see Appendices 6.1 and 6.2). As of October 2024, these papers have garnered 2532 and 4460 citations, respectively, according to Google Scholar. While not encompassing the entirety of STR literature, these seed papers were selected for their representativeness of the field, thus enhancing replicability. All articles cited within these papers were downloaded in PDF format. After an initial coding of the full corpus, the PDFs were processed in Wordstat (Provalis®), where each article was coded as a unique variable to construct the dataset. To validate the approach, a random sample of 50 articles was tested. The automated topic extraction confirmed the validity of the technique, as it successfully identified the key themes discussed in Section 2. Following this validation, a reliability assessment was performed using Cohen's Kappa (Potter & Levine-Donnerstein, 1999; Weber, 1990). Once reliability and robustness were confirmed through the random sample, the analysis proceeded according to the method outlined by Drisko and Maschi (2016), with additional refinements detailed in the appendix.

3.2.2. Latent dirichlet allocation

After selecting a corpus and performing pre-cleaning, more advanced techniques such as Latent Dirichlet Allocation (LDA) can be applied. LDA, a statistical method, tokenises data and uses variational Bayesian analysis to identify patterns within the text (Hoffman et al., 2013). It is widely used in topic modelling to detect underlying themes by dividing the corpus into smaller components. Beyond analysing scientific literature (He et al., 2009), LDA has been applied to a range of fields, including patenting and innovation (Suominen et al., 2017), synthesizing policy documents (Massey et al., 2013), electric vehicle adoption (Debnath et al., 2021), urban climate transitions (Jin et al., 2023), renewable energy policies (Oosthuizen & Inglesi-Lotz, 2022), and environmental regulations and organizations (Dugoua et al., 2022; Gardezi et al., 2022; Qin et al., 2021). LDA's versatility highlights its relevance for identifying patterns across diverse datasets, making it valuable for synthesizing insights across research domains.

3.2.3. Extraction, statistics, topic modelling, and clustering

Reducing the dimensionality of textual data involves applying factor analysis with varimax rotation to generate eigenvalues and scree plots, which are used to cluster keywords, topics, and research papers (Newman, 2006). Documents with the highest centrality scores are deemed most relevant to the overall corpus, with topics further categorized into thematic subjects and research areas. A widely used metric for textual analysis is TF-IDF (Term Frequency-Inverse Document Frequency) (Uto et al., 2017). This statistic quantifies the uniqueness of terms within a document relative to the entire corpus. A higher TF-IDF value indicates that a term is more representative of a specific document but less frequent across multiple documents, thus distinguishing its relevance (Provalis Research, 2021; Qaiser & Ali, 2018).

In addition to TF-IDF, topic modelling serves as a robust NLP technique to reduce large amounts of text into a set of key topics and keywords (Blei & Lafferty, 2007; Crain et al., 2012). This probabilistic, unsupervised machine learning method relies on word co-occurrence patterns within documents or across the corpus. The resulting topics and keywords can be visualized using cluster maps, dendrograms, or networks (Callon et al., 1991; Furukawa et al., 2015). Automated clustering, based on extracted keywords or topics, is then performed using techniques such as Adjusted Phi, Agglomeration Order, and Inclusion Index. For detailed methodological explanations, readers are directed to the WordStat Provalis® manual.[2]

4. Results

The previous section outlined the automated textual analysis methods. This section presents the machine-aided results, structured as follows: raw data, extracted keywords and associated statistics, automated phrase extraction, and topic modelling. The results are then synthesized, followed by a discussion of the limitations and the method's potential contributions to the STR field.

4.1. Raw data output: Keywords

The first set of results comprises the extracted keywords, visualized in Figures 1 and 2, along with statistical analysis provided in Appendix Tables 1 and 2. The top 50 keywords were selected based on their TF-IDF scores. Results are presented first for the Markard et al. (2012) corpus, followed by those for Köhler et al. (2019). Appendix Table 1 includes keyword frequency across the corpus, the percentage of cases (i.e. the proportion of articles in which each keyword appears), TF-IDF scores (representing keyword uniqueness), and keyword prominence (identifying the articles where each keyword is most prevalent).

4.2. Automated phrase extraction

Automated phrase extraction reveals latent and previously unobserved dimensions within the research corpus (Boyd-Barrett et al., 2002). By incorporating multiple keywords simultaneously, phrase extraction extends beyond basic keyword identification, offering a more nuanced understanding of underlying themes and conceptual structures (Boyd-Barrett et al., 2002). While certain anticipated keywords, such as governance, evolutionary, and institutions, may be less prominent in individual keyword analyses, they become more central in the context of phrase extraction. The automated phrase extraction followed specific criteria: phrases were composed of a minimum of 2 and a maximum of 5 words, with a cap of 50 phrases. The window of words within each article was set to a loading threshold of 0.30, and the coherence matrix was evaluated using Pearson's R. The automated phrases are shown in Appendix Tables 3 and 4.

For Markard et al. (2012), Sociotechnical (transitions and systems) emerges as the most prominent keyword, based on TF-IDF. The seminal article in this field is Geels (2004), who develops the initial framework for socio-technical transitions and is indeed cited over 5,000 times as of May 2023. Other seminal articles include Geels and Schot (2007), and Smith et al. (2005), the latter taking up a governance focus. Bos and Brown (2012) also look at sustainable governance in the urban water sector. Edmondson et al. (2019) apply the policy mixes concept to socio-technical systems, showing how feedback and experimentation are crucial, as well as a related article that explores socio-technical transitions for solar electricity in Canada (Rosenbloom et al., 2016).

Theoretical frameworks for sociotechnical change are also explored (Sovacool & Hess, 2017). Fuenfschilling and Truffer (2014) unpack the structures, theories, and foundations of socio-technical regimes, building on institutional theories. Rotmans et al. (2001), as well as R. Kemp and Loorbach (2006), are two seminal articles for the second most prominent keyword, Transition Management (TM). Meadowcroft (2009) is considered a seminal article, drawing on political dimensions that are sometimes ignored in sustainability governance and policy research. Voß (2014) and Voß et al. (2009) deal with integrating TM in practice, providing the basis for action-based sustainability governance. Implementation strategies for TM are a subject taken up as well by Kern and Howlett (2009) in the Dutch case.

The results of the phrase extraction for Köhler et al. (2019) show socio-technical (transitions and systems) again as the most prominent, with TM coming in a - close second, based on TF-IDF. Yet the third phrase, Innovation Systems, is 7th in Markard et al. (2012). Evidently, innovation Systems are taken up more recently by many scholars in the community (Bento & Fontes, 2015; Binz et al., 2014; Reichardt et al., 2016; Tigabu et al., 2015; Wieczorek et al., 2015), but also from the Markard et al. seed paper (Markard & Truffer, 2008;

Figure 1. Automated word mapping (Markard et al., 2012).

Musiolik & Markard, 2011; Negro & Hekkert, 2008). In addition, Long Term [transitions] and Multi-Level [Perspective] emerge with high TF-IDF in both seed papers (Grin et al., 2010; Meadowcroft, 2009).

4.3. *Automated topic extraction and latent analysis*

Automated topic extraction generates phrases by clustering keywords, topics, and themes. This process is entirely automated, identifying topics based on common patterns and themes within the text (Mora et al., 2020). The key advantage of this method is its ability to uncover latent themes within individual documents and across the entire corpus that may otherwise remain undetected (Boyd-Barrett et al., 2002; Mora et al., 2020). The following parameters were used for topic extraction: Factor Analysis, a window of 200 words, with a loading threshold of 0.30, and moderate topic enrichment. Coherence was assessed using Pearson's R. The results, along with associated statistical outputs, are detailed in Appendix Tables 5 and 6. These tables include eigenvalues and variance, providing insights into how each topic diverges based on its associated categories and keywords. Despite the automation, additional refinement is necessary to remove irrelevant or spurious topics, such as 'University Press' and 'Case Study'.

From Markard et al. (2012), Transition Power emerges as the most coherent topic, based on Pearson's R. This includes the following keywords:

Figure 2. Automated word mapping (Köhler et al., 2019).

transition, power, research, sustainable transitions, conceptual, management, social, analytical, analysis, theory. Based on the last three keywords, it is evident that this topic is largely analytical and theoretical. System Innovation and Energy Policy and Power Relations emerge as the next two topics. These are largely based in Transitions Management Literature and begin to demonstrate the policy and political foci of the body of literature currently.

Differently, in Köhler et al. (2019), Innovation System emerges as the most coherent topic, which includes system, innovation, functions, innovation system, technological system. The recognition of power within transitions, as found in Markard et al., has changed to a focus on innovation systems and policies that can steer innovation systems in a sustainable direction. Relatedly, Technological Systems and Sustainable Development are the second and third most coherent topics. Technological Systems also, like Markard et al., relate to TM, but also to Strategic Niche Management. The Sustainable Development topic includes, importantly, actors and society, again showing how socio-political aspects of the STR community continue to be a main research theme.

Similarities between the automated phrase and topic extractions can be observed (Appendix Tables 5 and 6). Power Shifts, however, is a new finding from the topic extraction. This subject was tackled by Avelino (2011), Ahlborg (2017), who explore the power shifts required for low-carbon transformations. More concretely, Avelino (2017) discusses power and disempowerment in sustainability transitions. Meanwhile, Partzsch (2017) invokes the different concepts separating power to and power with environmental politics, and the consequences for sustainability transition's governance.//To a certain extent, due in part to the relationship between governance and politics, sustainability transitions frameworks revolve around power, influence, cooperation, and experimentation.

Stirling (2014) investigates opportunities for transformative power, building on strengths in social science research to drive bottom-up, consumer choices for clean energy. Furthermore, power relations are taken up by Avelino et al. (2016) and Walker (2000), drawing attention to intransigent incumbent actors. Geels (2005) provides the seminal piece on system innovation, developing the co-evolutionary MLP, building on a closely related article (Elzen et al., 2004). Kern (2011) and Van Mierlo et al. (2010) expand these concepts by bringing in learning and experimentation. Recent studies have modelled firm interactions with climate laws (Gilligan & Vandenbergh, 2020) and explored how incumbent industries obstruct sustainability policies (Turnheim & Geels, 2019).

The other automated topics are similar to the results of the phrase extraction (e.g. innovation systems, technological systems). However, for Köhler et al. (2019), Sustainable Development, Policy Makers, and Actors emerge as three important topics. Sustainable development is taken up by Grin et al. (2010), Loorbach (2010), Newig et al. (2007), and Middlemiss (2014)—many of the same leading researchers that emerged from the automated keyword and phrase extraction findings.

4.4. Limitations

Several limitations should be acknowledged. First, the automated content analysis conducted here does not fully capture the breadth of the STR research domain. The analysis is based on only two seed papers, which are insufficiently representative of the rapidly expanding STR field, now consisting of thousands of publications (Sovacool, 2014). Consequently, the scope of this study is constrained by the scale of the literature. Another limitation stems from the TF-IDF algorithm, which treats morphologically similar words as distinct (e.g. 'play' and 'playing', 'mark' and 'marking') (Qaiser & Ali, 2018: 29). Although these terms share semantic similarities, the algorithm does not account for such variations. To mitigate this issue, manual checks were performed to ensure accuracy in the final results. A further constraint of this study is its focus on published articles, due to practical and access limitations. Including submitted or rejected works could have provided valuable insights into editorial decision-making processes. Additionally, analysing research in progress or near-publication manuscripts might have offered a more contemporary view of the field. Future research should aim to address these gaps, potentially involving collaboration with journal editors to explore these under-examined areas.

5. Conclusion and future research

Building on foundational work by Markard et al. (2012) and Köhler et al. (2019), this study identifies and analyses 448 published articles within the field of Sustainable Transitions Research (STR). Employing machine-assisted textual analysis, the investigation uncovered both prominent and latent themes, offering avenues for future research synergies—particularly in bridging qualitative and quantitative methodologies. These analytical techniques could further serve to systematically organize extensive research bodies across other disciplines. Additionally, their application to large corpora of policy documents, which are pivotal for sustainability governance, holds significant potential. Notwithstanding the limitations discussed, the findings underscore the urgent need for more robust interdisciplinary studies in STR, where a lack of consensus between economists and social scientists persists (Mercure et al., 2019). This schism, rooted in conflicting knowledge bases and limited engagement with environmental economics (Köhler et al., 2019), constrains STR's capacity to effectively integrate insights from other social sciences. As sustainability governance gains importance, it becomes crucial for social scientists to develop causal links and predictive frameworks to inform policy (Schmidt & Sewerin, 2017).

5.1. Future research directions

Recent efforts to bridge the qualitative-quantitative divide are becoming more common, addressing overlapping research questions and methods aligned with grand challenges like climate change (Van Assche et al., 2024). The automated analysis conducted here supports this trend, corroborating the emergence of bridging, linking, and hybrid approaches across disciplines (McDowall, 2014; Turnheim et al., 2015). A key contribution of this article is the application of machine-learning content analysis to facilitate these connections, helping identify opportunities for future interdisciplinary synergies, as outlined in the final section here.

The automated textual analysis revealed several research gaps that suggest promising avenues for future exploration. While patterns of sustainability transitions are well covered in the literature (Geels & Schot, 2007; De; Haan & Rotmans, 2011), the underlying governance and industry mechanisms driving these transitions are underexplored (Geels, 2002; Papachristos & Adamides, 2016). The current body of work leans heavily toward theoretical and analytical frameworks (Geels et al., 2017), with a relative lack of quantitative empirical studies.

This empirical gap may stem from the predominant focus on macro-level questions (Geels, 2004), which are inherently difficult to model quantitatively. To address this, STR researchers should build upon established foundations of institutional, political, and power relations (Savaget et al., 2019) and develop these within quantitative frameworks to explore new research frontiers. Additionally, governance, learning, and institutional dynamics—key aspects of STR—can be better integrated with evaluative frameworks for innovation and sustainability programs, particularly in experimental settings like niche experiments and transition arenas (Burnett & Nunes, 2021; Kronsell et al., 2019). Therefore, despite some promising developments and new frameworks (Zolfagharian et al., 2019), the field still calls for more quantitative-qualitative and interdisciplinary studies (Turnheim et al., 2015).

There is also a pressing need for comprehensive methods to model sustainability transitions (Moallemi & De Haan, 2019; Moallemi et al., 2017). Truffer et al. (2022) suggest that while STR has historically contributed valuable theoretical insights, its continued relevance depends on a stronger emphasis on quantitative modelling and mixed-methods approaches. The community must shift from case studies and explanatory analyses toward more integrative and predictive approaches. This challenge, bridging analytical research with practical applications, has been addressed by Papachristos et al. (2024) through their work on merging project management with sustainability transitions, particularly in the context of megaprojects (Davies et al., 2009). Recent calls advocate for a whole-systems approach that transcends the siloed focus on individual aspects of sociotechnical transitions (McMeekin et al., 2019; Papachristos, 2019), indicating a rich area for future research. Finally, Sovacool et al. (2020) identify critical themes for future research, including systemic change, embedded agency, justice, power, identity, public engagement, and governance.

Notes

1. https://transitionsnetwork.org/
2. https://provalisresearch.com/Documents/WordStat9.pdf

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data used in this manuscript are the published articles from the two seed papers. The content analysis used WordStat by Provalis Research®, which is a paid software platform, and therefore the cleaned data cannot be shared.

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