Received: 18 March 2023 | Revised: 12 February 2024 | Accepted: 27 February 2024

DOI: 10.1002/bse.3748

RESEARCH ARTICLE

Business Strategy and the Environment

WILEY

Mapping the signaling environment between sustainability-focused entrepreneurship and investment inputs: A topic modeling approach

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Abstract

The need for climate action has increased attention to sustainability-focused entrepreneurship. In this context, entrepreneurial firms play a fundamental role in developing high-technology solutions for decarbonization but face funding gaps due to the liabilities of newness and smallness. Despite the importance of signaling in entrepreneurship, little is known about what and how to effectively signal to attract investor interest in small ventures that develop sustainable technologies. To address this gap, the present study is anchored in signaling theory and suggests a topic modeling solution to identify signals presented in company self-descriptions and areas of activity, alongside their investment inputs. Using data extracted from Crunchbase, a corpus of 5099 self-descriptions of small sustainable technology ventures over a period of 10 years, this study provides novel insights into the signaling environment of sustainability-focused entrepreneurship. The study's findings have implications for the sustainability ecosystem, namely, start-ups, small- and medium-sized enterprises, investors, and policymakers.

KEYWORDS

latent Dirichlet allocation, signaling theory, sustainability-focused entrepreneurship, sustainable technologies, topic modeling

1 | INTRODUCTION

The growing emphasis on developing climate-focused technologies suggests an evolutionary shift towards cleaner production venturing (Hegeman & Sørheim, 2021; Shahzad et al., 2022). The level of attention given to supporting the commercialization of sustainability technologies has mushroomed, despite the risks associated with funding such endeavors (Mazzucato & Semieniuk, 2018; Stern & Valero, 2021). Despite the urgency of limiting global warming and achieving net zero targets, in 2023, investment into climate technology startups declined by nearly 40%.[1] To this end, the intertwined realities of sustainable energy, high technology, and social impact depend upon the capacity of entrepreneurs to develop actionable responses and address the climate challenge (Embry et al., 2019).

In this context, new ventures assume a seminal role in introducing high-technology solutions to concurrently support decarbonization and climate innovation (Hakovirta et al., 2023). However, a successful

Abbreviations: ECDF, empirical cumulative distribution function; FREX, frequency and exclusivity; IPO, initial public offering; LDA, latent Dirichlet allocation; PCA, principal component analysis; POS, part of speech; STM, structural topic model.

[1]PwC State of Climate Tech 2023: How can the world reverse the fall in climate tech investment? https://www.pwc.com/gx/en/issues/esg/state-of-climate-tech-2023-investment.html.

transition from a new venture to an "impact start-up" able to scale sustainability-oriented technologies (Horne & Fichter, 2022; Olteanu & Fichter, 2022), is linked to the firm's ability to mitigate liabilities of newness and smallness, which suggest a greater risk of failure (Gimenez-Fernandez et al., 2020). Liabilities of this kind indicate limited control over productive resources (Eggers, 2020) and access to funding (Brown & Lee, 2019). Funding is acknowledged as a key barrier to entrepreneurial growth (Cavallo et al., 2019) and has been an issue of prevalent importance for sustainability-focused venturing (Dhayal et al., 2023; Van den Heuvel & Popp, 2023).

In investigating factors that affect funding inputs, information asymmetries have been identified as contaminants in relationships between new ventures and investors (Bergh et al., 2015). Investment decisions in sustainability funding may be related to the information available, especially in early-stage and series funding (Islam et al., 2018; Pollock et al., 2010). Asymmetries may be more pronounced in firms that are in the early phases of developing sustainable technologies (Dou & Gao, 2023; Kong et al., 2022; Siefkes et al., 2023), where value propositions are not yet considered as important to investors or entrepreneurs are developing technologies that are not yet fully understood. In response to asymmetries, stakeholders search for signals—the latent qualities that provide information about attributes and likely outcomes (Connelly et al., 2011; Spence, 1978)—to help firms gain investment attention (Wesley et al., 2022). With particular emphasis on sustainability-focused venturing, the role of signals has been examined in relation to voluntary environmental practices (Abdesselam et al., 2024), corporate social responsibility initiatives (Zerbini, 2017), and notably, initiatives reflecting product–market fit in sustainable industries (Mrkajic et al., 2019). However, this focal emphasis solely on initiatives largely neglects the explanatory value of quality signals that can be depicted from self-reported information and related areas of activity. This is a critical omission, as sustainable technologies are inherently disruptive (Khan & Bohnsack, 2020; Kivimaa et al., 2021; Sehnem et al., 2022), and sustainable innovation assumes a long-term planning perspective (Cillo et al., 2019; Longoni & Cagliano, 2018). More importantly, the role of signals and their investment input implications is scarcely discussed in the literature (Shahid et al., 2023). In addressing these gaps, the present study presents a timely approach for mapping the signaling environment in sustainability-focused entrepreneurship. Utilizing a large sample of 5099 firms over a 10-year period, collected through the Crunchbase platform, topic modeling was employed to unmask latent signals presented in company descriptions and areas of sustainability activities. Following this first step, the impact of task and institutional signals on investment inputs was evaluated. By drawing from signaling theory, the study provides explanatory detail in two interrelated areas of intellectual inquiry. First, we provide information on the nature and complex dynamics of the signaling environment in sustainability-focused entrepreneurship. Sustainable start-ups profess their qualities not only through firm-level practices but also through institutional and task-related signals. Second, by linking the impact of these signals on investment inputs, the study's findings may be useful for research that is interested in understanding the reasoning behind the recent fall in climate technology investments. The rest of the paper is organized as follows: The next section presents the study's theoretical framework, where we discuss the nature of information asymmetries in the context of sustainability-oriented venturing and present an overview of the signaling framework. This allows us to theorize on the task and institutional signals depicted from company self-descriptions in sustainability-focused technology ventures. This is followed by a discussion of the study's methods, where we provide details on the dataset and the analytical steps employed. We then discuss the key findings and the study's implications for sustainable technology firms, investors, and policymakers.

2 | THEORETICAL FRAMEWORK

2.1 | Sustainable technologies and information asymmetries

Sustainability-oriented entrepreneurship envisages the pursuit of opportunities with positive environmental tradeoffs. Sustainable technologies, typically brought to market by start-ups (Aagaard et al., 2021; Colombelli & Quartaro, 2019), hold the promise of disrupting existing industries and, in addition to having implications for socially responsible venturing, may also give rise to payoffs for investors (Kwon et al., 2018; Leendertse et al., 2021). Relatedly, sustainable technologies are characterized by complexity (Wicki & Hansen, 2019) and challenges in consumer adoption (Li et al., 2019). To demonstrate their value to external entities, firms must encompass a venturing context riddled with information asymmetries, complexities, and unforeseeable uncertainty.

In this context, investors are tasked with the perennial challenge of evaluating novel and complex sources of asymmetric information, skepticism about the cleaner production impact of proposed projects (Gladysz & Kluczek, 2017; Mohaghegh & Shirazi, 2017; Yoon et al., 2018), and difficulties identifying where market opportunities for sustainability-focused investments currently reside (Apostolopoulos et al., 2020). The main outcomes of asymmetrical information have been principally depicted in terms of agency costs (Norton, 1996), financial assessment of risk and future profitability (Bergset & Fichter, 2015), firm capital constraints (Mrkajic et al., 2019), and the role of government support in choosing market winners (Pitelis et al., 2019, 2020). As such, it is important to examine the nature of asymmetries in the sustainable technologies debate to understand whether funding input is driven by an underlying dynamic with regard to the firm's signaling environment.

Extant literature discusses the characteristics of information asymmetry by examining the impact of signals under different levels of information access in discursive market conditions (Reuer et al., 2012). Asymmetries of its kind can be traced at the equivocality stage (Daft & Lengel, 1986; Dahlmann & Roehrich, 2019), where information ambiguity is prevalent, leading to conflicting priorities between evaluating project risk and interpreting investment potential. Equivocality describes the "… existence of multiple meanings or

interpretations in a specific context, each of which is individually unambiguous, but collectively, they are either mutually exclusive or in conflict with one another" (Fisher & Neubert, 2023, p. 3). Asymmetries in the sustainability context suggest misalignment of conflicting and unstructured sources of data that make information processing crucial (Harrer & Owen, 2022; Jolink & Niesten, 2021; Owen et al., 2021). By implication, this suggests that funding providers must make resource provision decisions based on limited information related to the viability of such an entrepreneurial endeavor. To better realize equivocality boundaries in this context, signaling theory offers an explanatory lens to determine how organizations convey information about themselves to external parties (Truong et al., 2022) and a foundation to interpret signals that reduce uncertainty associated with making selections among a choice in situations with inconsistently distributed information (Spence, 1978).

2.2 | Signaling actions and sustainability-focused entrepreneurship

Signals can be broadly classified in line with their characteristics, costs, and intentional actions (Bafera & Kleinert, 2023). The effectiveness of signaling actions is contingent upon the industry maturity of the new venture (Hsu, 2007) and signaling strength, respectively (Tumasjan et al., 2021). In identifying the range of signaling actions, past research suggests key distinctions among economic and quality signals (Connelly et al., 2011), with the latter demonstrating a respective focus on productive quality signals. In addition, rhetorical signals suggest a recent and timely addition to the signaling debate, professing the relevance of language-based information that helps investors determine funding decisions (Antons et al., 2019; McLeod et al., 2022), representing a communication signal that is relevant in sustainable technologies (Baskoro et al., 2023).

In explaining selection decisions, economic signals communicate the ability to generate financial returns (Yang et al., 2020), as interpreted by business angels (Shahid et al., 2023), venture capitalists (Plummer et al., 2016), and financial institutions (Eddleston et al., 2016). On the other hand, previous work also examined the potential for funding success in terms of new venture quality signals such as human capital (Baum & Silverman, 2004), intellectual capital (Block et al., 2014; Zhou et al., 2016), and firm size (Wang, 2017). In terms of productive quality signals, research stresses the importance of the firm's environmental certification (Djupdal & Westhead, 2015) and its collaborative capacity. With respect to the latter point, alliances and collaborations represent a productive capacity signal (Hoenig & Henkel, 2015), demonstrating the firm's capitalization of its networking capability. Alliance capital allows sustainable start-ups to gain access to complementary resources (Chung et al., 2000) and represents an observable quality of the firm's technological legitimacy (Baum & Silverman, 2004). Collaborations demonstrate the firm's potential for market acceptance (Block et al., 2014) and enable a sustainability start-up to develop know-how and expertise.

Investors may be more inclined to support start-ups that signal short-term returns rather than long-term technology development (Masini & Menichetti, 2012). For example, patents, alliances, and team experience represent important institutional signals for venture capital funding (Hoenig & Henkel, 2015). Patents and trademarks represent indicators of esteem in terms of innovation activities (Mendonça et al., 2004). Studies suggest that patents act as a source of credibility underpinning the value of innovation (Audretsch et al., 2012; Hsu & Ziedonis, 2013), but with varying impacts in early rounds of capital financing (Hoenen et al., 2014). Trademarks indicate a key point of differentiation among a firm and its competitors (Block et al., 2014), representing the marketing side of an innovation (Flikkema et al., 2019). However, in the sustainability context, such signals may have paradoxical or even diminishing effects on investment inputs when considering the long-term outcome of proposed technologies (Harrer & Owen, 2022), and asymmetries of this kind may drive underfunding in sustainability-focused start-ups (Owen et al., 2021). To this end, research suggests that signal strength variability is important in entrepreneurial settings (Vanacker et al., 2020).

The value of information sought from company self-descriptions and related venturing activities represents a novel approach to better understanding its role as a signaling source and its corresponding functions. Selectively, this method has been embraced to understand global trends in start-ups (Savin et al., 2022), sustainable business practices and their links to national contexts (de Lange, 2017), and the connections between specializations and technological complementarities in cleantech firms (Marra et al., 2015). Textual descriptions provide information related to business and operational characteristics (Te et al., 2023), which in turn reflect observable actions (Passavanti et al., 2024). As such, the signaling context of sustainability-focused firms can be examined in two interrelated areas of activity, namely, the task and institutional environments (Connelly et al., 2011). The task environment refers to activities undertaken by sustainability-focused technology start-ups and small firms, whereas institutional signals depict organizational characteristics that firms utilize as indicators of esteem. The following sections further elaborate on these attributes on the merits of their characteristics, costs, and intentionality (Bafera & Kleinert, 2023), leading to the exploration of their joint value.

2.2.1 | Task signals

Task signals assume the central characteristic of observability (Connelly et al., 2011), which suggests the extent to which the signal is noticed and understood by potential investors (Ahlers et al., 2015). Such indicators reflect innovative actions related to projects, suggesting higher venture quality. In the early stages of development, observability is associated with the proof points that demonstrate the firm's commitment to commercialize technologies with uncertain merits (Islam et al., 2018). In a new firm context where there is no proven track record of successful project development and technological novelty is commonplace, the capacity to convey the "right" signals

irrespective of equivocality limitations may provide explanatory value to stakeholders for making sound investment decisions (Giones & Miralles, 2015). This is consistent with the value of deliberate experimentation as a purposeful interaction for achieving strategic legitimacy (Bojovic et al., 2018).

In the empirical context of this investigation, task signals reflect critical information (Steigenberger & Wilhelm, 2018), representing the firm's fit and business interests in innovative activities related to an emerging sector context (Criscuolo et al., 2012; Sick et al., 2018). In the sustainable technology agenda, the proposed innovations can be identified in areas such as renewable energy, recycling, green transportation, buildings, electric vehicles, chemistry, and lighting (Marra et al., 2017). Commitment to sustainable activities indicates engagement in costly processes that deliver higher value (Qureshi et al., 2021). The literature suggests that internal task signals can be observed on a broad range of product, market, team, and financial characteristics (Bafera & Kleinert, 2023; Kleinert et al., 2022; Petty & Gruber, 2011). Product characteristics relate to protected products or services that the firm currently offers that align with sustainability goals. This is important as, in the broader context of technology ventures, such characteristics complement the value of market or investment signals (Bapna, 2019). Market characteristics reflect market opportunities related to carbon emission reduction or promotion of the circular economy (Blasi et al., 2021). Team characteristics point towards entrepreneurial skills and expertise relevant to the renewable economy, while financial characteristics refer to current and future sources of funding (Islam et al., 2018). To this end, task signals that reflect sustainability actions manifest signal intentionality (Nam et al., 2014; Vanacker & Forbes, 2016) by strategically positioning the firm in emerging sectors, allowing it to transition towards the latter stages of development.

2.2.2 | Institutional signals

In understanding venture quality, institutional-level signals represent a quality indicator due to the costs associated with the development of novel activities (Connelly et al., 2011). These endeavors reflect signal-worthy options, demonstrating the strategic use of indicators that demonstrate the allocation of valuable resources (Islam et al., 2018). This is an important depiction of the institutional signaling logic that characterizes sustainability venturing when considering the nature of their developmental activities, which are preoccupied with technology development and strategic positioning as options that bear long-term signaling value. As such, signaling costs can be observed in institutional activities that demonstrate how start-ups describe their vision, advances, and operational model (Payne et al., 2013; Steigenberger & Wilhelm, 2018). Innovative start-ups must overcome the difficulties of new organizations in terms of formulating routines and are also characterized by unstable links to customers, suppliers, and partners (Gimenez-Fernandez et al., 2020). From a signaling perspective, newness may represent an institutional-level characteristic that is advantageous in terms of business model flexibility (Kapoor & Klueter, 2015) and presents fewer limitations based on lower risk aversion (Audretsch & Keilbach, 2007). In addition to newness, start-ups also must deal with a lack of resources required for business development and difficult access to resources necessary to grow (Lefebvre, 2022).

Research suggests that institutional characteristics may signal the firm's underlying qualities (Courtney et al., 2017), with investors seeking evidence related to the future success of the business through institutional signals that demonstrate service orientation. In examining the unobservable potential for funding success, new venture quality signals that portray a firm's sustainable consideration (Connelly et al., 2011) represent a possible differentiator, with investor preferences for service-driven business models for renewable energy that focus on addressing customer needs rather than technology or price (Loock, 2012). One way to mitigate asymmetries through institutional signals is to channel such information on the firm's qualities and intentions to formulate credible signals (Kleinert et al., 2022), and there is recent work following that line of reasoning. For example, the role of economic and social credibility signals in social impact acceleration selection has been depicted (Yang et al., 2020), along with sustainability signals that increase corporate brand performance and brand equity, respectively (Cowan & Guzman, 2020).

2.2.3 | Task and institutional signal consistency

By signaling, firms portray information on their qualities and intentions to support investment decision-making (Elitzur & Gavious, 2003). To overcome concerns about information equivocality and mitigate asymmetries, firms may also consider the joint effect of multiple signals (Colombo, 2021). This conceptual depiction is of particular importance in sustainability ventures.

Transmission of multiple signals may have a positive, additive effect when signals demonstrate quality in different domains and avoid replication (Colombo et al., 2019). This is an important depiction that is currently not well understood in the context of sustainability technologies. Firms that are operating in markets that are currently evolving and demonstrate volatility and regulatory change may find the existence of multiple signals valuable to indicate venture quality (Bafera & Kleinert, 2023). In addition—and considering the wide skepticism regarding the authenticity of sustainability claims due to greenwashing practices (Falchi et al., 2022)—multiple signals may provide corroborative information that is of particular importance for firms in the early stages of development to overcome investor concerns. Multiple observable signals could also provide firms with marginal benefits regarding investment inputs. Research exploring joint signaling effects is paradigmatically limited, yet suggestive of a complex relationship on how these add value (Pollock et al., 2010). In the context of sustainability-focused entrepreneurship, the interplay between task and institutional signals communicates firm qualities and characteristics and may very well sharpen investors' understanding of where future investment opportunities can be identified. This is an important assertion, as potential investors are presented with information to

evaluate firm potential by overcoming the boundary conditions of multiple signaling that leads to signal conflict (Chan et al., 2020; Huang et al., 2022) and determining venture quality through complementary sources of information (Chen et al., 2018; Courtney et al., 2017). To this end, task signals reflect the innovative and operational characteristics relevant to the firm that position it in emerging areas of sustainable technologies, whereas the institutional signaling environment demonstrates a venture's sustainability consideration and service orientation. The joint effect of both signals suggests an additive effect, as it allows investors to fully realize its potential and commitment to sustainability practices. Considering the rather noisy industry environment and value proposition ambiguity associated with sustainability initiatives, the interplay between different signals may also present an amplification effect where one signal increases attention to others (Bafera & Kleinert, 2023; Steigenberger & Wilhelm, 2018; Vanacker et al., 2020).

2.3 | Investment inputs

Research depicted the links between a firm's signaling environment and resource acquisition (Connelly et al., 2011), and notable work further expanded on this assertion to explore the essential connection between signals and investment inputs (Islam et al., 2018). However, the sustainable finance investment domain is characterized by fragmentation and a lack of consensus with respect to its outcomes (Cunha et al., 2021). The overarching theoretical sentiment suggests that investors' a priori beliefs and attitudes towards technological risk affect the likelihood of investing in such projects (Masini & Menichetti, 2013).

Sustainability-focused funding is characterized by high investment risks (Hegeman & Sørheim, 2021), substantial initial capital requirements, and commercializing with long lead times (Islam et al., 2018). The typical early investment model is consistent with technology development (Bürer & Wüstenhagen, 2009) and can be broadly classified on the basis of identifying investment inputs at seed and series funding. Seed funding is related to early-stage investment (Marcus et al., 2013), usually connected to prototype development, where most of the funding comes through informal sources such as business angels (Barringer & Ireland, 2010). Once a market dynamic is accomplished, venture capital and private equity investment are attracted (Puri & Zarutskie, 2012), leading to series funding that is linked to venture expansion (Marcus et al., 2013) and venture capitalist involvement, respectively.

The opportunity to attract initial funding from venture capitalists contributes to a positive outcome, demonstrating credibility towards commercialization (Islam et al., 2018). However, a cumulative body of previous work examined the effects of signaling at the initial public offering (IPO) and post-IPO stages (Chen et al., 2018; Colombo et al., 2019; Payne et al., 2013; Wang et al., 2019), with a similar pattern observed in sustainability-related research (Harasheh, 2022, 2023; Kang & Lam, 2023). This emphasis on the latter stages of the funding process is restrictive in the case of sustainability-focused ventures, as research is silent in depicting the nature of resource acquisition in the early stages of venture formation (Ko & McKelvie, 2018). This is an unexplored area of inquiry, considering that the strength of signaling in investment outcomes seems to be higher in conditions of uncertainty when asymmetric information between firms and investors is higher (Ko & McKelvie, 2018).

3 | DATA AND METHODS

3.1 | Dataset description

Data were sourced from Crunchbase (Felgueiras et al., 2020). As a database for acquiring and categorizing business information, including investments, funding information, and acquisitions, regarding private and public companies in various areas of economic activity, the platform has been previously used in sustainability-focused entrepreneurship research (Kwon et al., 2018; Marra et al., 2015, 2017, 2020). Crunchbase obtains data in four ways: the Crunchbase community, an in-house data team, artificial intelligence and machine learning, and the Crunchbase venture program (Dalle et al., 2017). Despite its well-documented merits, there are biases and issues of representation that need to be acknowledged. While Crunchbase portrays its global coverage capability, technology ventures from North America and Europe tend to be overrepresented, according to the contributor base (Dalle et al., 2017). In addition, there is considerable variation in terms of how frequently company self-descriptors are updated. To mitigate both issues, the final sample employed the following screening criteria: First, the focal point of this investigation was only on active ventures identified under the sustainability-related industry tags, founded from 2005 to 2022. This encompasses the current entrepreneurial dynamics and allows us to exclude legacy firms. Second, any firm entries with missing information for variables of empirical interest were also excluded. Following these procedures, the final sample was composed of information from 5099 companies founded from 2005 to 2022, encompassing 19 specific industries categorized by Crunchbase.

Table 1 displays the distribution of sustainable technology companies across 19 industries within the sustainability industry group. Most companies are in the renewable energy industry, amounting to 1775 (34.81%), followed by solar (776), and sustainability (759). The least number of companies occurs in the pollution control industry (42), the biomass energy industry (51), and the biofuel industry (54). The dataset contained organizations' names, their full descriptions, specific industries, operational elements (number of employees and year of incorporation), and investment inputs (funding rounds and total funding amount). Table 2 summarizes the distributions of operational elements and text length in our sample. The number of employees was counted as a discrete ordinal variable, with companies having 1–10 employees accounting for the majority of the dataset (44.04% of the total). More mature companies with more than 11 employees (11–50) represent the other significant part of the sample (39.78%), suggesting a skewness towards micro and small

TABLE 1 Distribution of companies across 19 industries within the sustainable technologies group.

Industry	Number of companies	% of total
Renewable energy	1775	34.81
Solar	776	15.22
Sustainability	759	14.89
Cleantech	740	14.51
Energy efficiency	580	11.37
Clean energy	520	10.20
Waste management	400	7.84
Environmental engineering	389	7.63
Greentech	341	6.69
Recycling	335	6.57
Natural resources	269	5.28
Organic	209	4.10
Water purification	199	3.90
Wind energy	106	2.08
Green consumer goods	76	1.49
Green building	71	1.39
Biofuel	54	1.06
Biomass energy	51	1.00
Pollution control	42	0.82

enterprises.[2] The rest of the sample was composed of companies having 51–100 (6.45%), 101–250 (5.35%), 251–500 (2.14%), 501–1000 (1.20%), 1001–5000 (0.63%), 5001–10,000 (0.18%), and more than 10,001 employees (0.24%).

3.2 | Latent Dirichlet allocation and structural topic model

Structural topic modeling was employed to discover the latent signals within companies' descriptions. This approach has considerable computational advantages in extracting latent variables from complex datasets, including several types of algorithms that can expose, discover, and extract the thematic structure from a collection of documents (Vayansky & Kumar, 2020). As a type of bag-of-words model, the topic modeling approach disregards the order of words in a document but considers the frequency of occurrence of each term as a significant factor (Blei et al., 2003). In text analysis, topic modeling is utilized to identify the events of themes, which are usually called "topics." In topic models, "topic" is defined as a distribution over a vocabulary of words representing a theme that could be interpreted semantically (Roberts et al., 2016). It is considered an unsupervised approach as it could infer the topics instead of assuming the content of topics under supervision.

[2]European Union. SME definition. From Internal Market, Industry, Entrepreneurship and SMEs. Retrieved from: https://single-market-economy.ec.europa.eu/smes/sme-definition_en (Last Access Date February 2024).

There are two varieties of topic models: single-membership models and mixed-membership models. Between two types of topic models, mixed membership allows each document to cover multiple topics rather than being restricted to only one topic in single-membership topic models. The most widely applied mixed-membership topic model is latent Dirichlet allocation (LDA) (Blei et al., 2003). By introducing the metadata into LDA, the proposed structural topic models (STMs) emphasize the influence of covariates from the metadata (Roberts et al., 2014). The core assumption behind LDA and STM is that a document could be represented as a mixture of multiple topics, and each topic is a distribution over a collection of words. Compared to LDA, STM allows us to introduce document-level covariates to the prior distributions and influence the document-topic proportions and topic-word distributions. Besides, the inclusion of topic correlation could visualize the internal relationship across topics.

Let us assume a corpus of D company descriptions, with each description d indexed as $d \in (1,...,D)$. Each description contains w observed words indexed as $n \in (1,...,N_d)$, which are from a vocabulary of words, indexed by $v \in \{1,...,V\}$. The number of topics K is indexed by $k \in \{1,...,K\}$, which needs to be specified as an input before the model estimation process. The graphical illustration of STM is displayed in Figure 1, where the model consists of three components. The topic prevalence model controls the proportion of each topic contributing to a document. The topical content model allows metadata to affect the word frequency within each topic. The core language model generates actual words for each document using a combination of variations from the topic prevalence model and the topical content model, respectively.

The text-generative process is as follows:

First, the document-level relation to each topic is drawn from a logistic normal generalized liner model based on covariates X_d.

$$\underset{\theta_d}{\rightarrow} | X_{d\gamma}, \Sigma \sim LogisticNormal\left(\mu = X_{d\gamma}, \Sigma\right)$$

where X_d is a $p \times 1$ vector, γ is a $p \times (K-1)$ matrix coefficient, and Σ represents a $(K-1) \times (K-1)$ covariance matrix.

From the description-specific distribution over words representing each topic (k) using the baseline word frequency (m), the topic-specific derivation $\kappa_k^{(t)}$, as well as the covariate group derivation $\kappa_{y_d}^{(c)}$ and the interaction $\kappa_{y_d,k}^{(i)}$ between them.

$$\beta_{d,k} \propto \exp\left(m + \kappa_k^{(t)} + \kappa_{y_d}^{(c)} + \kappa_{y_d,k}^{(i)}\right)$$

When no topical content covariate is present, β can be simplified as $\beta_{d,k} \propto \exp\left(m + \kappa_k^{(t)}\right)$.

For each word $n \in (1,...,N_d)$ in a company description, based on the description-specific distribution over words, draw the word-specific topic assignment $Z_{d,n}$.

$$Z_{d,n} | \underset{\theta_d}{\rightarrow} \sim Mutinomial\left(\underset{\theta_d}{\rightarrow}\right)$$

Draw an observed word from the topic chosen.

TABLE 2 Summary statistics of the sample.

Variables	Mean	Median	SD	Min	Max
Years of incorporation	9.43	9	4.32	1	18
Funding amount (USD)	43,720,613	2,434,426	298,470,802	1000	15,811,577,400
Funding rounds	2.72	2	2.45	1	34
Length of company description (words)	70.64	58	55.80	3	697
	Median	**% of total**	**Min (%)**		**Max (%)**
Number of employees (band)	11–50	39.78	1–10 (44.04%)		10,000 + 1 (0.24%)

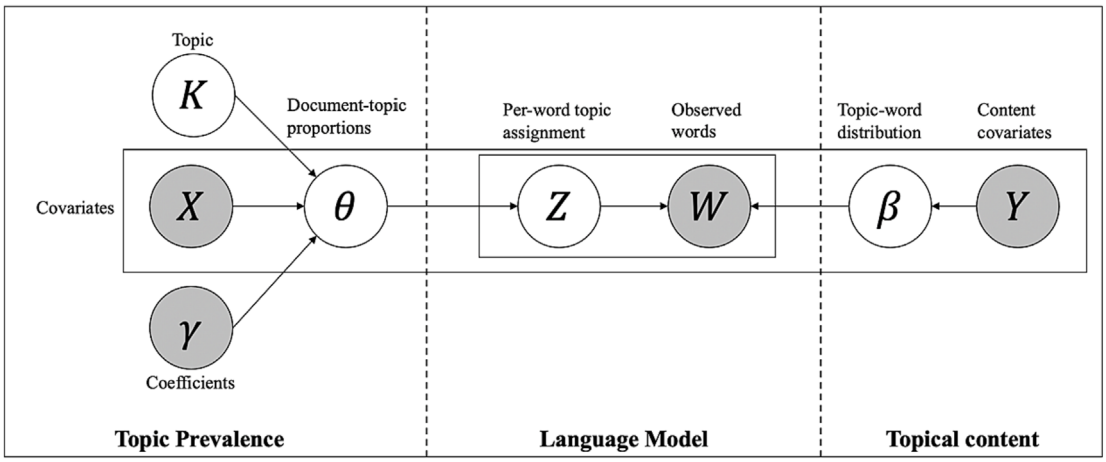

FIGURE 1 A graphical demonstration of STM (adopted by Roberts et al., 2016).

$$w_{d,n} \mid z_{d,n}, \beta_{d,k=z_{d,n}} \sim Mutinomial\left(\beta_{d,k=z_{d,n}}\right)$$

As shown in the process, STM allows covariates to influence topic prevalence and topical content, which is the biggest advantage compared to LDA. Instead of prior distributions sharing a global mean, the distribution that controls the document-topic proportions is a logistic normal distribution, and the mean is parameterized as a linear function of covariates. The inclusion of covariates makes the estimation of quantities of interest more accurate and more useful for inference than LDA (Korfiatis et al., 2019; Roberts et al., 2014). Additionally, the relationships between latent topics and covariates could be estimated to explore the marginal effects of covariates on topic prevalence. In this study, there are several variables that are employed as covariates to influence the topic prevalence, including the year of incorporation, the funding amount, the funding round, and the number of employees.

3.3 | Corpus pre-processing

To prepare the corpus, the following steps are applied to the textual descriptions of companies: (i) tokenization (sentences separated into a list of tokens with word as a unit); (ii) stopword removal according to the SMART list; and (iii) after POS (part of speech) and lemmatization, choosing nouns, adjectives, and adverbs as they state the company's vision and status. By excluding words with low frequency (<1% of the total amount of company descriptions), the total amount decreases to 5088.

3.4 | Estimation of the topic solution

We performed models in R using the "stm" package (Roberts et al., 2019). STM allows us to introduce document-level covariates to influence how latent topics are distributed. In this study, we included the characteristics of companies (*year of incorporation*, *funding amount*, *funding round*, and *number of employees*) to influence how often a topic is discussed, which is the topic prevalence. To find the optimal number of topics (K), we established and performed models with different K numbers from 11 to 20. We adopt two metrics to evaluate their performances: held-out likelihood and exclusivity. As shown in the shaded region, we select K number 17 as the optimal topic number (Figure 2).

In addition, we adopt the FREX score (Roberts et al., 2016) to measure the topic quality using a combination of frequency and exclusivity.

$$FREX_{k,v} = \left(\frac{\omega}{ECDF\left(\frac{\beta_{k,v}}{\sum_{j=1}^{K}\beta_{j,v}}\right)} + \frac{1-\omega}{ECDF\left(\beta_{k,v}\right)} \right)^{-1} \quad (1)$$

where ECDF is the empirical cumulative distribution function, and we set the weight of exclusivity ω to 0.7 (Korfiatis et al., 2019).

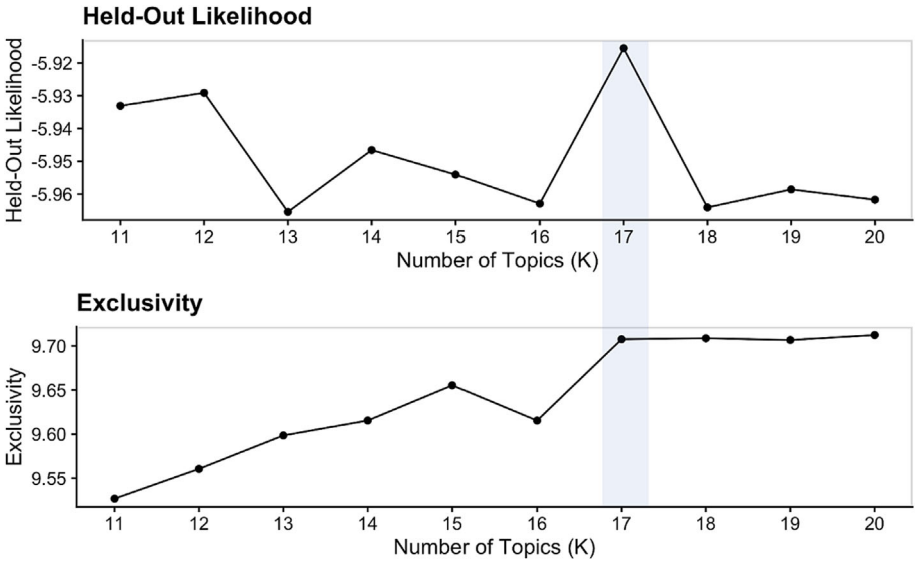

FIGURE 2 Diagnostic values for topic solution with 11–20 topics.

4 | RESULTS

4.1 | Summary of the topic solution

We summarize the outputs from our STM model with the optimal number of topics ($K = 17$) in Table 3. It shows an overview of the 17-topic solution and the corpus-level topic proportions. For each topic, the top 7 loading words are shown by calculating the FREX score. We manually labeled each topic in the second column, as well as their corresponding topic proportions (the mean of each topic's proportion) across the whole corpus.

As shown in the table, topics extracted from company descriptions could be classified into task and institutional signals. The former (85.99%) reflects activities, and based on the top loading words and original text from company descriptions, several topics demonstrate a prevalence of innovative actions related to energy. Topic 12 (fuel technology) emphasizes innovations in fuel and hydrogen technology. Topic 5 (solar energy) mainly illustrates innovations related to solar technologies. Institutional signals (14.01%) reveal the quality indicators employed by companies, including Topics 8, 9, 14, and 16. Topic 14 (sustainable consideration) emphasizes a venture's sustainable consideration and awareness of the carbon-reducing impact of their innovations, whereas Topic 8 (market operations), Topic 9 (client support), and Topic 16 (analytics) demonstrate a firm's prevalence towards service-driven solutions.

4.2 | Marginal effects

As mentioned, document-level covariates could be included in STM to influence the topic solution, which allows us to measure the systematic changes in topic prevalence over the metadata (Roberts et al., 2014). In more detail, we constructed regression models for each topic where the topic proportion is the dependent variable and document-level covariates from the topic prevalence component (Section 3.4) in STM are independent variables. The regression for each topic is as follows:

$$\theta_{k,d} = \beta_1 FundAmount_d + \beta_2 FundRounds_d + \beta_3 CorpYear_d + \beta_4 EmpNum_d + \varepsilon \quad (2)$$

where $k \in (1,\ldots,K)$, and θ represents the proportion of topic from topic solution.

We computed the coefficients in small batches by drawing topic proportions from the variational posterior and getting the average of the results. Then we can capture the changes in topic proportions using a marginal effect framework. Figure 3 represents the marginal effects of the amount of raised funding on the prevalence of signals when each other variable (number of funding rounds, year of corporation, and number of employees) is held at its sample median. The dotted line illustrates the zero effect. The distance of each topic from the dotted line shows how much its proportion across the whole corpus changes as the funding amount shifts from the smallest (1000 USD) to the largest (>15.8 billion USD). The topics on the right-hand side indicate increases in topic prevalence as the funding amount grows, while the topics on the left-hand side demonstrate more popularity within descriptions of companies that raised less funding.

As shown in Figure 3, five topics (on the right-hand side) show increases when we shift from the smallest funding amount to the largest funding amount. Among them, energy efficiency (Topic 11) and battery storage (Topic 4) indicate the most significant increase (approximately 9%), indicating that these two signals are more dominant in the companies' descriptions with a larger amount of funding. Three other signals are also popularly adopted by companies that have raised a larger amount of funding, including fuel technology (Topic 12), analytics (Topic 16), and sustainable consideration (Topic 14). Sustainable consideration is the only institutional signal more likely to be utilized by ventures to describe themselves. In contrast, more topics indicate more popularity within descriptions from firms

TABLE 3 Labels, distribution, and the top 7 loading words in the 17-topic solution.

#	Topic	Prop (%)	Top 7 loading words
1	Waste management	5.34	Waste, end, tech, collection, management, start-up, disposal
2	Water treatment	5.10	Water, air, treatment, wastewater, quality, purification, pollution
3	Sustainable materials	6.43	Material, plastic, economy, sustainable, circular, product, alternative
4	Battery storage	5.46	Battery, storage, cell, manufacturing, generation, high, manufacturer
5	Solar energy	7.89	Solar, electricity, power, grid, developer, photovoltaic, panel
6	Wind power generation	2.80	Wind, turbine, long, term, structure, small, generator
7	Community well-being	4.53	Local, community, city, people, space, food, network
8	Market operations	6.56	Consumer, online, supply, customer, brand, marketplace, chain
9	Client support	5.05	Range, client, wide, expertise, entire, full, team
10	Gas/oil exploration	9.14	Oil, development, exploration, property, gas, project, mining
11	Energy efficiency	7.87	Energy, renewable, efficiency, consumption, lighting, building, utility
12	Fuel technology	8.40	Fuel, heat, research, hydrogen, technology, patent, low
13	Organic farming	5.77	Organic, plant, crop, soil, ingredient, protein, biomass
14	Sustainable consideration	6.82	Climate, impact, sustainability, social, change, carbon, organization
15	Electric vehicle	3.03	Vehicle, electric, car, transportation, infrastructure, charge, electronic
16	Analytics	7.39	Software, analytic, data, control, monitoring, cloud, intelligent
17	Retail solutions	2.41	Part, retail, market, solution, new, company, large

that raised smaller funding amounts. For instance, the topic proportion of organic farming (Topic 13) from companies that obtain a larger amount of funding is approximately 6% lower than that from companies that raise a smaller amount of funding, indicating that organic farming attracts less interest from large capital investments.

In the same way, we also estimated the marginal effects of the number of funding rounds on the prevalence of signals when each other variable was held at its sample median. The topics on the right-hand side indicate their increases in topic prevalence as the funding rounds grow, while the topics on the left-hand side demonstrate more popularity within descriptions from companies that underwent fewer funding rounds (Figure 4).

The biggest change occurs in the proportion of the organic farming topic, which increases by over 3% when we shift from the least funding amount to the most funding rounds, while the proportion of the sustainable consideration topic decreases the most. Organic farming is a popular task signal, and it is more dominant within descriptions from companies that went through more funding rounds. In contrast, the sustainable consideration topic is more popular among companies that have undergone fewer funding rounds. There are some distinct changes for task signals, including waste management and water treatment, which have fewer prevalences as the funding round increase continues, while one institutional signal, online market operations, is more emphasized by companies. Similarly, we also examined the marginal effects of the number of years of incorporation to identify the signaling actions of start-ups. On the right-hand side of the dotted line in Figure 5, there are seven topics that have more proportions in descriptions from newer companies. These are related to signals including waste management, organic farming, electric vehicles, and analytics, which have more popularity among newer companies.

Among them, the biggest change in topic proportion occurs for the waste management topic. It indicates that the attention of start-ups is increasing to these sustainability activities. The other three are institutional signals, including online market operations, client support services, and sustainable consideration. It represents that newer companies are more likely to emphasize their quality through these indicators. By contrast, topics on the left-hand side of the dotted line are more prevalent among mature companies. The topic describing companies active in wind power generation has the biggest decrease in topic proportion, representing its decreasing attractiveness for new start-ups, as this can also be considered a mature technology with an established innovation stack.

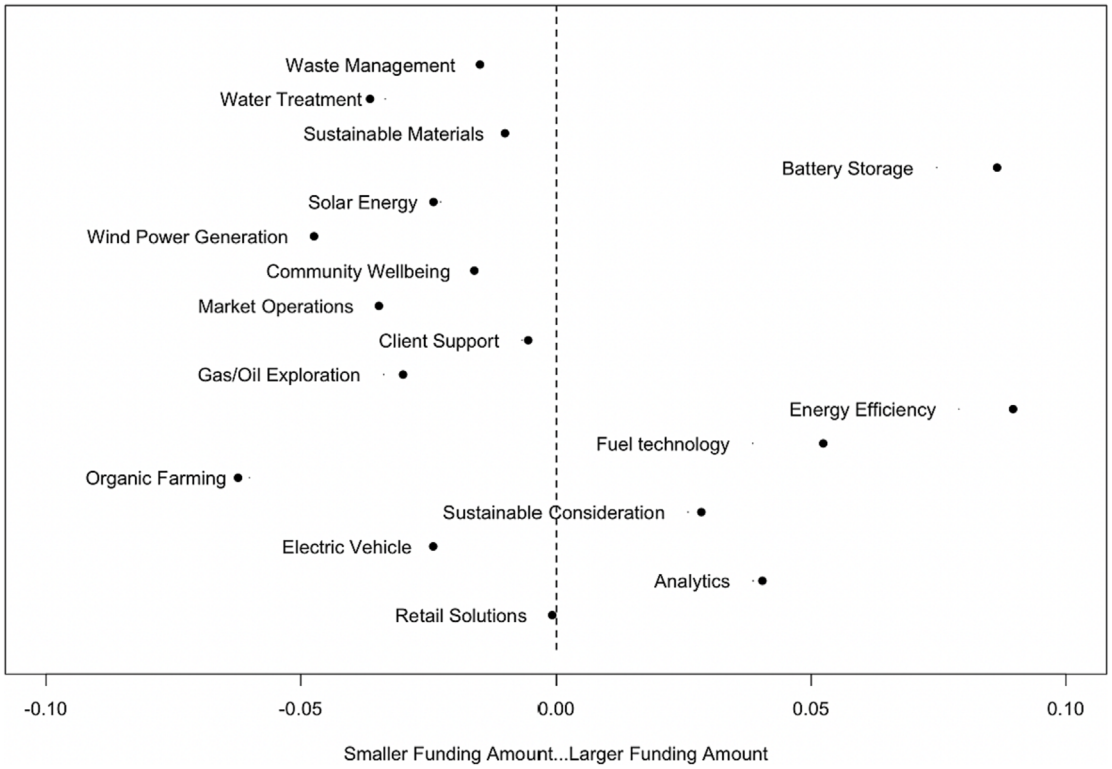

FIGURE 3 The changes in the expected topic proportions from a smaller funding amount to a larger funding amount.

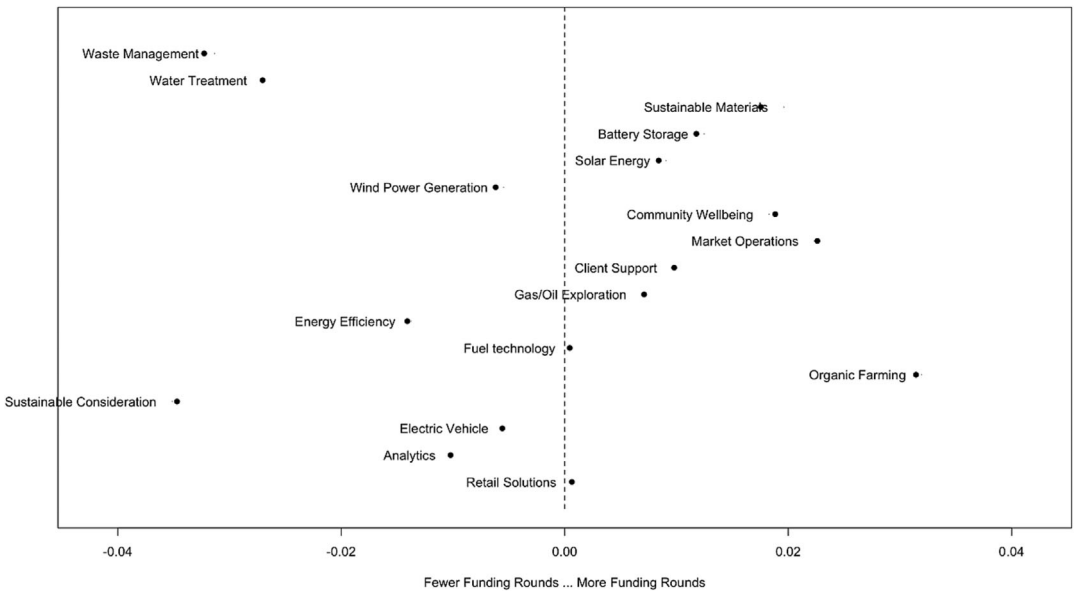

FIGURE 4 The changes in the expected topic proportions from fewer funding rounds to more funding rounds.

4.3 | Mapping the dependence between topics

To display the internal relationships of topics within companies' descriptions, we performed a principal component analysis (PCA) among the prevalence of 17 topics extracted from the STM result. Figure 6 shows how these signals are correlated in companies' descriptions. The arrows show the correlation among 17 topics. In addition, we selected 1872 companies by limiting the funding rounds to >2, which are shown as points distributed around the arrows.

As shown in the figure, several clusters can be observed. For instance, solar energy and energy efficiency are correlated. Energy-efficient technologies, such as LED lighting, are widely applied in homes or buildings paired with solar panels, decreasing reliance on conventional energy sources. In addition, online market operations,

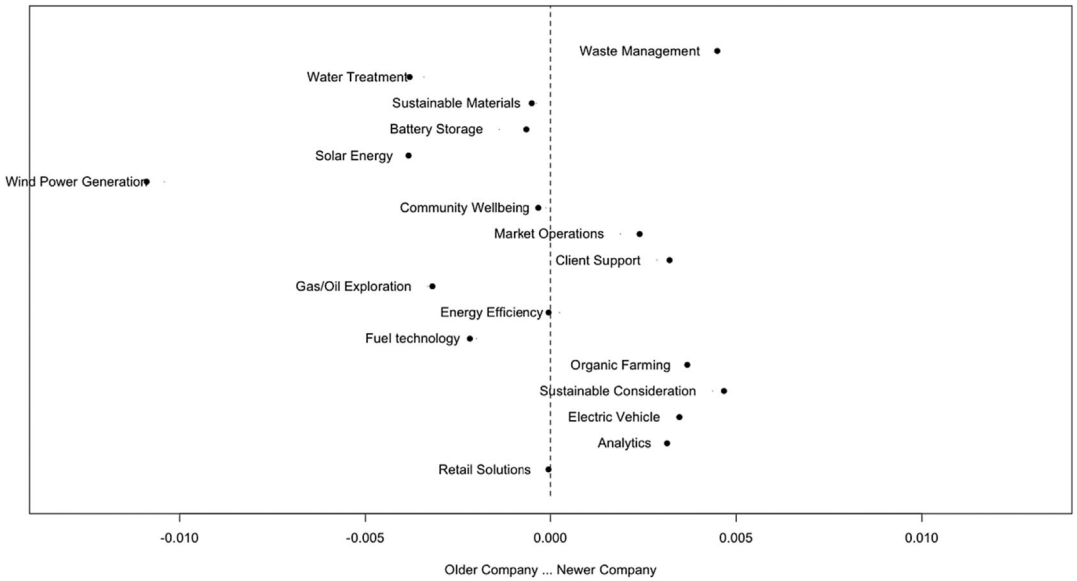

FIGURE 5 The changes in the expected topic proportions from older company to newer company.

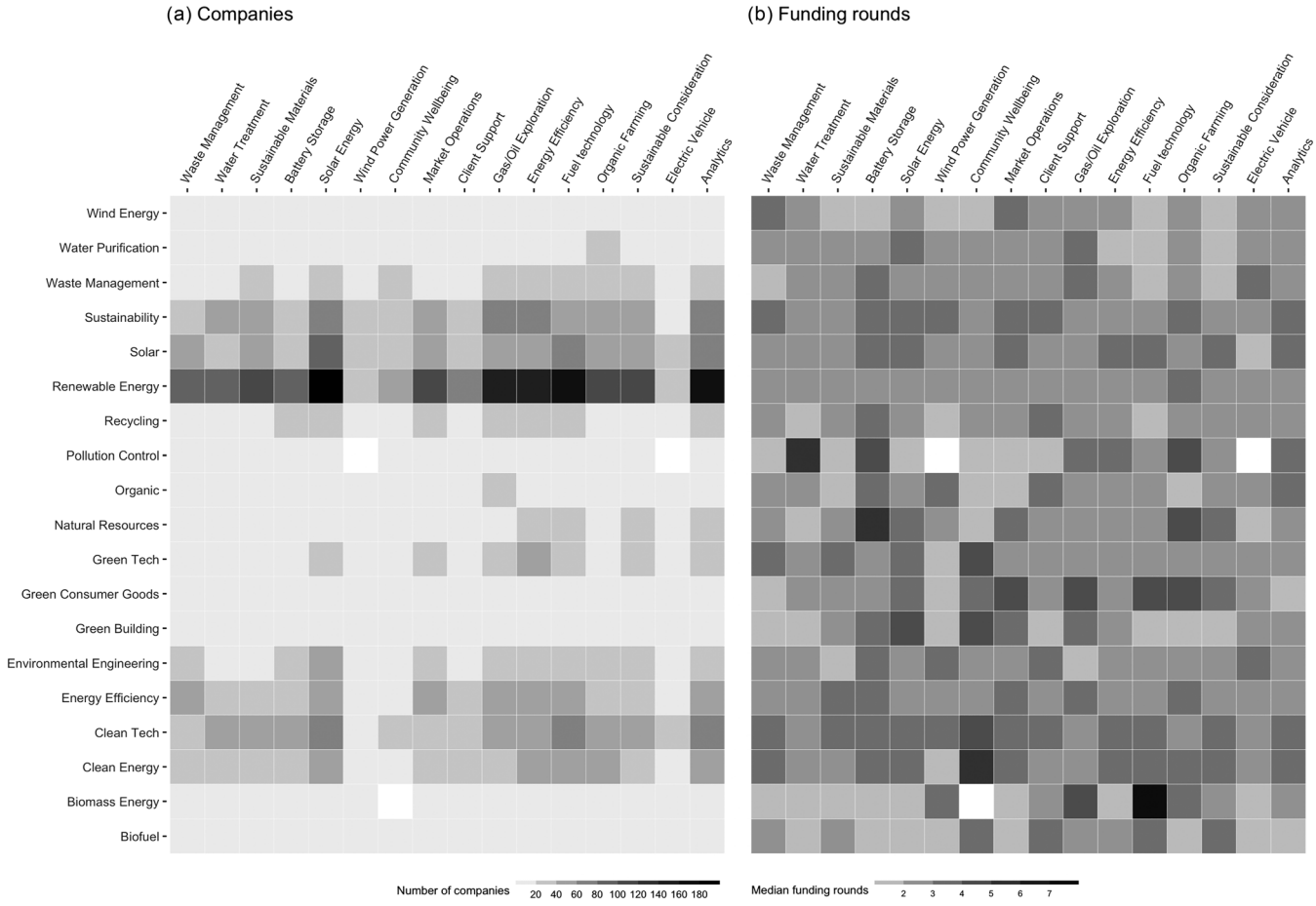

FIGURE 6 Topic correlation maps for (a) companies and (b) funding rounds. Tile contrast represents high correlation.

community well-being, and sustainable consideration also show a close connection, as community well-being and sustainability consideration in online marketing could lead to increased innovation and the development of environmentally friendly products and services. On the other hand, there are several pairs of 90° angles: analytics and battery storage, market operations and water treatment, energy

efficiency and fuel technology, as well as organic farming and fuel technology, which means there is no correlation among each pair of signals. In addition, several clusters of points can also be observed alongside the signals. For instance, several points are close to two institutional signals (sustainable consideration and market operations), which represent that companies are more likely to include the two signals to prove their quality to investors.

5 | DISCUSSION AND IMPLICATIONS

The present paper contributes to our understanding of the signaling environment in sustainability-focused ventures and provides recommendations relevant for theory development and investment decision-making. By demonstrating pertinent signaling activities and their investment input implications, we also provide suggestions useful for firms developing sustainable technologies and policymakers working towards enlarging the footprint of sustainable venturing.

The empirical results of this study indicate that sustainability-focused firms convey information about venture quality using several latent task and institutional signals. The identified topic modeling solution revealed 17 distinct topics, which were categorized as signals of institutional and task relevance. Task signals related to specific sustainable technologies demonstrate the innovative activities and operational priorities of firms in nascent sectors of venturing activity. In our sample, these dominated company descriptions, with prominence in topics such as solar energy and energy efficiency. On the other hand, institutional signals such as online market operations and analytics were also identified, indicating a service alignment towards current market needs. Both sets of signals demonstrate significance as indicators of quality in attracting investment interest. In addition, the study's depiction of a correlation between several types of signals suggests that, in the case of sustainable technology venturing, the transmission of multiple quality signals enhances signaling consistency and is effective in attracting investment inputs.

5.1 | Implications for theory

As an important theoretical framework, signaling theory has been utilized in entrepreneurship research to explain investment behavior (Bafera & Kleinert, 2023). Its main premise indicates that to resolve information asymmetries, firms demonstrate unobservable qualities that can be reflected through task and institutional signals. The literature further developed a robust understanding of various signals and their connections to their investment potential (Colombo, 2021; Mochkabadi & Volkmann, 2020). Despite its centrality for depicting connections between firms and investors, there is little understanding of the signaling environment in the intricate case of sustainability-focused venturing. Based on our findings, there are interesting directions for theory development when considering the context of our work.

The study suggests that the extension of signaling theory in the sustainability context allows scholarly thought to better understand the unique characteristics of sustainable technology ventures. By applying a topic modeling approach to unstructured data, the study demonstrated how to depict the most salient sustainability signals that companies demonstrate in self-descriptions. More specifically, we extracted two types of signals from self-descriptions: task signals and institutional signals, which indicate how companies demonstrate their quality and reduce information asymmetries.

In addition, previous studies suggested that some signals could be equally effective during different funding stages (Colombo, 2021) and have unique value over time (Khoury et al., 2013). To examine this, the study empirically investigated the dynamic of signals alongside investment inputs by taking into consideration the total funding amount. Our findings suggest that heterogeneity exists between investment outcomes and the prevalence of signals, as captured in our identified topics. This suggests that in the case of sustainability-focused entrepreneurship, the impact of signals on investment inputs may be varying, considering the venture's stage of development (Ko & McKelvie, 2018). With particular emphasis on our depiction of task and institutional signals, findings indicate that signal impact is dynamic and consistent with the firm's development stage. Moreover, several studies have illustrated how multiple signals interact (Drover et al., 2018; Huang et al., 2022). Our empirical depiction of a correlation among task and institutional signals suggests that signal consistency is complimentary to investment inputs in sustainability-focused entrepreneurship.

These assertions provide three possible avenues for normative theory development. First, theoretical prescriptions are needed to frame the conditions of applicability of different signals at different stages of development in sustainability ventures. This is important when considering the task and institutional signals that may allow sustainability-focused ventures to alleviate the liabilities of newness and smallness. Moreover, the link between task and institutional signals provides fresh evidence on the importance of signal portfolios (Bafera & Kleinert, 2023; Kleinert, 2024), which in sustainability-focused venturing is not clearly understood. By understanding the role of multiple signals and their dynamics for sustainable ventures, the study suggests an interesting theoretical extension to better understand how investment decisions are shaped in sustainability-focused entrepreneurship (Demirel et al., 2019; Wöhler & Haase, 2022) by strategically leveraging synergies among signals of varying values and their effectiveness in securing investment inputs.

5.2 | Implications for practice

The findings of our study bear considerable relevance to practitioners, notably entrepreneurs interested in launching ventures related to sustainable technologies and investors in the green finance ecosystem. The potential risks emanating from information asymmetries represent a critical assumption, as investors may lack the necessary understanding of the proposed technologies and value propositions

developed by start-ups. In turn, this may lead to inconsistent investment decision-making.

By understanding the fabric of signaling in the investment process, ventures can take important steps towards bridging the asymmetry gap and communicating their offerings to potential investors (Handrito et al., 2021). Our results highlight the increasing importance of institutional signaling. This finding is relevant for firms that are actively engaged in early-stage funding, which may benefit from institutional signaling (Vismara, 2016) by demonstrating a stronger commitment to emphasize market-driven and service-oriented features. In addition to institutional signals, task signals also represent an important differentiator. By demonstrating expertise in key areas such as waste management, water treatment, sustainable materials, battery storage, solar energy, and energy efficiency, firms can realize their investment potential.

The study's findings are equally important for investors and suggest the need to pay close attention to the nature of signaling activities, as manifested in sustainability-focused start-ups. While investment in sustainable technologies is risky (Cumming et al., 2017), our study suggests that institutional and task signals are valuable to identify those ventures that have greater potential for success. Investors would usually pay attention to information including product, team, and elements of macroeconomic significance as factors affecting venture performance (Kaplan et al., 2009; Vazirani & Bhattacharjee, 2021). However, based on our study's empirical evidence, this would provide an incomplete understanding of the growth potential of these firms, considering the long-term development cycle of sustainable technology offerings. Instead of emphasizing observable signals conveyed by entrepreneurs (Piva & Rossi-Lamastra, 2018), the study suggests that latent signals conveyed in self-descriptions of ventures associated with sustainable technologies hold valuable explanatory potential. For example, the use of signals demonstrating online market operations, client support services, sustainable consideration, and retail innovation solutions provides quality indicators that may be considered favorably by investors, as these are less vertical to the sustainability domain yet centered around it (Schönwälder & Weber, 2023).

5.3 | Implications for policy

Policymakers can inform their agenda based on our study's findings, consistent with an industry view that suggests a shifting pattern of investment towards sustainable technologies with more emission reduction potential.[3] In more detail, the depiction of task and institutional signals specific to sustainable technology ventures enables a targeted implementation of sectoral policies to prioritize the design of funding schemes in their domains of interest. By the same token, these findings also suggest targeted support for ventures that profess these characteristics.

[3]PwC Net Zero Economy Index 2023: Bending the curve: Can climate ambition and reality still converge? https://www.pwc.co.uk/services/sustainability-climate-change/insights/net-zero-economy-index.html.

In terms of policy design and implementation, the study's findings suggest an adaptation of the use of funds to support firms that portray certain funding characteristics. As such, the introduction of a framework that can be utilized in policy to evaluate a venture's task signals would enable funding to be allocated on the basis of the value and operational advantages of these ventures, mitigating investment risks. Criteria related to task signals may relate to the strategic positioning of a firm in emerging sectors, which in turn indicates a policy shift from current sectors of interest towards support for ventures that are positioned at the forefront of emerging policy priority areas.

The study's empirical findings are equally important for sustainable technology venture support in general. With particular emphasis on the institutional signals depicted in our work, funding should be redirected towards new ventures that emphasize service-driven signals as a means to overcome the liabilities of smallness and newness. This is important, as it reflects the attractiveness of such signals for investors and suggests the need for tailored policy support against a blanket approach to all sustainable new ventures. In addition to funding, regulatory conduits that aim to lower entry barriers alongside support programs that facilitate network access and provide mentorship and partnerships with incumbents would provide equally reliable indicators to investors.

5.4 | Limitations and future research recommendations

While the study's innovative depiction of signals with the use of company self-descriptions portrays a fruitful avenue for future research in sustainability-focused entrepreneurship, as with all studies, the study's findings need to be considered within the context of its limitations.

Our sample of ventures was drawn from Crunchbase, which may not be representative of all sustainability-focused technology ventures. Future research could address this limitation by constructing samples from multiple sources. In addition, according to the study's principal focus, only company self-descriptions have been utilized. Future research could expand this line of reasoning by incorporating other sources of signal quality information from unstructured data, such as investor communications, news articles, and social media sentiment (Tumasjan et al., 2021). This is beneficial for extracting additional signals of unique value and complexity, such as rhetorical signals.

Finally, data analysis is restricted to the textual data available and does not take into consideration other influencing factors, such as performance metrics. Future research could build further and expand our findings by incorporating market and financial performance metrics to better understand their interrelationships with task and institutional signals. This is important to reinforce the study's assertion that new ventures can overcome the liabilities of newness and smallness and effectively signal to attract investor interest in a rather noisy and opaque signaling environment.

ACKNOWLEDGMENTS

The authors would like to thank the participants at seminars at Athens University of Economics and Business, the University of Warwick, and Copenhagen Business School.

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How to cite this article: Yang, N., Dousios, D., Korfiatis, N., & Chalvatzis, K. (2024). Mapping the signaling environment between sustainability-focused entrepreneurship and investment inputs: A topic modeling approach. *Business Strategy and the Environment*, 1–18. https://doi.org/10.1002/bse.3748