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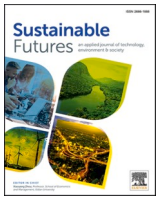

Selective coupling or genuine integration? Startups in the twin transformation

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ABSTRACT

Startups actively shape innovation during the twin transformation to sustainability and digitalization. Our analysis of >21,000 ventures reveals that genuine twin-transformers, i.e., startups able to integrate digital and green technologies, are rare and primarily driven by software. While sustainable ventures readily adopt digital tools, digital ventures rarely embrace sustainability. This asymmetry reflects different configurations of complementarities between digital and sustainable technologies, which investor preferences reinforce. Eventually, this may lead to superficial coupling rather than deep integration. To address the issue, we offer targeted recommendations for practitioners, policymakers, and researchers aiming to foster scalable, hardware-based solutions critical for sustainability.

1. Introduction

The notion of twin transformation describes parallel, potentially mutually reinforcing transformations aimed at fostering a more sustainable and digital future [1]. Within the European Union, it has also emerged as a policy strategy to achieve the targets set under the European Green Deal [2], and it is on the agenda of many firms today [3]. For many, digital transformation is inextricably linked to innovation and entrepreneurship [4,5]. Research also indicates that entrepreneurship plays a crucial role in driving sustainable transformation [6,7].

What remains unclear is the role of startups within the twin transformation and how they could integrate digital and sustainable aspects into their business models. Prior research suggests that digital technologies can facilitate sustainable business practices and drive the creation of new ventures [8]. However, digital technologies often attract more attention than sustainable technologies [3], and leveraging the synergies between digital and sustainable technologies is a complex process [9–11]. This short communication aims to shed light on the role of startups in advancing the twin transformation, how they integrate digital and sustainable technologies into their business models, and how their emergence and development could be best supported.

2. Empirical insights on twin-transforming startups

To aid our understanding of twin-transforming startups, we accessed the Crunchbase database to download data on 21,398 startups founded between November 1, 2021, and May 21, 2025. The firms were classified as belonging to Crunchbase's sustainability or a digital transformation-related industry group (i.e., software, information technology, internet services, and data and analytics). No firm in our sample was older than 3.5 years at the time of data collection, which is a standard-defining criterion for startups. Crunchbase is a premium database that covers all aspects of entrepreneurial ecosystems [12] and has been used as a data source in numerous entrepreneurship studies (e.g., [13,14]), including industry-specific studies relying on Crunchbase's industry categorization [15,16]. Examining that dataset generated three key insights.

The startups in the sample were, on average, 2.09 years old, and 33.8 % of them had received some form of funding and completed at least one funding round. The majority (97.34 %) had adopted a digital business model, whereas 4.62 % operate in sustainability-oriented industries, already indicating a slight overlap between the categories. We classify those startups pursuing both sustainable and digital innovation as twin-transformers. This procedure results in 95.38 % being classifiable as digital-only startups, 2.66 % as sustainable-only startups, and 1.95 % as twin-transformers. This process already yields the first insight: while only 2.01 % of digital startups are twin-transformers, a dramatically larger proportion of all sustainable startups (42.3 %) are twin-transformers. In other words, sustainability and digitization largely complement each other from a sustainability perspective, whereas

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digitization, as a starting point, is not necessarily associated with sustainability.

In the next step, we computed a biterm topic model (BTM) [17]. A BTM was appropriate because the method was developed explicitly for analyzing comparatively short texts. We inserted the full description of the twin-transformer (n = 418) startups in Crunchbase using the R package _BTM [18]. We selected the final BTM by minimizing the log-likelihood and stopping the procedure once a single topic dropped below our defined relevance cut-off of 10 % (1,000 Gibbs iterations, α = 12.5, β = 0.01, log-likelihood $\approx$ −3.6 M, 4633 unique words in the vocabulary). This procedure elicited four different topics (Table 1), which we labelled:

- ESG & Carbon Accounting Software (Topic 1)
- AI-Optimized Renewable Grids (Topic 2)
- Climate Impact Platforms (Topic 3)
- Circular Lifestyle Apps (Topic 4)

A glance at the top 15 words per topic reveals the second insight: Twin-transforming startups are overwhelmingly software- and/or platform-based, rather than hardware-driven. Much activity centers on monitoring, dashboards, and efficiency tools rather than on core material innovation.

In a final step, we performed a multinomial logistic regression analysis comparing sustainable-only startups to twin-transforming startups relative to the digital-only category. We controlled for the five most common countries in the dataset. We collapsed all other countries into a single *other* category to ensure model stability and avoid issues related to sparse data and perfect separation. Table 2 shows the results of the regression analysis. While differences between the coefficients for the number of funding rounds should be interpreted cautiously, they point to our third and final insight: twin-transforming startups may achieve comparable visibility or success with fewer funding rounds than sustainability-only ventures. In comparison, both require more funding rounds than digital-only startups. This finding suggests that digital scalability offers twin-transformers a speed advantage in obtaining funding.

3. Selective coupling or genuine integration?

The data insights described above raise the question of whether twin-transforming startups selectively couple digitalization and sustainability rather than genuinely integrate the goals of both transformations. The asymmetry in the sheer number of digital-only, twin-transforming, and sustainable-only startups in the Crunchbase database already indicates greater investor interest in digital business models. Moreover, it suggests that investors are more accepting of digital business models that do not prioritize sustainability goals than of non-digital sustainable business models. The fact that digital-only startups require fewer rounds of funding to raise similar total funding amounts compared to twin-transforming and sustainable-only startups further supports those observations.

Taken together, these patterns raise the question of how digital and sustainability technologies interact within startups, and whether their combination reflects superficial add-ons or more profound technological interdependence. This distinction can be clarified through a complementarities perspective. To differentiate how startups combine digital and sustainability technologies, we draw on Markard and Hoffmann's [19] framework of complementarities. Their work builds on a socio-technical transitions perspective [20], which emphasizes that transitions are multi-dimensional changes that depend on the alignment of interdependent components such as technologies, infrastructures, skills, and institutional arrangements. In the context of sociotechnical transitions, complementarities describe the dependencies between components whose effectiveness increases when they co-evolve and align [19]. Because the idea of a twin transformation similarly assumes mutual

Table 1
Biterm topic model. θ indicates topic distribution relative to the corpus.

Topic	ESG & Carbon Accounting Software (θ: 0.293)	AI-Optimized Renewable Grids (θ: 0.315)	Climate Impact Platforms (θ: 0.29)	Circular Lifestyle Apps (θ: 0.102)
Tokens (probability)	data (0.0211), carbon (0.0167), platform (0.0139), ai (0.0119), energy (0.0105), management (0.0073), companies (0.0068), sustainability (0.0064), technology (0.0058), esg (0.0054), environmental (0.0053), solution (0.0051), compliance (0.0051), time (0.0050), risk (0.0050)	energy (0.0379), ai (0.0140), solutions (0.0139), technology (0.0091), solar (0.0087), sustainable (0.0084), systems (0.0075), data (0.0074), technologies (0.0066), power (0.0064), efficiency (0.0060), infrastructure (0.0059), renewable (0.0058), grid (0.0052), advanced (0.0052)	sustainable (0.0155), sustainability (0.0131), platform (0.0110), products (0.0098), carbon (0.0094), businesses (0.0080), impact (0.0070), mission (0.0070), future (0.0069), climate (0.0068), environmental (0.0064), solutions (0.0064), technology (0.0062), global (0.0059), waste (0.0054)	waste (0.0075), platform (0.0060), time (0.0060), food (0.0054), solar (0.0053), users (0.0050), company (0.0049), app (0.0047), sustainability (0.0043), ev (0.0043), experience (0.0041), customers (0.0040), service (0.0040), pre (0.0039), offers (0.0038)

Token vocabulary: 4.633 Loglikelihood: −3597,026. Trained with 1,000 Gibbs iterations, α = 12.5, β = 0.01.

Table 2
Multinomial logistic regression model. Sustainable only startups and twin-transforming startups vs. digital-only startups (base category).

	Sustainable only startups Coef. (z)	Twin-transforming startups Coef. (z)
Intercept	−4.2 (−5.59)***	−4.364 (−5.81)***
Age	.063 (0.95)	.037 (0.56)
Number of funding rounds	.273 (4.98)***	.186 (2.87)**
Number of founders	−0.103 (−1.48)	.156 (2.84)**
Total funding in USD (logged)	−0.011 (−0.95)	.001 (0.1)
Startup is still active	.077 (0.11)	.087 (0.12)
Number of investors	−0.002 (−0.10)	−0.043 (−1.59)
Country: Canada	.380 (1.06)	.528 (1.69)
Country: Germany	1.115 (4.05)***	1.086 (4.26)***
Country: India	.291 (1.36)	−1.102 (−3.13)**
Country: United Kingdom	.783 (3.79)***	.676 (3.41)***
Country: Other	.484 (3.32)***	.366 (2.66)**
Model Fit		
Loglikelihood	−2725.276	
AIC	5498.552	
McFadden R^2	0.417	

n = 21,398. ***p ≤ .00.

reinforcement between digitalization and sustainability across socio-technical systems, the complementarity framework provides an analytically fitting foundation for our inquiry.

Adapting this framework to the firm level, twin-transforming startups can be understood as technology bundles that rely on specific configurations of complementarities to deliver value. Consequently, we conceptualize selective coupling as a configuration of weak and often unidirectional complementarities. Sustainability-oriented startups add digital functionalities—such as dashboards, analytics layers, or monitoring tools—that rely on mature digital infrastructures but do not reshape their underlying technology. These digital complements are also attractive because they align with investor preferences for scalable, low-capex software models. As a result, selective coupling is comparatively easy to achieve and frequently used to enhance perceived scalability.

In contrast, genuine integration reflects strong and typically bidirectional complementarities, in which digital and sustainability technologies are co-developed and mutually dependent. Such configurations require hardware–software integration, the development of new organizational capabilities, and access to patient capital, making them structurally more demanding. The differing maturity and availability of complementary components in digital versus sustainability domains help explain both the prevalence of selective coupling and the uneven distribution of twin-transforming startups across industries.

4. Implications for the twin transformation narrative

Eventually, the developments described above may lead to sustainable startups strategically integrating digital components into their business models, thereby increasing their attractiveness to investors and, consequently, their chances of securing funding. However, this would mean conflating digital add-ons that support sustainable business models with true twin transformation. Similar to our findings, Tabares et al. [[1], p. 13] note that "digital transformation serves as the means, while green transformation represents the goal that contributes to planetary goals and policy agendas." This asymmetry is also evident within organizations, where digital technologies are often employed to indirectly promote pro-environmental behavior rather than drive sustainability directly [21]; an observation that the topic models described above also reflect. Thus, these observations and developments necessitate a reevaluation of the twin transformation. In the following, we summarize the implications of our findings for practitioners, policymakers, and researchers to support a realignment of the twin transformation's original goals.

4.1. Implications for practitioners

Twin-transforming startups must move toward genuine integration, rather than selective coupling, to secure speed advantages when raising capital. Of course, there will be a demand for monitoring tools, climate dashboards, and software solutions to support the intelligent digitalization of existing infrastructure, such as energy grids. However, the success of the twin transformation ultimately depends on scalable physical innovation that is digital by default, shifting away from over-favoring low-capex, rapid-scale business models toward hardware technology that is often the so-called *first-of-a-kind* solution, which can entail greater risk. For example, German cleantech startup C1 combines AI-powered quantum modeling with autonomous process control to produce low-CO_2 green methanol, a drop-in fuel for shipping and a sustainable feedstock for the chemicals industry. The approach showcases the integration of digital and sustainability in a single solution [22].

Similarly, investors need to re-adjust their investment strategies toward startups that are genuinely integrating digital and sustainable technologies. This requires sharpening the focus on hardware and providing the patient capital needed to develop such hardware. Ultimately, it is hardware that is so crucial to decarbonizing our still largely fossil-fueled economies. Something that Danijel Višević, co-founder and general partner at World Fund, one of Europe's most prominent climate tech venture capital (VC) firms, also notes: "This is one thing we are doing wrong in Europe—not concentrating on hardware for climate" [23]. Word Fund's investment strategies differ from those of other VCs and account for the difficulties described above that sustainable startups face in raising funding: "We only invest in decarbonization technologies, and we reserve more than two-thirds of our capital for follow-on investments because in Europe it's hard to bridge the later-stage gap" [23].

4.2. Implications for policymakers

Policymakers can support startups' contributions to the twin transformation. However, the European Union's twin transformation strategy has not yet considered entrepreneurship [2]. Hence, we make concrete suggestions based on the six dimensions of the framework used by the OECD to measure the determinants of entrepreneurial action on a national level in its Entrepreneurship Indicators Program [24]:

- Regulatory framework: Establish regulatory sandboxes for twin-tech that enable startups to develop pilots combining digital and hardware climate solutions under streamlined data protection rules and other regulations, providing an opportunity to co-develop suitable new regulations by involving startups.
- Market conditions: Leverage the purchasing power of public procurement by making it easier for public actors to buy from startups and to collaborate with them to develop new twin-tech solutions.
- Access to finance: Intensify investments in venture capital funds that provide patient capital for climate deep tech, such as the European Investment Fund's investment in the World Fund's climate tech fund.
- Knowledge creation and diffusion: Include a clear commitment to deep tech and the genuine integration of digitalization and sustainability in the respective strategies, as well as the underlying funding schemes and research grants.
- Entrepreneurial capabilities: Move beyond simple green accelerator and incubator programs, and instead include clear selection criteria for deep-tech and true twin-transformers.
- Culture: Introduce a high-profile annual award for twin-transforming pioneers who can serve as role models for the genuine integration of digitalization and sustainability, rather than merely selective coupling.

4.3. Implications for researchers

The complementarity perspective used in this study opens promising avenues for future research. Markard and Hoffmann [19] emphasize that complementarities are not static but evolve over time, and that bottlenecks—such as missing capabilities, regulatory misalignment, or the absence of supporting infrastructures—can prevent strong complementarities from emerging. The pronounced time lag between the maturity of digital and sustainability technologies suggests that many twin-transforming ventures may currently be constrained by such bottlenecks, particularly on the sustainability side. Future research could therefore investigate how complementarities develop, strengthen, or dissolve as startups progress from early-stage experimentation to scaling. Longitudinal studies would be especially valuable for identifying when and how weak, unidirectional complementarities transition into stronger, bidirectional ones, or why they fail to do so.

In addition, the complementarity framework encourages scholars to examine how investors, accelerators, and regulatory environments shape the trajectories of these complementarities. Because investor preferences for software-based scalability often reinforce selective coupling, future work could explore under what conditions complementary infrastructures, patient capital, and hardware-oriented support mechanisms enable genuine integration. Finally, applying the complementarity lens not only to startups but to the twin transformation in general can help investigate under which conditions the underlying premise of mutual reinforcement between digital and sustainable transitions holds [1].

5. Conclusion

Our analysis of 21,398 ventures listed on Crunchbase reveals that genuine twin-transforming startups, which combine green and digital technologies, remain rare and are predominantly focused on introducing new digital applications to the market. While firms marketing sustainability-based products readily adopt digital tools, those with a digital product seldom pursue environmental objectives. Investor preferences strengthen the uneven yet complementary ties between digital and sustainable technologies: Digital models reach maturity after fewer funding rounds, whereas hardware-intensive climate solutions struggle to clear capital hurdles. This selective coupling risks diluting the twin transformation into incremental data dashboards rather than material decarbonization. To unlock its full potential, funding architectures must reward patient, late-stage hardware development, and accelerators must recalibrate their selection criteria to focus on deep-tech climate impact. Future research should therefore further analyze the complementarities of the twin transformation, map financing pathways for pioneering green technologies, and track whether policy interventions align with the genuine integration of the twin transformation's goals. The achievement of that shift will determine whether the twin transformation delivers its promised societal and planetary dividends.

CRediT authorship contribution statement

Andreas Kuckertz: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Sebastian Hinderer:** Writing – original draft, Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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