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RESEARCH ARTICLE

Balancing act or two roads to travel: Evaluating the trade-offs between digitalization and net zero innovation in SMEs

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Abstract As firms face the dual challenges of digitalization and net zero innovation to combat climate change, understanding how these twin transitions relate is crucial. This study examines potential synergies or trade-offs between digital technologies and net zero innovations in UK SMEs. By integrating the Resource-Based View (RBV) and the Attention-Based View (ABV), we explore how categories of digital adopters relate to categories of net zero innovation adopters. Utilizing novel survey data for 964 UK SMEs, we employ ordered Probit estimation to examine the relationship between digital and net zero adoption. Our results reveal that digitally advanced SMEs are more likely to be advanced adopters of net zero innovations, suggesting that digital complementarities and enhanced capabilities can reinforce environmental innovations that reduce carbon emissions. We offer valuable contributions for both theory and practice, highlighting the importance of supporting SMEs in their twin transitions.

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Plain English Summary Based on a survey of 964 UK SMEs, we show that digitally advanced firms are more likely to adopt net zero innovations. Understanding the link between digital technologies and net zero innovations is crucial for combating climate change. Our study integrates the Resource-Based View and the Attention-Based View, demonstrating that digitally advanced SMEs are more likely to be advanced adopters of net zero innovations. Our results offer crucial implications to SMEs, indicating that despite SMEs' constraints, digitalization allows them to introduce innovations that reduce carbon emissions. Thus, supporting SMEs in their twin transition is vital.

Keywords Digitalization · Net zero innovation · SMEs

JEL Classifications O32 · Q01 · L26

1 Introduction

In Robert Frost's poem 'The Road Not Taken', the traveller faces the choice of which road to take, being unable to travel both. Today, with the unfolding of two major structural transformational processes – *digitalization* enabled by new digital technologies (DT) and *net zero innovation* (NZI) aimed at limiting global warming to 1.5˚C by reducing net carbon emissions to zero by 2050 (Fankhauser et al., 2022) – businesses face a similar choice. Unlike the traveller in Frost's poem, businesses are expected to take both roads, as stipulated by the twin transitions policy agenda, especially post-covid (BEIS, 2020; European Commission, 2020, 2022; Muench et al., 2022).

Understanding these ongoing structural transformations is crucial as they are likely to shape the future economy (Geels et al., 2021; Muench et al., 2022) and may be a pathway to sustainable recovery (Bai et al., 2020; Hanelt et al., 2017; Kunapatarawong & Martínez-Ros, 2016). Digitalization and net zero innovation are expected to have substantial implications for productivity (Geels et al., 2021; Kalantzis & Niczyporuk, 2022; Pilat & Criscuolo, 2018), albeit with potential time-lags (Brynjolfsson et al., 2018).

Digitalization is defined as a socio-technical phenomenon[1] driven by new *digital technologie*s (DTs), sometimes described as Social, Mobile, Analytics, and Cloud technologies, which facilitate the collection and processing of information, communication and collaboration, interconnectedness, mobility and virtualization. Coupled with developing digital infrastructure, DTs have a profound influence on society, business, and the economy (Calderon-Monge & Ribeiro-Soriano, 2024; Kraus et al., 2022; Teubner & Stockhinger, 2020). The study of the adoption and implementation of these technologies by businesses continues the long tradition of information technology (IT)[2] research in Information Systems (IS) (Jeyaraj et al., 2006), and it has also received increasing attention from management, entrepreneurship and innovation scholars. Management and entrepreneurship research has been focusing on DT's role in redefining boundaries and shaping firms' innovation activity and outcomes (Hassan et al., 2024; Nafizah et al., 2024; Nambisan et al., 2019). However, not all innovations are equal regarding their impact on the natural environment, with some being detrimental.

Net zero innovation is introducing, generating or adopting products or processes new to the firm or the market, which reduce carbon emissions. In this sense, net zero innovations represent a subset of eco-innovations, which are conducive to reducing adverse environmental risks and impacts more broadly (Kemp & Pearson, 2007). The main specificity of eco-innovations relates to their contribution to environmental sustainability, whether intentional or not (Cecere et al., 2014; Horbach et al., 2013; Rennings, 2000).

However, little is known about how digitalization and net zero innovation relate to each other and if firms can leverage DT to innovate for environmental sustainability (Cattani et al., 2023; Elliott & Webster, 2017; Melville, 2010). George et al. (2021) point out that despite growing interest in both business and government, the intersection of sustainability and DT lacks comprehensive and rigorous academic investigation. Until recently, studies have mainly been focused on large firms, typically more significant polluters and front-runners of DT adoption. For instance, growing research focuses on the effects of digitalization on the eco-innovation of publicly listed firms in China (He et al., 2024) and on the green patents of European firms (Montresor & Quatraro, 2020). Empirical, quantitative micro-evidence in the context of small and medium enterprises (SMEs) is scarce, with a few recent exceptions in the context of innovation (Ardito, 2023; Arranz et al., 2023; Avelar, 2024; Jibril et al., 2024) and eco-innovation (Montresor & Vezzani, 2023). Additionally, our study focuses on net zero innovations, a subset of eco-innovations aimed at reducing carbon emissions, which are crucial for addressing climate change.

Understanding the relationship between digitalization and net zero innovation in SMEs is important in both substantive and conceptual terms. In substantive terms, SMEs (with less than 250 employees) typically account for around half of all employment and output in an economy, and in the UK – our empirical focus

[1] Digitalization is not a purely technical phenomenon describing the conversion of information from analog to digital format (Teubner & Stockhinger, 2020).

[2] Teubner and Stockhinger (2020) explicate the progressive replacement of 'Information Technologies' (IT) and Information Systems (IS) terminology commonly used in pre-digitalization era by 'digital technologies', 'digitalization' and 'digital transformation' even in IS literature, with the first signs of this change taking place around 2008.

– around half of all business emissions (BBB, 2021). This large group of firms are, therefore, critical in any economy-wide moves towards net zero. In conceptual terms, SMEs are of particular interest in the twin transition because they typically face resource constraints, implying that trade-offs between digital and net zero innovation may be more significant than in larger firms (OECD, 2021). These trade-offs may relate to either resources – skills, finance – or limited managerial attention, where a focus on one type of innovation limits the attention available for other topics.

Here we ask: Do SMEs balance digitalization with net zero innovation, or are these two distinct paths? To address this question, we build on the Diffusion of Innovation (DoI) theory and examine whether more advanced digital technology adopters are more or less likely to be advanced adopters of net zero innovations. To guide our theory building, we consider two opposing arguments. First, using insights from the Resource-based View of the firm (RBV), we hypothesize that *digital* (technology) *affordances* enable SMEs to engage with net zero innovations (NZI). We argue that DTs hold an action potential (Majchrzak & Markus, 2012), giving rise to complementarities and augmenting SMEs' managerial capabilities for net zero innovation. Second, considering insights from the Attention Based View (ABV), we formulate an alternative hypothesis suggesting that SMEs face management-attention trade-offs between DT and NZI. We argue that SMEs are highly constrained in their managerial attention and resources (Borsatto & Bazani, 2023; Soluk, 2022), implying that SMEs would concentrate their limited resources and attention on either DT or NZI.

Our analysis utilizes novel data on 964 firms from a dedicated survey, providing representative coverage of UK SMEs. The novelty of our dataset lies in its comprehensive coverage of a wide range of DTs and NZI. Previous studies often focus on the adoption of a single digital technology, such as Customer Relationship Management (CRM) systems (e.g. Cruz-Jesus et al., 2019), or a specific aspect of eco-innovation, such as green patents (Fabrizi et al., 2018). However, achieving net zero requires technological innovations and organizational practice changes (García-Quevedo et al., 2020). We argue that, to provide an overarching view of both digitalization and net zero innovation—and their interrelationship—data across a spectrum of technologies and practices is essential. Our survey instrument is unique because it captures information on a broad array of NZI and DTs relevant to businesses across various sectors and sizes. We employ ordered Probit estimation to test whether membership of specific categories of digital adopters (e.g., early adopters, innovators) is positively or negatively related to comparable net zero adopter categories. Estimation results support the first hypothesis, indicating that the probability of belonging to more advanced net zero categories increases with higher adoption of digital technologies.

We make three main contributions to the existing literature. First, we provide empirical evidence for complementarities in the context of UK SMEs, showing that digitally more advanced firms are also more likely to be advanced net zero adopters. While recent literature has explored the role of digitalization in SMEs (Arranz et al., 2023; Avelar, 2024), there is limited knowledge about its relationship with net zero innovations aimed at reducing carbon emissions. Most existing research focuses on eco-innovation and the general reduction of environmental impact (Montresor & Vezzani, 2023). Second, by integrating insights from the RBV (Barney, 1991) and the ABV (Ocasio, 1997), we unravel the conceptual mechanisms through which the adoption of DT complements rather than creates trade-offs with NZI. Finally, we make a methodological contribution to research on the Diffusion of Innovation by introducing a new approach for conceptualizing and operationalizing innovativeness. Instead of focusing on the time of adoption, we base our approach on the number of multiple interrelated innovations adopted.

2 Theory and hypotheses

2.1 Simultaneous diffusion of multiple interrelated innovations and innovativeness

Diffusion is defined as 'the process by which an innovation is communicated through certain channels over time among the members of a social system' (Rogers, 2003, p.21). Rogers' (1962, 2003) Diffusion of Innovation theory has received widespread recognition, bringing together different strands of diffusion-adoption research that have been prolific over the last half-century (Van Oorschot et al., 2018). Scholars have applied

DoI to explore inter-firm and intra-firm diffusion of a wide variety of technological innovations, including digital and eco-innovations (Battisti & Stoneman, 2003; Johnson, 2015; Kapoor et al., 2014; Völlink et al., 2002; Zhu et al., 2006).

To model the diffusion processes of net zero and digital, we employ the notion of *adopter categories* that Rogers proposed in his 1958 article and developed in the first and subsequent editions of DoI (Rogers, 1958, 1962, 2003). Adopter categories represent a taxonomy of actors, individuals, or organizations, within a system based on their innovativeness. Innovativeness is a core behavioral indicator in Rogers' (1962, 2003) conceptualization of the diffusion process and refers to the relative speed of adoption of new ideas by actors within a system. It captures a shift in behavior, not just a change in thoughts or beliefs (Rogers, 2003) and conceptualizes innovativeness based on the time of adoption.

Here, we extend Rogers' (2003) framework to the situation where multiple interrelated innovations (e.g., different types of NZI) diffuse simultaneously. This simultaneous diffusion process is illustrated by Fig. 1. For the three S-shape curves, the diffusion speed is different with 'Innovation 1' diffusing faster among the population of firms than 'Innovation 2' and 'Innovation 3'. At a certain point in time A, all three innovations are adopted by earlier adopters, while later adopters—'late majority' or 'laggards'—have not adopted either of the three innovations. Later, at time point B, these later adopters' categories would have adopted only one technology, i.e., Innovation 1. Finally, after some time, all three innovations will be adopted by all categories of adopters, including laggards (point C).

For related innovations in the same domain (e.g., NZI), adopter categories may also be derived from innovativeness measured by the number of innovations adopted rather than by time. For instance, consider a certain fixed number of innovations (or technologies) and assume they are relevant to all firms (i.e., general-purpose technologies, although the applications may differ). Then, for each firm at a certain moment, higher innovativeness is associated with a higher number of innovations that have been adopted. Figure 2 illustrates our conceptualization of adopter categories derived from innovativeness measured by the number of innovations diffusing simultaneously. Because innovativeness decreases with the time needed to adopt and, on the contrary, increases with the number of individual innovations adopted at a certain point in time, the image in Fig. 2 appears flipped compared to the well-know bell shape in Rogers' (1958, 1962, 2003) conceptualization (Fig. 9 in Appendix) with innovators situated on the right of the diffusion curve.

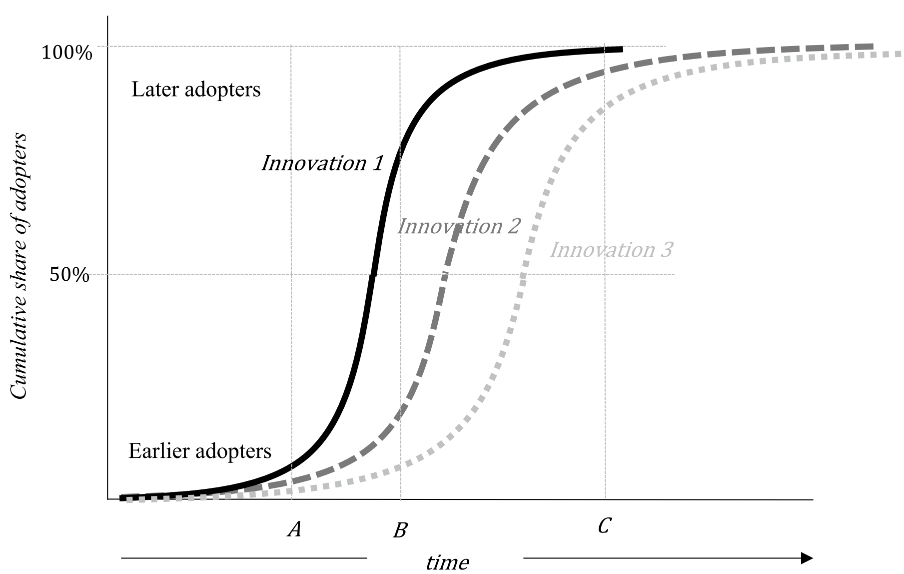


Fig. 1 The simultaneous diffusion of multiple interrelated innovations Source: Rogers (2003) and authors' elaboration

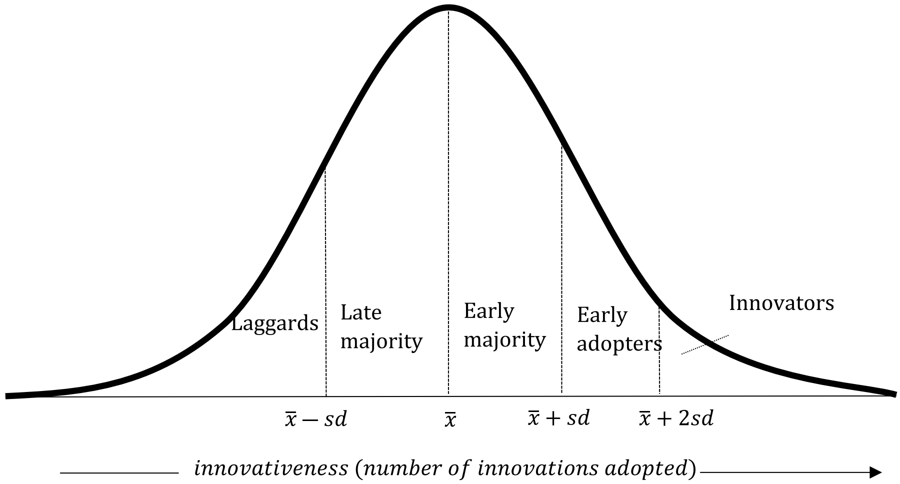


Fig. 2 Adopter categories based on innovativeness measured by number of adopted innovations Source: authors' elaboration

2.2 Diffusion of innovations in different domains: digital and net zero

So far, we have been thinking about innovations belonging to the same domain. This reflection can be extended to the case of innovations belonging to different technological domains such as digital and net zero. Previous studies have raised the question of the generality or specificity of innovativeness by differentiating between global innovativeness from domain-specific innovativeness (Flores & Jansson, 2022; Goldsmith et al., 1995; Midgley & Dowling, 1978). Domain-specific innovativeness[3] refers to the creation or adoption of new technologies or innovations that pertain to a specific field.

Here, we propose that digitalization is underpinned by *innovativeness in the digital domain,* which is reflected in *digital adopter categories*. At the same time, net zero innovation arises with an increase in *net zero innovativeness* reflected in *net zero adopter categories*. It explores the relationship between these two distinct *diffusion processes in two different domains*. Van Oorshot et al. (2018) highlight that diffusion-adoption research, despite its maturity, would benefit from bringing in other theoretical perspectives from management, organizational behavior and marketing studies. In the next sections, we use insights from the RBV and ABV literatures to suggest the mechanisms that could underpin the relationship, synergetic or, on the contrary, characterized by trade-offs, between the two domain-specific diffusion processes (Fig. 3).

2.3 Synergies between digital technologies and net zero innovations

The Resource-Based View theory is useful for understanding potential synergies between digital technologies and net zero innovations. The RBV focuses on the role of a firm's internal resources and capabilities in stimulating competitiveness (Barney, 1991). Building on RBV, our conjecture is that digitalization enables net zero innovations through two mechanisms: (i) complementarities between the two diffusion processes and (ii) digitally augmented managerial capabilities. Digital technologies reinforce firms' managerial capabilities enabling new or improved functionalities for net zero innovation.

[3] Goldsmith et al. (1995) stressed that domain-specific innovativeness is a better predictor of consumers' purchase behavior compared to global innovativeness and highlighted the hierarchical structure of innovativeness constructs where domain-specific innovativeness plays a mediating role in the relationship between global innovativeness and concrete behavior. Following this line of research, a number of studies focused on this intermediate level of innovativeness (domain-specific) to analyze innovation adoption behavior of consumers. Flores and Jansson (2022) in a study of the adoption of green transport innovations by individuals (shared e-bike and e-scooters) have demonstrated that domain-specific innovativeness (in the field of transport) is associated with the adoption of green transport innovations and reinforces the positive emotions associated with the use of these innovations. Paparoidamis and Tran (2019) have used the concept of domain-specific innovativeness in the domain of eco-innovative products and have found that it affects innovation adoption intentions indirectly via enhanced consumers' perceptions of product eco-friendliness.

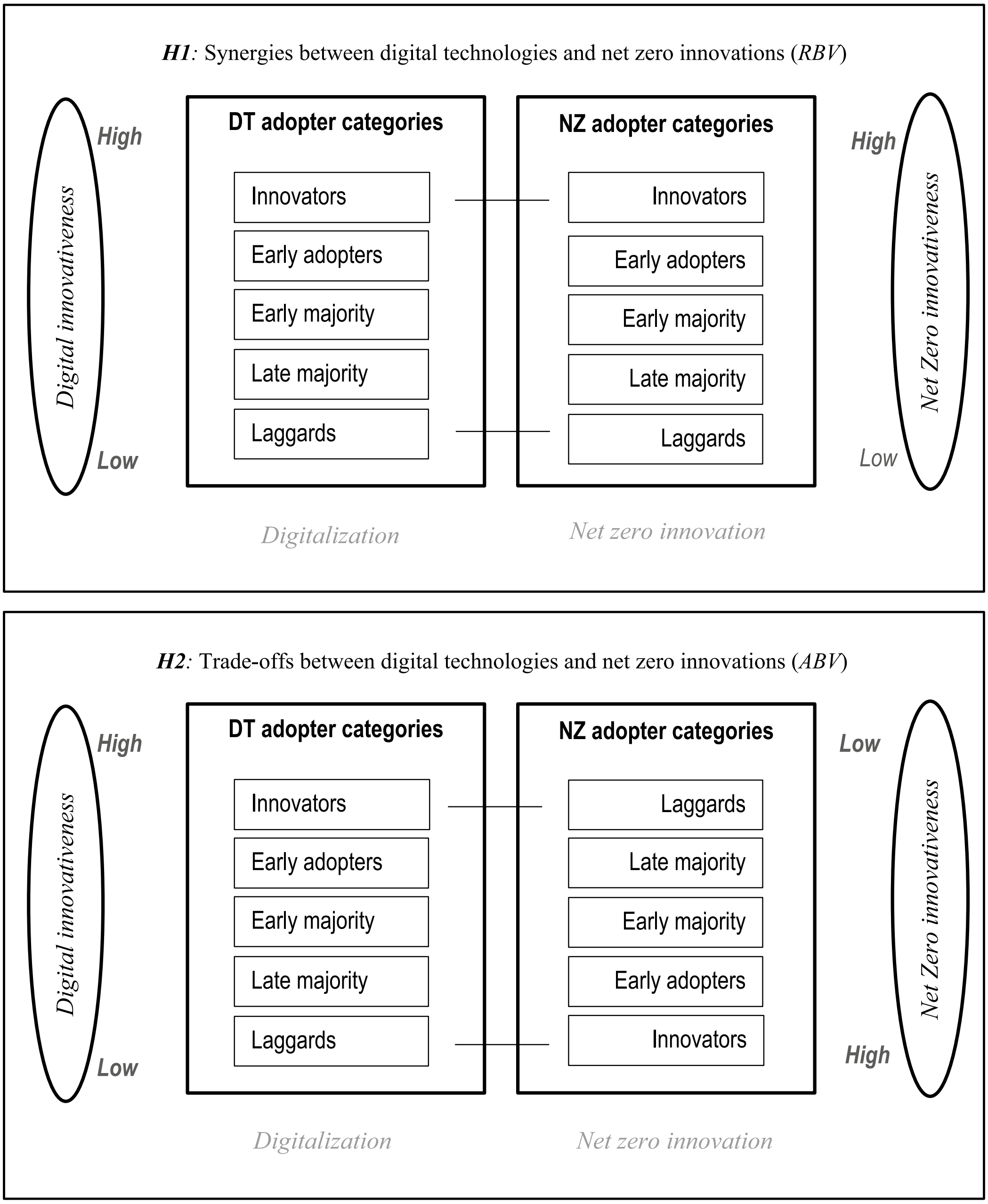


Fig. 3 Conceptual Framework Source: authors' elaboration

First, complementarities between the two diffusion processes could arise because, according to RBV, firms can enhance their performance by strategically bundling complementary assets (Teece, 1997). Asset complementarity refers to synergistic effects when a firm combines different assets or resources. This perspective is helpful in understanding potential synergies between different diffusion processes, highlighting how relationships between system elements could generate greater value than the system's individual parts (Milgrom & Roberts, 1990, 1995). The same argument can be extended to the process of adoption of DT, which allows firms to learn how to manage change, and in turn, facilitates the adoption of NZI.

Second, DTs, being complementary assets, can enhance a firm's managerial capabilities, positively affecting innovation performance (Ahuja & Morris Lampert, 2001). We build on the notion of *digital affordances*, arguing that DTs have the potential to enhance a firm's capabilities, enabling net zero innovations. The idea of digital affordances has emerged in the recent literature as an extension of well-established IS concepts of 'functional' (Marcus & Silver, 2008), 'technology' (Nambisan et al., 2017), or 'IT' affordances (Faik et al., 2020), to the context of digitalization with fast-paced emergence of DTs and digital infrastructure (Autio et al., 2018; Belitski et al., 2023; Meurer et al., 2022).

Digital affordances are defined as functional possibilities or 'action potentials' offered by DTs, which emerge from the relationship between the user and the technology in a particular context (Faik et al., 2020; Majchrzak & Markus, 2012; Nambisan et al., 2017; Tim et al., 2018). Departing from the focus on in-built functionalities or features of DTs, this relationship describes what the user can do with DT, given the user's goals and capabilities (Marcus & Silver, 2008; Nambisan et al., 2017). This implies that DTs may be used for purposes for which they were not initially designed, leading to unintended or unexpected uses and outcomes in the net zero domain.

Conversely, the potential of technology may remain unrealized even if it is part of built-in functionalities. Therefore, different firms may use the same DTs in various ways depending on business goals, capabilities, and the external environment (such as institutional and regulatory frameworks or customer preferences), which may affect the realization of DTs' potential (Ciulli & Kolk, 2023).

Over the last decade, IS scholars have called for a better conceptual and empirical understanding of the role that DTs may play in enabling environmental change (Cooper & Molla, 2017; Elliott, 2011; Elliott & Webster, 2017; Faik et al., 2020; Tim et al., 2018). New concepts emerged in the literature, such as 'IT for green' (Faucheux & Nicolaï, 2011),[4] 'IS for environmental sustainability' (Melville, 2010),[5] and 'digital sustainability' (George et al., 2021).[6] Studies have suggested key digital affordances for sustainability at individual (entrepreneur), firm, and societal levels. For example, Elliot (2011) proposes that DTs offer the following primary action potentials to tackle sustainability: (i) supporting the technical aspects of generic systems designed to tackle the sustainability issue; (ii) facilitating communication among individuals working on solutions; (iii) encouraging a shift towards more environmentally responsible human behavior; and (iv) aiding in the monitoring and evaluation of both behavioral changes and their environmental impact. Seidel et al. (2013) suggest that digital technologies with in-built features such as monitoring, analysis, presentation and communication of information may be used to collect, monitor, and analyze environmental indicators such as carbon emissions, energy consumption, waste generation, and equipment productivity. Information sharing internally and externally enables managers and teams to process information more efficiently and facilitate decision-making regarding net zero practices.

Based on the above, we hypothesize that digital technologies have the potential to create complementary resources through *digital affordances,* enhancing a firm's capabilities for net zero innovations.

H1. More advanced digital technology adopters are *more* likely to be more advanced net zero innovation adopters.

2.4 Trade-offs between digital technologies and net zero innovations

Implementing digital and net zero innovations can be time-consuming, resource-intensive, and often require significant organizational change. This is reflected in the diverse perspectives in a range of SME-related literature, although key themes are

[4] This is defined as 'the impact of IT on other sectors' environmental productivity, particularly in terms of energy efficiency and carbon footprint' (Faucheux & Nicolaï, 2011, p. 11).

[5] This is defined as 'IS-enabled organizational practices and processes that improve environmental and economic performance' (Melville, 2010, p.2).

[6] This is defined as 'the organizational activities that seek to advance the sustainable development goals through creative deployment of technologies that create, use, transmit, or source electronic data' (George et al., 2021, p.1000).

resource constraints and limited managerial attention. For example, for German family firms, Soluk (2022) describes resource allocation and re-allocation as firms undertook digital innovation to respond to the COVID-19 crisis. Here, managerial attention, along with financial and human resources, was focused initially on digital process innovation as a crisis response before 'resource recombination' to develop digital product and business model innovations subsequently. Critically, resource and managerial constraints in these firms meant that digital product innovation followed process change as scarce resources were redeployed rather than undertaken simultaneously. More generally, De Massis et al. (2018) discuss the challenges involved in innovation in resource-constrained smaller firms, particularly where firms such as those in the Mittelstand place a strong priority on self-financing and funding innovation and investment from prior profits. Such reliance on internal funding and other resources may limit the scope of SMEs' investment in any given period and their ability to respond to significant new market opportunities (Audretsch & Elston, 1997).

Both studies suggest that resource constraints and limits to managerial attention in smaller firms may restrict the scope of firms' developmental activity requiring prioritization, and indicate the relevance of arguments relating both to the RBV (Barney, 1991) and ABV (Ocasio, 1997). However, more recent perspectives on the ABV suggest that rather than allocating a fixed attention budget, managerial decisions instead reflect decisions about the primary focus of attention (Joseph et al., 2024). In either case, the ABV – like the RBV – suggests the potential for a trade-off between the allocation of managerial attention to either digitalization or NZI. This trade-off is more likely evident in smaller firms with more limited managerial resources (Weber & Kokott, 2024). This effect may be intensified where the returns to any investment are uncertain or delayed. Rezende et al. (2019), for example, suggest that green innovation only positively affects financial performance two years or more after its introduction. This reflects firms' experience of introducing other types of management and digital innovations, which cause short-term disruption and a consequent deterioration in performance before yielding positive performance benefits (Bourke & Roper, 2016, 2017). Effectively implementing green or net zero innovation may also be complex. For example, Gupta and Barua (2018) identify seven implementation barriers that may be particularly significant in resource-constrained SMEs: management and human resources, technologies, finance, weak connectivity, lack of policy support, market resistance, and insufficient knowledge. Pinkse and Kolk (2010) discuss the related trade-offs which may be involved in green innovation. They argue this situation is complicated further by the lack of clarity on which environmental innovations will likely bring the most significant commercial and environmental benefits.

Limits to managerial attention may also be particularly stringent in smaller firms where leadership teams may be smaller with managers playing numerous roles and performing different functions, often acting as executive and middle managers on projects but also executing non-managerial operational work as a 'backup' person (Florén, 2006). In small firms, managerial time is characterized by a particularly high degree of fragmentation, with managers changing their focus of attention constantly from one issue to another, being often interrupted and feeling the necessity to react immediately and to keep control (Florén, 2006). This suggests a need to balance the proportion of managerial attention allocated to different types of innovation and more operational aspects of firms' operations (e.g., Von Stamm, 2003). Eggers and Kaplan (2008), for example, show that CEO attention is a key factor determining the timing of firms' adoption of new technologies, while Turner et al. (2022) consider allocating limited managerial attention to firms' competitive and cooperative strategies. Other studies have focused on trade-offs between firms' operational, customer-facing and innovation activities (e.g., Von Stamm, 2003). As Hortinha et al., (2011, p. 37) comment: 'the trade-off between customer orientation and technology orientation is of the utmost importance … resources are limited, and firms must make choices in their allocation'.

Attentional constraints on firms' innovation portfolio may be exacerbated by resource constraints related to human resources, finance or cooperation capacity (Hewitt-Dundas, 2006). As Kamm (1986, p. 26) comments: 'Innovative personnel are needed to develop new products and implement new technologies for their production. All three types of innovation—product, technological process, and administrative system—must be juggled simultaneously. Failure in one area can cause problems in other areas, as when development projects are delayed because manufacturing processes are not available to produce the device, or when there are not enough engineers to staff project teams'. Financial constraints may also limit firms' portfolios of innovation activity, requiring trade-offs and prioritization, issues which again may be more significant for SMEs (Madrid-Guijarro et al., 2016).

Such resource and managerial attention trade-offs between digital and green innovation will likely be most impactful in smaller companies or those with more limited technological resources. However, Pinkse and Kolk (2010) suggest that such trade-offs may be mitigated to some degree where green innovation or digital innovation are complementary to firms' existing technological assets. Resource trade-offs may also be mitigated by collaboration with external partners but, as collaboration is often time-consuming to manage, this may exacerbate any shortage of management attention (Laursen & Salter, 2006). Despite these potential mitigations, the potential attentional and resource trade-offs suggest our second hypothesis:

> H2. More advanced digital adopters are *less* likely to be more advanced net zero adopters.

3 Data and methods

3.1 Data

We employ novel data from a dedicated survey of around 1,000 UK SMEs conducted in 2020 (Business Futures survey). The sample focused on businesses employing between 7 and 250 employees, with small businesses representing 86% and medium-sized businesses (employing 50 or more) accounting for 14% of the sample. The sampling frame for the survey was provided by a commercial list broker and intended to represent the UK SME population by size, sector and geography.[7] Well-established businesses trading for more than five years represent the vast majority sample, with younger businesses accounting for less than 5%. Because the research relates to two different domains, digital and NZI the respondent needed to have a comprehensive understanding of business operations and strategic planning rather than being a specialist in one area (e.g. IT Manager). All interviewed respondents were senior people in day-to-day control of the business, typically business owner-managers.[8] The questionnaire design relies on previous literature on eco-innovation and DT adoption (e.g. Bourke & Roper, 2018; Bruque & Moyano, 2007; Craig & Dibrell, 2006; Cruz-Jesus et al., 2019; Demirel & Kesidou, 2019; Dibrell et al., 2011; Horvath & Szabo, 2019; Horbach et al., 2013; Premkumar & Roberts, 1999) and was piloted on a small sub-sample of firms during summer 2020.

Data collection for the main survey was undertaken in Autumn 2020, between the first two UK COVID-19 lockdowns. As this was relatively early in the period covered by the pandemic, the results are likely to reflect more strongly the pre-pandemic pattern of DT use than that which developed as the pandemic extended through 2021 and 2022. Some studies have noted, however, that even by late 2020, when our survey data was collected, the pandemic had stimulated a marked shift in digital adoption patterns (Mikhaylova et al., 2021).

The dataset is unique as it includes questions on a wide range of DT and NZI that SMEs undertake and use in their business operations. Specifically, NZI represents both technological and organizational innovations that firms adopted to reduce their carbon emissions. Crucially, DT coverage includes rich information about both basic and advanced digital technologies. Table 1 shows adoption rates of ten DT and 8 NZI covered by the dataset.

Additionally, the survey includes questions on business goals, barriers and attitudes towards environmental sustainability and business characteristics. After restricting the sample to only those observations containing complete information, our final estimation sample includes 964 firms.

[7] Northern Ireland SMEs were overrepresented in the sample. Thus, in order to provide results which are representative of the UK population of SMEs, data was weighted.

[8] Previous research showed that ideally, such a person would be a CEO or a business owner (Dibrell et al., 2011). While we always aimed to speak to this person, it was not always possible. Therefore, we widened the scope to a Board-level 'senior person' with a detailed knowledge of business operations and planning, such as Managing Director, Operations Director, Partner or similar.

Table 1 DT and NZI adoption rates

DT and NZI	Adoption rate
Digital technologies	
Website to sell goods/services	74%
Online marketing and social media	77%
Accounting and HR software	80%
Customer Relationship Management (CRM)	47%
Video conferencing	64%
Cloud computing solutions	61%
Computer Aided Design (CAD)	36%
Internet of things (IoT)	73%
Augmented and Virtual Reality	11%
Artificial intelligence (AI) and Machine learning (ML)	12%
Net zero innovations	
Undertaken environmental reports or audits	22%
Conducted training on environmental matters	26%
Conducted market research related to low carbon products or services	16%
Changed processes or transport/logistics to reduce carbon emissions	39%
Switched to more renewable energy	30%
Introduced air pollution monitoring and filtering	20%
Invested in research and development related to the environment	14%
Introduced new low carbon products or services	26%

Source: authors' elaboration

3.2 Defining categories of adopters

Rogers (2003) obtains adopter categories by categorizing members of a system into five discrete categories based on their innovativeness. Specifically, he uses the average time of adoption ($\underline{x}$) and standard deviations (*sd*) to construct the adopter categories (see Figure 9 in the Appendix). As mentioned in Sect. 2.1., we conceptualize that for multiple interrelated innovations, innovativeness can be captured by the number of innovations adopted by a firm (Fig. 2). We assume that all interrelated innovations are relevant for all firms. Then, for each firm at a specific moment of time, higher innovativeness will be associated with a higher number of innovations which have been adopted. Next, we explain the operationalization of the DT and net zero adopter categories consistent with this conceptualization.

3.2.1 Digital technologies adopter categories

We operationalize digital diffusion by constructing '*DT adopter categories*' based on the number of DT firms have adopted, and each firm's innovativeness in relation to the mean. Figure 4, drawing on our final estimation sample, shows that the digital diffusion process among UK SMEs, represented by the distribution of firms depending on digital innovativeness (number of digital technologies adopted), has the classic 'bell' shape. Adopter categories are therefore defined using the average ($\underline{x}$) and standard deviations (*sd*) of innovativeness measured by the number of technologies (Fig. 2). The 'Laggards' category includes firms that have not adopted any DT and firms that have adopted less than the difference between the mean ($\underline{x}$) and the standard deviation (*sd*) of DT [0 to ($\underline{x}$—*sd*)]. This category represents around 18% of the sample (Table 2). 'Late majority' and 'Early majority' categories include firms in the interval of one standard deviation below or above the mean and represent around 33% of the sample each. 'Early adopters' use more than ($\underline{x}$ + *sd*) but less than ($\underline{x}$ + 2*sd*) DTs, with around 14% of firms of the sample falling into this category. Finally, 'Innovators' are the 2% of firms who adopted the most DTs, i.e., more than ($\underline{x}$ + 2*sd*).

To illustrate what DTs are more likely to be adopted by each DT adopter category, Fig. 5 provides adoption rates of 10 DTs for UK SMEs for each adopter category. It shows that digital innovators and early adopters are typically firms that

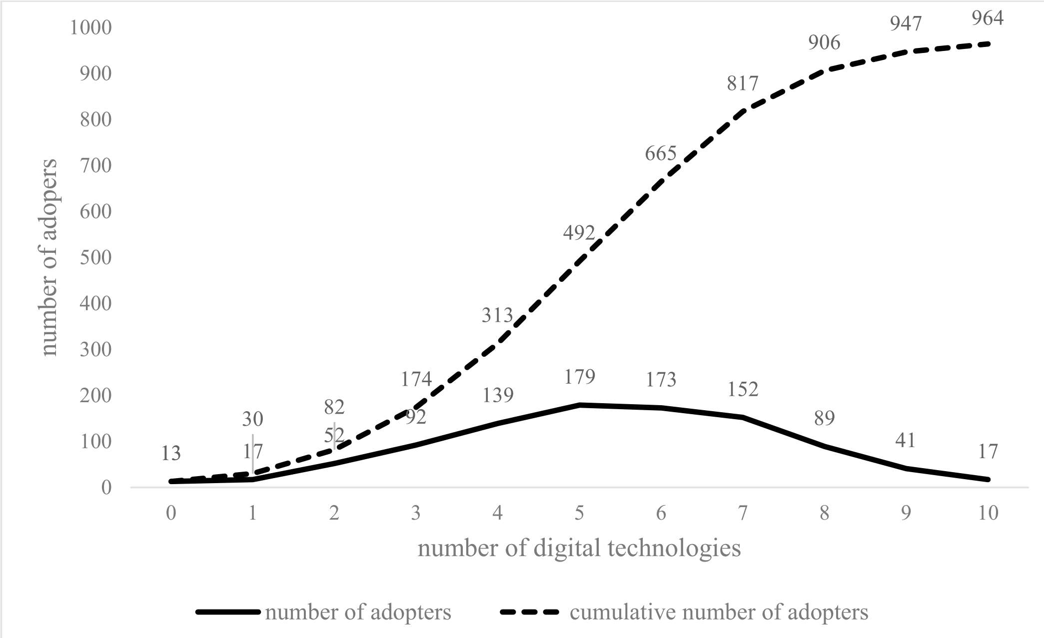


Fig. 4 Distribution of 'digital innovativeness' (number of technologies adopted) Source: authors' elaboration

adopted either all ten DT or have very high adoption rates of the most advanced DTs including AI. On the other hand, digital laggards demonstrate modest adoption rates even for low-cost and common DTs, such as online marketing, e-commerce, CRM and even video conferencing.

3.2.2 Net zero adopter categories

Figure 6 shows that the net zero diffusion process is not as advanced as digital, with about a third of SMEs not yet engaging with NZI. This is in line with previous findings (BBB, 2021). Similarly to the digital diffusion process, we construct NZ adopter categories using innovativeness in the net zero domain measured by the number of NZI. Given that for net zero innovations (*NZI*), standard deviation is higher than the mean, the 'laggards' category has 0 observations (Table 2), so that all firms with below average NZ innovativeness are categorized as 'late majority'. We conjuncture that as the diffusion of NZI among SMEs started later than the diffusion of DT, it is too early to observe 'lagging' NZI behavior.

Figure 7 shows that in all NZ adopter categories changes in production processes or transport and logistics demonstrate the highest adoption rates, followed by integrating renewable energy sources in firms' energy mix. Low carbon market research and R&D on environmental matters have the lowest adoption rates among most UK SMEs.

3.3 Model specification

Considering the ordinal nature of our dependent variable (NZ adopter categories have clear order), we consider an ordered probit model[9] to test our hypotheses. More specifically, we estimate the

[9] The ordered probit model is used to understand how independent variables affect the likelihood of falling into each category of the dependent variable. The model assumes that there is a latent (not directly observed) normally distributed continuous variable (that is, here, NZ innovativeness) that determines the the observed categorical outcome (NZ adopter category, i.e. late majority, etc.). The latent variable is influenced by a set of independent variables through a linear relationship. The model introduces thresholds (cut-points) which divide the continuous variable into categories. These cut-points are estimated along with the model parameters. Thus, ordered probit model is used to estimate the probability that the unobserved latent variable falls within the threshold limits. To simplify, the ordered probit model can be considered as a nonlinear probability model, where the probability of different outcomes (net zero late majority, early majority, etc.) are predicted.

Table 2 Summary statistics

Variable	Observations	Mean	SD	Minimum	Maximum
Dependent variable					
NZcat—NZ adopter categories					
Laggards	964	0	0	0	0
Late majority	964	0.662	0.473	0	1
Early majority	964	0.208	0.406	0	1
Early adopters	964	0.088	0.284	0	1
Innovators	964	0.041	0.199	0	1
Explanatory variables					
DTcat—DT adopter categories					
Laggards	964	0.181	0.385	0	1
Late majority	964	0.336	0.473	0	1
Early majority	964	0.328	0.470	0	1
Early adopters	964	0.138	0.346	0	1
Innovators	964	0.016	0.126	0	1
Drivers					
Attitudes	964	-0.014	1.000	-3.018	1.413
Reputation	964	2.623	1.504	1	5
Costs	964	2.722	1.522	1	5
Regulations	964	2.215	1.357	1	5
Grants	964	2.166	1.435	1	5
Customer demand	964	1.983	1.287	1	5
Voluntary agreements	964	1.987	1.275	1	5
Bank funding	964	1.872	1.278	1	5
Other controls					
Business plan	964	0.635	0.482	0	1
Exporting	964	0.306	0.461	0	1
Skills	964	0.699	0.459	0	1
Barriers	964	1.993	1.932	0	7
Business model change	964	0.151	0.359	0	1
Size	964	3.063	0.749	2.079	5.517
Age	964	3.236	0.888	1	4
Sector	964	4.231	1.278	1	6
Nation	964	1.291	0.769	1	4

Source: authors' elaboration

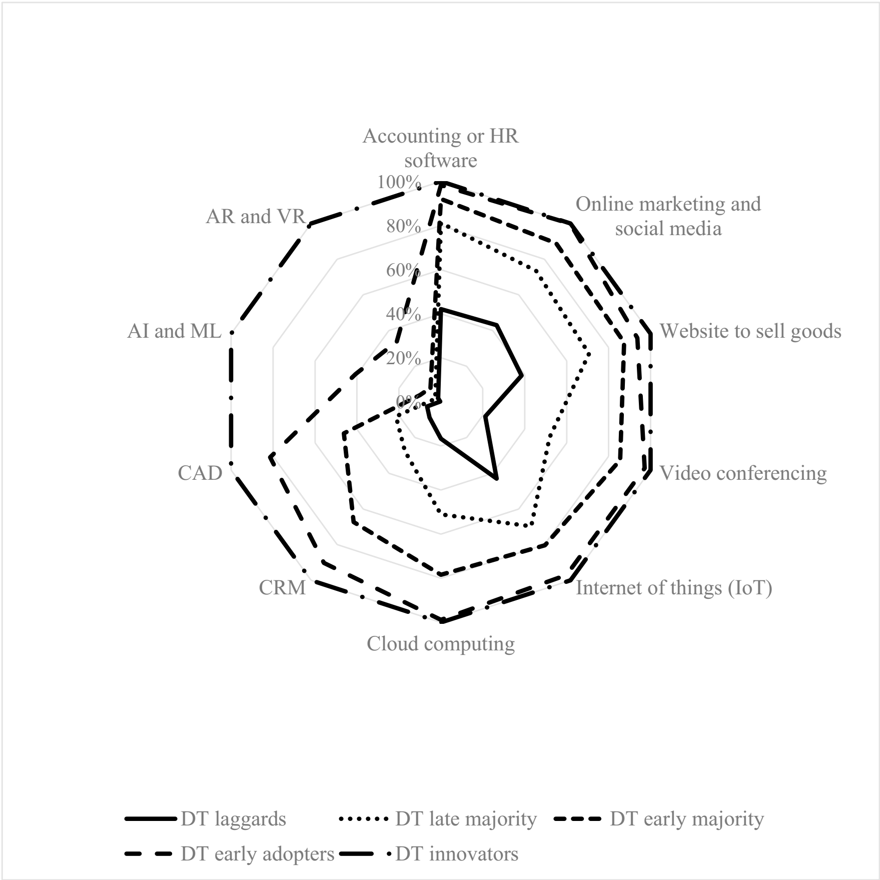
probability of belonging to any NZ adopter category ($NZcat_i$) depending on DT adopter category ($DTcat_i$) controlling for a set of other factors that may influence the adoption of NZI:

$$NZcat_i = \beta_1 DTcat_i + \beta_2 Drivers_i + \beta_3 Controls_i + \beta_0 + \varepsilon_i$$

where $Drivers_i$ are a set of variables relating to individual, internal and external drivers that may spur net zero engagement of a firm, and $Controls_i$ are a series of firm-level controls.

Drivers of net zero adoption Net zero adoption may be driven by both internal and external factors (Kesidou & Demirel, 2012). Previous studies highlighted the importance of external factors such as *environmental regulations and taxes*, *government grants and subsidies* (Fabrizi et al., 2018; Hockerts & Wüstenhagen, 2010; Hofmann et al., 2012), *voluntary agreements within the sectors or across the supply chain* (Iatridis & Kesidou, 2018; Prakash & Potoski, 2013), *availability of external funding from*

Fig. 5 Adoption rates of 10 DT by digital adopter category Source: authors' elaboration



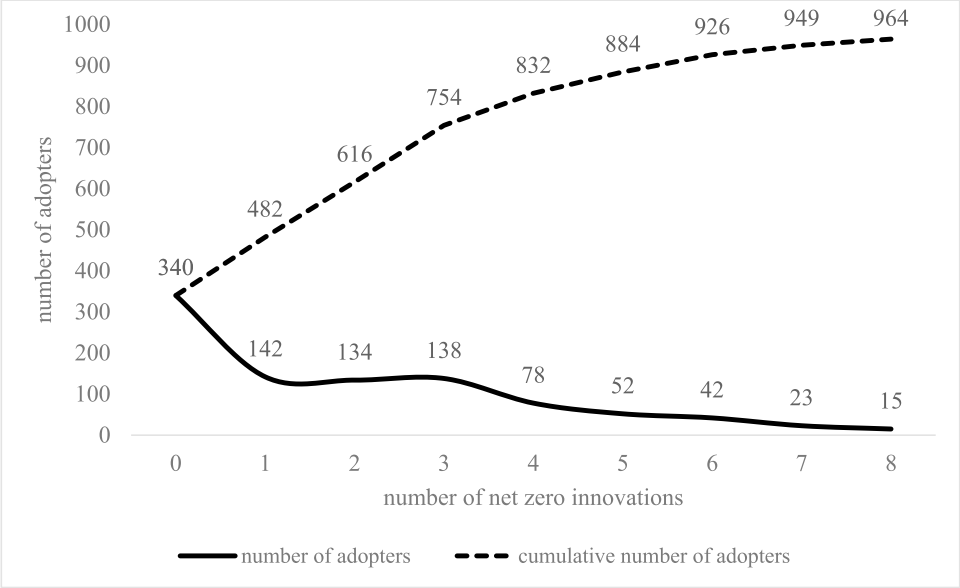


Fig. 6 Distribution of 'net zero innovativeness' (number of innovations adopted) Source: authors' elaboration

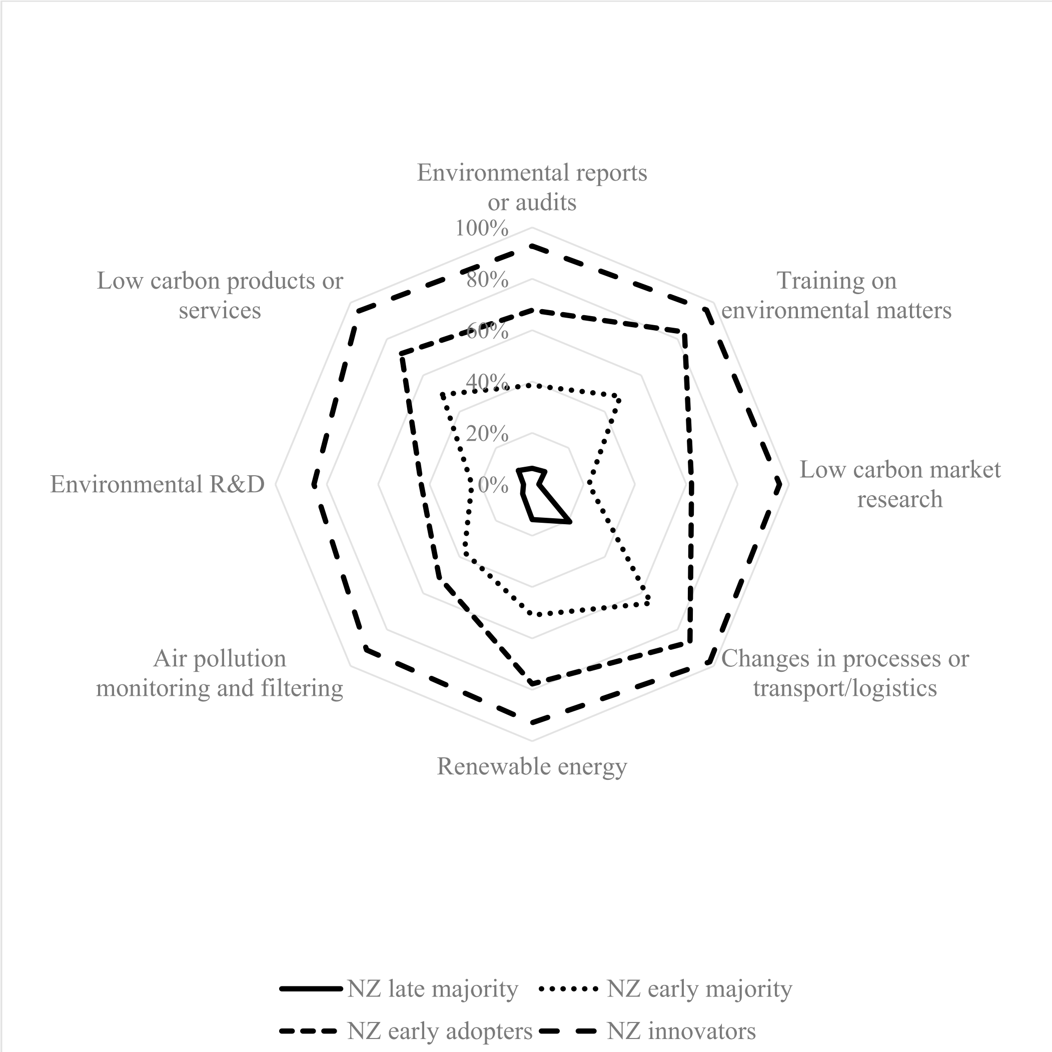


Fig. 7 Adoption rates of 8 NZI by net zero adopter category Source: authors' elaboration

banks, and *customer demand for low-carbon products or services* (Kesidou & Demirel, 2012) in driving net zero adoption.

Among internal factors that may motivate net zero adoption, we introduce *image and reputation* and *cost reduction objectives*, which may be achieved through improved production efficiency or input replacement (Kesidou & Demirel, 2012). Additionally, as has been suggested previously, in the context of SMEs, the personal traits and attitudes of the owner-manager may play a crucial role in innovation decisions. Therefore, following Dibrell et al. (2011), we also introduce the attitudes of business owner-managers towards the natural environment.

Controls Turning to the control variables, we include a dummy reflecting if a firm has a regularly updated business plan to indicate managerial capabilities. We also included in our analysis another binary variable, taking the value of one if a firm exports. This follows previous studies which have established a relationship between exporting activity and innovation via learning and competition mechanisms (Love & Roper, 2015). We also control for firm size by incorporating the (log) of employment as an indicator of SME's resources. We include firm age measured as the number of years since starting the business as it might shape a firm's strategic flexibility and propensity to innovate business model (Miroshnychenko et al., 2021). Finally, we also control for sectoral and geographic heterogeneity.

In alternative specifications, we consider additional controls. Prior studies have stressed that SMEs, even those willing to adapt sustainability practices, may face constraints related to a deficit of skills and knowledge, including digital, to assess available technologies and practices and successfully implement them (OECD, 2021). Because sustainability practices are sometimes associated with important costs, smaller firms may also face difficulties in securing funding and access government support schemes compared to their larger counterparts. To account for heterogeneity in skills, we introduce a dummy variable *Skills* which takes value 1 when firms replied 'strongly agree' or 'somewhat agree' to the statement 'We have the skills to introduce any new technologies', and 0 otherwise. To evaluate the overall hindrance to net zero transition, we also include the *Barriers* variable, taking values from 0 to 7, reflecting the number of barriers encountered by the firm.[10]

Additionally, we explore how the results change depending on whether firms' digital transition resulted in a significant change in business model. Prior literature underlines an important distinction between 'digitalization' (standardizing of business processes) and becoming 'digital' (Ross, 2019), i.e. profound transformation that a business undergoes to take advantage of opportunities that digital technologies create, involving a significant business model change reflected in new 'digital offering'. Hence, we introduce a dummy variable *Business model change* taking the value of 1 if a firm replied 'Yes, significantly' to the question 'Thinking about all digital technologies you introduced, to what extent has your business model evolved/changed as a result?'. Table 2 presents the summary statistics, and Table A1 in the Annex summarizes variable descriptions.

4 Empirical results

4.1 Main results

Table 3 presents the results of the econometric estimation of the ordered probit models. In column (1) we report the odds ratios of our baseline model showing that the odds of belonging to a more advanced category of net zero adoption increase when a firm belongs to a more advanced category of digital adoption. Therefore, our estimation results provide strong evidence supporting *H1* and rejecting *H2*. We find a significant positive relationship between net zero innovativeness, operationalized by NZ adopter categories ($NZcat_i$), and digital innovativeness reflected in DT adopter categories ($DTcat_i$) and conclude that more advanced digital adopters are *more* likely to be more advanced net zero adopters. This relationship is also illustrated by Fig. 8, which shows that the probability of belonging to the least advanced category of net zero adoption (late majority) decreases with digital innovativeness. The probability of belonging to more advanced net zero categories (early majority, early adopters, and innovators) increases with more advanced levels of digital innovativeness.

In Table 4 we report marginal effects to identify the scale of this effect for each of four possible outcomes. Thus, for example, *digital innovators* are 9.6 percentage points more likely than *digital laggards* to become *net zero early adopters* (Table 4, column (3)). By contrast, *digital innovators* are 29.9 percentage points less likely than *digital laggards* to be categorized *as net zero late majority* (Table 4, column (1)).

Regarding other factors that may condition the net zero transition, as expected, we find that *customer demand for low carbon products and services* has the largest effect on net zero innovativeness. Thus, an increase in the scale of importance of customer demand by one point is associated with an increase in the probability of belonging to the net zero early adopter category by 2.1 percentage points and the probability of belonging to the net zero innovator category by 1.7 percentage points. Another external

[10] Businesses were asked the following questions: And thinking about the factors that might have prevented you from reducing [constrained your efforts to reduce] carbon emissions. Which of the following, if any, have been major obstacles? The response options were: lack of relevant skills, administrative or legal procedures, cost of meeting regulations or standards, difficulties in accessing finance, lack of information on low carbon technologies, uncertain demand for low carbon products and services, the COVID-19 pandemic.

Table 3 The probability of belonging to net zero adopter category depending on digital adopter category and other factors (odds ratios)

	Net zero adopter categories (NZcat)			
	Late majority	Early majority	Early adopters	Innovators
	(1)	(2)	(3)	(4)
DTcat *(benchmark Laggards)*				
Late Majority	1.475**	1.317	1.301	1.296
	(0.262)	(0.240)	(0.234)	(0.233)
Early Majority	2.401***	2.027***	1.989***	1.965***
	(0.428)	(0.374)	(0.363)	(0.360)
Early adopters	2.627***	2.240***	2.206***	2.156***
	(0.525)	(0.459)	(0.448)	(0.439)
Innovators	3.091***	2.511**	2.662**	2.609**
	(1.184)	(0.983)	(1.016)	(0.984)
Drivers				
Attitudes	1.163***	1.158***	1.158***	1.156***
	(0.064)	(0.064)	(0.063)	(0.063)
Reputation	1.165***	1.170***	1.183***	1.181***
	(0.058)	(0.057)	(0.059)	(0.059)
Costs	1.081	1.090*	1.081	1.079
	(0.052)	(0.053)	(0.054)	(0.053)
Regulations	1.092*	1.084	1.069	1.066
	(0.056)	(0.056)	(0.055)	(0.055)
Grants	0.982	0.975	0.971	0.972
	(0.048)	(0.048)	(0.049)	(0.050)
Customer demand	1.291***	1.290***	1.291***	1.291***
	(0.063)	(0.063)	(0.064)	(0.064)
Voluntary agreements	1.054	1.061	1.062	1.062
	(0.052)	(0.052)	(0.053)	(0.053)
Bank funding	0.931	0.933	0.917*	0.916*
	(0.044)	(0.045)	(0.044)	(0.045)
Other Controls				
Business plan	1.476***	1.448***	1.448***	1.444***
	(0.169)	(0.166)	(0.165)	(0.165)
Exporting	0.795**	0.804**	0.809*	0.808**
	(0.087)	(0.087)	(0.088)	(0.088)
Skills		1.474***	1.452***	1.436***
		(0.175)	(0.173)	(0.170)
Barriers			1.068**	1.068**
			(0.030)	(0.030)
Business model change				1.120
				(0.156)
Size	yes	yes	yes	yes
Age	yes	yes	yes	yes
Sector	yes	yes	yes	yes
Nation	yes	yes	yes	yes
Pseudo-R2	0.230	0.237	0.241	0.241
Number of observations	964	964	964	964

Standard errors in parentheses; *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

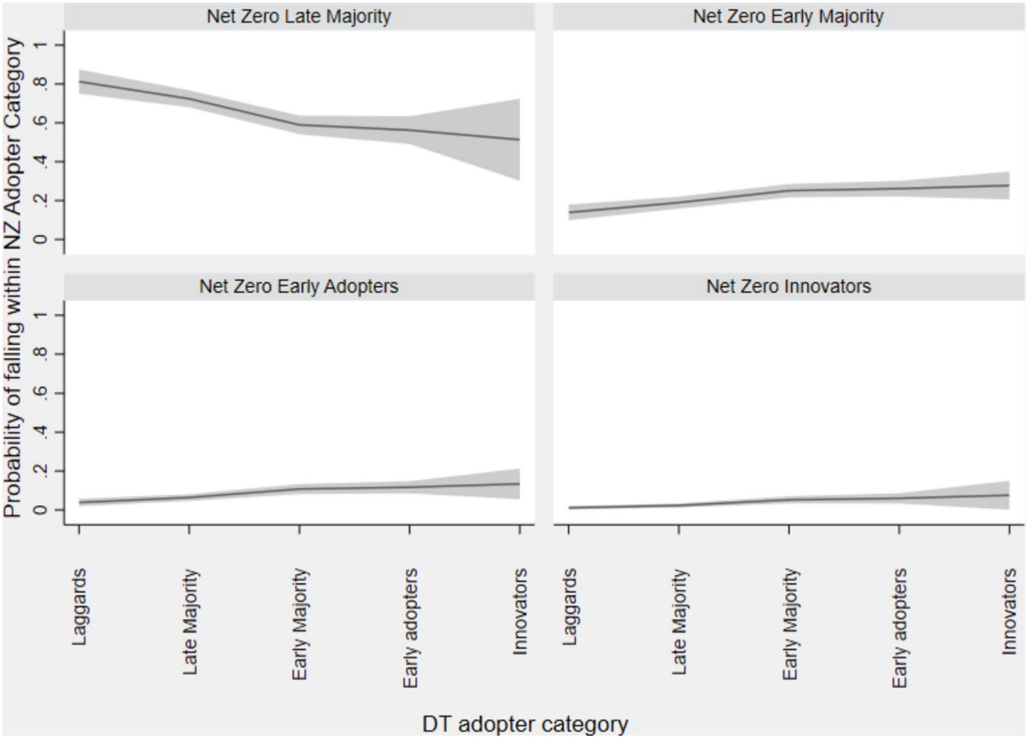


Fig. 8 Predictive margins by net zero adopter category Source: authors' elaboration

factor significantly affecting net zero innovativeness is *environmental regulations and taxes*, although here, the effect is smaller in magnitude.

Turning to internal factors, the results show statistically significant and relatively large effects of *attitudes toward the natural environment of owners-managers* and *image and reputation*. Thus, an increase in the scale of attitudes toward the natural environment by one point decreases the likelihood of belonging to the least advanced net zero category by 3.8 percentage points.

Additionally, in Table 3, we report alternative models including three additional controls: skills (column 2), obstacles encountered on the net zero journey (column 3), and business model change as a result of digital transition (column 4). The results still hold after the inclusion of these additional controls. However, the coefficients associated with the digital late majority category become insignificant. Unsurprisingly, *Skills* are positively and significantly associated with net zero innovativeness. Interestingly, the number of *Barriers* is also positively related to net zero transition advancement. Business model change, although positive, does not significantly affect the probability of belonging to net zero categories (Table 3, column 4).

4.2 Robustness checks

We also conducted some additional analysis to check the reliability of our baseline estimates. So far, we have assumed a certain homogeneity of the SME population when categorizing them by the level of their net zero and digital innovativeness, i.e. operationally we used the mean and the standard deviation over the whole sample when defining NZ and DT adopter categories. However, one can argue that SMEs of different sizes and operating in different sectors represent heterogenous groups with major differences in resources and capabilities, and with different access to technologies and knowledge. Therefore, to test the robustness of our results, we split the sample into subsamples by size (differentiating micro and small businesses of less than 50 employees from medium-sized businesses with 50 to 249 employees) and, before replicating

Table 4 Marginal effects of digital adopter categories on the probability of belonging to net zero adopter categories (baseline model)

Variables	*Net zero adopter categories (NZcat)*			
	Late majority	Early majority	Early adopters	Innovators
	(1)	(2)	(3)	(4)
DTcat *(benchmark Laggards)*				
Late Majority	-0.088**	0.051**	0.026**	0.012**
	(0.038)	(0.023)	(0.011)	(0.005)
Early Majority	-0.223***	0.112***	0.069***	0.041***
	(0.041)	(0.024)	(0.014)	(0.009)
Early adopters	-0.250***	0.122***	0.078***	0.049***
	(0.049)	(0.026)	(0.017)	(0.013)
Innovators	-0.299***	0.139***	0.096**	0.065*
	(0.113)	(0.040)	(0.041)	(0.038)
Drivers				
Attitudes	-0.038***	0.016***	0.012***	0.010**
	(0.014)	(0.006)	(0.005)	(0.004)
Reputation	-0.039***	0.016***	0.013***	0.010***
	(0.012)	(0.005)	(0.004)	(0.003)
Costs	-0.020	0.008	0.006	0.005
	(0.012)	(0.005)	(0.004)	(0.003)
Regulations	-0.022*	0.009*	0.007*	0.006*
	(0.013)	(0.006)	(0.004)	(0.003)
Grants	0.005	-0.002	-0.001	-0.001
	(0.012)	(0.005)	(0.004)	(0.003)
Customer demand	-0.065***	0.027***	0.021***	0.017***
	(0.012)	(0.005)	(0.004)	(0.004)
Voluntary agreements	-0.013	0.006	0.004	0.003
	(0.012)	(0.005)	(0.004)	(0.003)
Bank funding	0.018	-0.008	-0.006	-0.005
	(0.012)	(0.005)	(0.004)	(0.003)
Other Controls				
Business plan	-0.099***	0.041***	0.032***	0.025***
	(0.029)	(0.012)	(0.010)	(0.008)
Exporting	0.058**	-0.024**	-0.019**	-0.015**
	(0.027)	(0.011)	(0.009)	(0.007)
Number of observations	964	964	964	964

Standard errors in parentheses; *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

the analysis for each subsample, we define NZ and DT adopter categories separately for small and medium enterprises.

The ordered probit results for subsamples (Table 5) are consistent with the baseline results (presented for comparison in column 1), thus broadly confirming our main findings. We find evidence supporting H1, namely, synergetic effects between digitalization and NZI for both the small (column 2) and medium-sized (column 3) subgroups of SMEs. We do not find evidence in support H2 (trade-offs).

We repeated the same exercise by splitting our sample into two subsamples broadly corresponding to the primary sector, manufacturing and construction (col 4), and to transport, distribution, professional and other services (col 5). In both cases, we also find evidence supporting H1 despite the reduced significance due to smaller sample size.

Finally, we have also considered how the results may be biased by the information and communication sector where rates of digital adoption, especially of the newest emerging technologies such as AI, are much higher compared to other sectors. Therefore, we redefined NZ and DT adopter categories based on the distribution of number of NZI and DT, excluding digitally savvy ICT businesses. The estimation results for the subsample of non-ICT SMEs are presented in column 6 of Table 5, demonstrating consistency with our main findings.

5 Discussion

Conceptual arguments considering inter-relationships between innovations in different technological domains, such as digitalization and net zero innovations, are ambiguous: complementarities may provide a positive linkage, while limited managerial attention may suggest potential trade-offs. Based on data for UK SMEs, our analysis provides robust empirical evidence supporting the existence of synergies between digital technologies and net zero innovations. We find no evidence for the argument that limited managerial attention creates trade-offs between DT and NZI. Specifically, our results show that firms in more advanced DT adopter categories are also more likely to be more advanced NZ adopters. This is true even when considering other potential external and internal drivers of net zero adoption behavior.

These findings contribute to recent research exploring the links between digitalization and sustainability at firm-level (Ardito, 2023; Montresor & Vezzani, 2023), and in SMEs (Arranz et al., 2023; Avelar, 2024). For instance, Ardito's (2023) study found a positive relationship between the likelihood of environmental innovation and the degree of digitalization among European SMEs. Montresor and Vezzani's (2023) research identified a moderate positive relation between Industry 4.0 DT and eco-innovation in Italian firms. However, our study offers more granular insights by focusing on the progression across DT adopter categories rather than binary distinctions.

Overall, our findings suggest that the twin digital and net zero transitions are not only 'two concurrent transformational trends (the green and digital transitions)' but also entail potential synergies, where one can reinforce the other to 'accelerate necessary changes and bring societies closer to the level of transformation needed' (Muench et al., 2022, p. 7).

Building on the diffusion of innovation theory, we explore the mechanisms through which the innovations in these two domains could diffuse. We conjecture that complementarities between DT and NZI arise, allowing digital affordances in the net zero domain to unfold. Examples of such DT affordances include using social media to increase environmental awareness, CRM systems for market research on environmental matters, and AI to reduce energy consumption during the production process. However, adopting DT with environmental affordances does not guarantee that this potential will automatically result in net zero innovations. Nonetheless, such DT affordances can make adopting net zero practices more likely and easier to implement.

Our analytical approach takes advantage of the multidimensionality of digitalization and net zero innovations. The availability of a range of DT and NZI in each case allows us to link the number of technologies (or innovations) adopted to a firm's tendency to be a leader or follower. In the context of multiple technologies, this approach allows us to use cross-sectional data to categorize firms as early adopters, late adopters, etc., following the framework developed by Rodgers (2003). This adoption 'intensity' approach proves insightful and aligns with similar count-based methods used to capture firms' engagement with high-performance work systems (Martínez-del-Río et al., 2022) and knowledge search for innovation (Laursen & Salter, 2006).

In strategic terms, our results reinforce the results of earlier studies highlighting the innovation benefits of digital technologies for SMEs (Bourke & Roper, 2016, 2017). Digital technology affordances also mean that DTs allow SMEs to better adapt to and mitigate the impacts of the climate crisis. Where DTs promote flexibility or agility, they can enhance business continuity in the face of climatic disruptions. DTs that improve energy or resource efficiency can also reduce costs and have wider environmental benefits. These advantages strengthen the business case for adopting DT, particularly where firms seek to reduce carbon emissions.

Table 5 The probability of belonging to net zero adopter category depending on digital adopter category and other factors (odds ratios)

	(1)	(2)	(3)	(4)	(5)	(6)
	Full sample (baseline model)	Small	Medium	Primary, Manufacturing and Construction	Transport, Retail and Services	All sectors excluding Communication and IT
DTcat (*benchmark Laggards*)						
Late Majority	1.475**	1.568***	1.885**	1.114	1.431**	1.492**
	(0.262)	(0.252)	(0.496)	(0.264)	(0.214)	(0.273)
Early Majority	2.401***	2.018***	3.984***	1.668**	2.013***	2.481***
	(0.428)	(0.341)	(1.001)	(0.387)	(0.302)	(0.456)
Early adopters	2.627***	2.359***	3.174***	1.199	2.510***	2.885***
	(0.525)	(0.442)	(0.959)	(0.356)	(0.442)	(0.592)
Innovators	3.091***	3.932***	2.966**	2.917**	2.905**	3.409***
	(1.184)	(1.802)	(1.509)	(1.312)	(1.215)	(1.368)
Drivers						
Attitudes	1.163***	1.158***	1.032	1.042	1.035	1.181***
	(0.064)	(0.063)	(0.084)	(0.080)	(0.054)	(0.068)
Reputation	1.165***	1.221***	1.437***	1.569***	1.124**	1.167***
	(0.058)	(0.061)	(0.136)	(0.124)	(0.056)	(0.058)
Costs	1.081	1.208***	1.067	1.134*	1.231***	1.095*
	(0.052)	(0.061)	(0.084)	(0.077)	(0.055)	(0.055)
Regulations	1.092*	1.079	1.083	1.051	1.105**	1.073
	(0.056)	(0.058)	(0.105)	(0.089)	(0.051)	(0.057)
Grants	0.982	0.956	1.017	0.940	1.023	0.974
	(0.048)	(0.048)	(0.091)	(0.077)	(0.046)	(0.049)
Customer demand	1.291***	1.258***	1.212**	1.225***	1.245***	1.293***
	(0.063)	(0.062)	(0.114)	(0.093)	(0.057)	(0.064)
Voluntary agreements	1.054	1.024	1.184*	1.027	1.054	1.042
	(0.052)	(0.052)	(0.118)	(0.085)	(0.052)	(0.053)
Bank funding	0.931	0.989	0.939	0.932	0.947	0.939
	(0.044)	(0.052)	(0.074)	(0.073)	(0.043)	(0.045)
Other Controls						
Business plan	1.476***	1.536***	0.984	1.513**	1.287**	1.461***
	(0.169)	(0.177)	(0.186)	(0.262)	(0.135)	(0.170)
Exporting	0.795**	0.980	0.891	1.097	0.986	0.787**
	(0.087)	(0.111)	(0.156)	(0.174)	(0.102)	(0.088)
Size	yes	yes	yes	yes	yes	yes
Age	yes	yes	yes	yes	yes	yes
Sector	yes	yes	yes	no	no	yes
Nation	yes	yes	yes	yes	yes	yes
Pseudo-R2	0.230	0.240	0.321	0.253	0.230	0.232
LogL	-713.1	-734.6	-131.2	-257.9	-625.3	-683.5
Number of observations	964	707	257	239	725	922

'Primary, Manufacturing and Construction' includes businesses in the following SIC 2007 sections: A, B, C, D, E and F; 'Transport, Retail and Services' refers to sections from G to S

Standard errors in parentheses; $*p<0.1$, $** p<0.05$, $*** p<0.01$.

Our results also suggest that learning from innovation in one domain helps improve the effectiveness of adoption in the other, highlighting the potential for economies of scope in digital and net zero innovation. This has managerial implications suggesting that to maximize the value of learning, the same individuals or teams should lead digital and net zero innovation within a firm. This is most relevant for SMEs in our study, where the managerial and leadership teams are small. For larger firms, knowledge sharing between the teams leading digital and net zero innovations becomes crucial.

In policy terms, our findings align with Volkmann et al. (2021), suggesting that business support designed to facilitate the digital transition also promotes adaptability and progress towards net zero. Given the cumulative character of managerial capacity and the horizontal communication between adopter categories, i.e. innovators talking to other innovators (Rogers, 2003, p. 424–426), businesses that are late adopters of DT may also be doomed to remain net zero laggards. This creates the potential challenge that a net zero divide will also likely accompany any digital divide. Rural firms, for example, whose digital adoption may be constrained by limited broadband access, could miss out on the potential gains from moving towards net zero. Similarly, for smaller firms where the barriers to digital adoption may be stronger, this may make net zero innovation more challenging.

The coincidence of digital adoption and net zero innovation, which our results suggest, emphasizes the dual value of targeted policy initiatives that support digital adoption in slow adopter groups. Promoting digital adoption here will have both productivity and growth benefits while also enabling net zero innovation. However, the appropriate policy instruments may vary depending on whether the digital adoption constraints are internal or external. For example, smaller firms in urban locations will likely face resource constraints to digital adoption, making financial support or advisory services appropriate. In other, more rural locations, broadband access may be the key constraint on digital adoption. Here, infrastructure investment is likely to be critical.

6 Conclusions

We explore whether SMEs, constrained by resources and managerial attention spans, face trade-offs between digitalization and net zero innovation. Our results provide little evidence for such trade-offs emphasizing instead complementarities between digital adoption and net zero innovation. This strengthens the strategic and policy case for supporting digitalization but also suggests that where digital innovation lags, so will net zero innovation, creating a double-divide between innovating and lagging firms. This may have implications for business performance and firms' ability to contribute to net zero goals, emphasizing the value of policy support for digitalization in SMEs.

As part of our analysis, we develop a new approach to categorizing the innovative status of businesses in situations where adoption is multidimensional. Here, we find it valuable to replace the adoption time indicator at the core of the Rogers (2003) technology diffusion model with the intensity of adoption measured by the number of dimensions of net zero innovation and digitalization which firms face. These indicators prove meaningful and readily interpretable in our empirical analysis and provide an empirical framework which is readily transferrable to other contexts.

This study offers robust empirical evidence of synergies between digital technologies and net zero innovations within UK SMEs, but there are important boundary conditions that should be considered when generalizing these findings to other contexts, cultures, and economic conditions. First, our study is UK-based, and the UK's regulatory setting, economic structure, and cultural attitudes toward sustainability may influence our results. For instance, UK SMEs operate in a context where net zero goals are embedded in national policy targets, providing incentives for sustainability transformation. These conditions might be relevant in European countries, yet, not fully applicable in other countries where environmental regulations are less stringent. Second, economic conditions also matter in shaping these relationships. For instance, digital infrastructure and broadband access vary significantly across and within countries. For example, rural firms in the UK need more digital adoption due to poor broadband access, which may hinder their progress toward net zero. Finally, cultural differences in managerial practices may affect the applicability of our results. In countries with a strong environmental culture, such as Germany, where the Mittelstand is prevalent, the link between digital and net zero innovations may be even stronger due to cultural reinforcement of sustainability. However, in cultures where sustainability is not yet a key business driver, the emphasis on the synergies we observe could be weaker.

Our analysis has some limitations which suggest the potential for future research. First, our analysis is based on a single cross-sectional survey, which although providing novel data on innovation across both the digital and net zero domains, limits our ability to infer causality. Future longitudinal studies would help to clarify causality as well as establish any time lags involved between, say, digital adoption and net zero innovation. Second, as a quantitative exercise, we have little direct insight into the mechanisms connecting digital and net zero innovation. We conjecture that this is related to digital affordances, but confirming this would require more detailed case study or qualitative investigation. Finally, our analysis relates to data collected in 2020 during the early stages of the pandemic although at a time when digitalization had already increased sharply in many firms (Mikhaylova et al., 2021). Given the impact of the pandemic, which started in early 2020, any related increase in digital adoption was very recent at the time of our survey but may still be influencing our results. Confirmatory analysis in more 'normal' times would also be valuable.

Declarations

Conflict of Interests The authors declare no conflict of interests.

Appendix

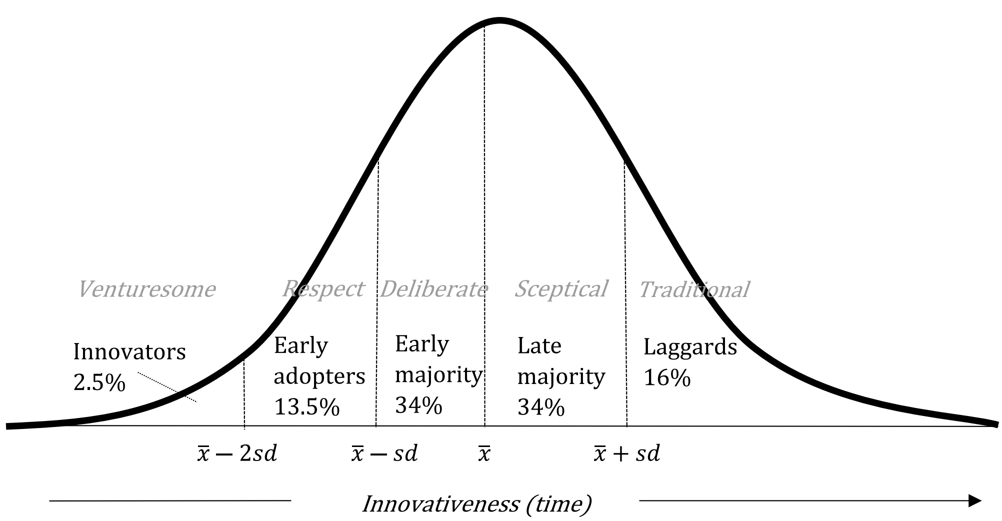


Fig. 9 Adopter categories based on innovativeness measured by time Source: Rogers (2003)

Table 6 Variables description

Variable name	Description	Measurement
NZcat	NZ adopter categories are mutually exclusive categories constructed based on the distribution of NZ innovativeness using the average ($\bar{x}$) and standard deviation (sd): (1) Laggards: 0 to ($\bar{x}$—sd) * (2) Late majority: ($\bar{x}$—sd) to $\bar{x}$ (3) Early majority: $\bar{x}$ to ($\bar{x}$ + sd) (4) Early adopters: ($\bar{x}$ + sd) to ($\bar{x}$ + 2sd) (5) Innovators: ($\bar{x}$ + 2sd) and higher *Because standard deviation is higher than the mean, Laggards category has 0 observations, so that all firm with below average NZ innovativeness are categorized as Late majority (See Table 2) NZ innovativeness is measured by the number of NZI adopted by the firm, by construction it varies from 0 to 8: 0 means that firm has not adopted any of the 8 NZ practices included in the survey and 8 means that firm has adopted all 8 practices (Question: Which of the following have steps you taken to minimize your environmental impact? (1) undertaken environmental reports or audits; (2) conducted training on environmental matters; (3) conducted market research related to low carbon products or services; (4) changed processes or transport/logistics to reduce carbon emissions; (5) switched to more renewable energy; (6) Introduced air pollution monitoring and filtering; (7) invested in research and development related to the environment; (8) introduced new low carbon products or services)	Categorical variable. 1 = Laggards, 2 = Late Majority, 3 = Early majority, 4 = Early adopters, 5 = Innovators
DTcat	*DT adopter categories* are mutually exclusive categories constructed based on the distribution of *digital innovativeness* using the average ($\bar{x}$) and standard deviation (*sd*): (1) Laggards: 0 to ($\bar{x}$—*sd*) (2) Late majority: ($\bar{x}$—*sd*) to $\bar{x}$ (3) Early majority: $\bar{x}$ to ($\bar{x}$ + *sd*) (4) Early adopters: ($\bar{x}$ + *sd*) to ($\bar{x}$ + 2*sd*) (5) Innovators: ($\bar{x}$ + 2*sd*) and higher *Digital innovativeness* is measured by the number of *DT* adopted by the firm, by construction it varies from 0 to 10: 0 means that firm has not adopted any of the 10 *DT* included in the survey and 10 means that firm has adopted all 10 *DT* (Question: Which of the following digital technologies does your business currently use? (1) website to sell goods/services; (2) online marketing and social media; (3) Accounting and HR software; (4) Customer Relationship Management (CRM); (5) Video conferencing; (6) Cloud computing solutions; (7) Computer Aided Design (CAD); (8) Internet of things (IoT); (9) Augmented and Virtual Reality; (10) Artificial intelligence (AI) and Machine learning (ML)	Categorical variable. 1 = Laggards, 2 = Late Majority, 3 = Early majority, 4 = Early adopters, 5 = Innovators
Attitudes	Owner–manager's attitudes toward the natural environment based on three item scale adapted from Craig and Dibrell (2006) and Dibrell et al. (2011); coefficient alpha 0.71: (1) Businesses should spend more to reduce their impact on the environment; (2) Businesses' environmental impact should be part of the bottom line; (3) Businesses should prioritize protecting environment above profitability or growth Scale from 1 = 'Strongly disagree' to 5 = 'Strongly agree' (Question: To what extent do you agree or disagree with the following statements?)	PCA Index

Table 6 (continued)

Variable name	Description	Measurement
Reputation	*Reputation* describes the importance of improving image and reputation in carbon emissions reduction efforts of the business (question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Improving your image and reputation)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Costs	*Costs* describes the importance of cost reduction in carbon emissions reduction efforts of the business (question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Reducing costs)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Regulations	*Regulations* describes the importance of environmental regulations and taxes in carbon emissions reduction efforts of the business (question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Environmental regulations or taxes)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Grants	*Grants* describes the importance of government grants or subsidies in carbon emissions reduction efforts of the business (question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Government grants or subsidies)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Customer demand	*Customer demand* describes the importance of customer demand for low-carbon products or services in carbon emissions reduction efforts of the business (question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Customer demand for low-carbon products or services)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Voluntary agreements	*Voluntary agreements* describes the importance of voluntary agreements within the business's sector or supply chain in carbon emissions reduction efforts of the business (Question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Voluntary agreements within your sector or supply chain)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Bank funding	*Bank funding* describes the importance of availability of external funding from banks in carbon emissions reduction efforts of the business (Question: How important have the following been in influencing your efforts to reduce carbon emissions over the past 12 months? Availability of external funding from banks)	Categorical variable. Five-point scale varying from 1 = 'Not at all important' to 5—'Extremely important'
Business plan	*Business plan* identifies businesses having a formal written business plan	Binary variable
Exporting	*Exporting* identifies businesses selling product/services outside the UK	Binary variable
Skills	*Skills* identifies businesses reporting having enough skills to introduce new technologies (Question: To what extent do you agree or disagree with the following statements about the adoption and implementation of technologies? We have the skills to introduce any new technologies)	Binary variable. 1 = answering 'Strongly agree' or 'Somewhat agree', 0 = otherwise

Table 6 (continued)

Variable name	Description	Measurement
Barriers	*Barriers* refers to number of factors preventing/constraining efforts to reduce carbon emissions among the following: lack of relevant skills, administrative or legal procedures, cost of meeting regulations or standards, difficulties in accessing finance, lack of information on low carbon technologies, uncertain demand for low carbon products or services, the Coronavirus pandemic (Question: Thinking about the factors that [might have prevented you from reducing / constrained your efforts to reduce] carbon emissions. Which of the following, if any, have been major obstacles?)	Categorical variable, from 0 = no barriers to 7 = all 7 factors reported as preventing/constraining carbon reduction efforts
Business model change	*Business model change* identifies businesses for which DT adoption leaded to significant changes in business model (Question: Thinking about all digital technologies you introduced, to what extent has your business model evolved/changed as a result?)	Binary variable
Size	Log of number of employees	Continuous variable
Age	*Age* represents business age categories based on number of years since starting trading	Categorical variable. 1 = 0 to 5 years, 2 = 6 to 10 years, 3 = 11 to 20 years, 4 = more than 20 years
Sector	*Sector* represents broad sector of activity of the business (SIC 2007): (1) Primary – Sections A, B, D, E (2) Manufacturing—Section C (3) Construction – Section F (4) Transport, retail and distribution – Sections G, H, I (5) Business services—Sections J, K, L, M, N (6) Other services—Sections P, Q, R, S	Categorical variable. 1 = Primary, 2 = Manufacturing, 3 = Construction, 4 = Transport, retail and distribution5 = Business services, 6 = Other services
Nation	*Nation* describes the location of the business in one of the four UK nations	Categorical variable. 1 = England, 2 = Northern Ireland, 3 = Scotland, 4 = Northern Ireland

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