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Unravelling the relationship between digitalisation and sustainable energy transitions using socio-technical-ecological scripts

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ABSTRACT

Sustainable energy transitions are closely intertwined with digitalisation processes. In this paper, we analyse how the development and implementation of digital technologies are deeply embedded in socio-technical-ecological configurations of sustainable energy transitions and consequently reflect these configurations. We contribute to the emerging body of literature that investigates the complex relationship between digitalisation and sustainability transitions, often framed as "twin transitions". We develop a conceptual framework that combines the interplay of actors, institutions, technologies and ecological boundaries as core analytical dimensions in transition studies with the concept of *scripts* from Science and Technology Studies. Scripts allow us to investigate how actor constellations, institutional settings as well as technological and ecological requirements are *in-scribed* into a digital technology and *de-scribed* – i.e., interpreted and put into action – by a variety of actors. In this way, we analyse how and which configurations of ongoing transitions are manifested in the technological script. This offers an approach to better understand and reflect on whether and how digital technologies may unfold their often anticipated transformational capacity in transition processes. We illustrate the applicability of our framework with insights from a case study on digital technologies to be installed at onshore wind power plants to detect avian species and curtail turbines when protected birds are at risk of collision.

1. Introduction

The question of whether and how digital technologies can facilitate sustainability transitions drives both researchers and decision-makers worldwide. The assumed complementarity between digitalisation and sustainability transitions is increasingly discussed under the label “twin transitions” (Husain et al., 2022; Muench et al., 2022). Particularly in the energy sector, high hopes and expectations are pinned on digitalisation to unlock and accelerate transitions towards more sustainable forms of energy production and consumption. Underlying arguments include that information and communication technologies (ICT) and AI-based tools have the potential to advance energy efficiency (Lange et al., 2020), support the integration of renewable energy technologies through improved grid services (Al Kez et al., 2021), and enable more sustainable consumption patterns through digital platforms (Noussan and Tagliapietra 2020). Yet, the situation is not as straightforward: Digital technologies themselves often require significant amounts of energy and natural resources (Al Kez et al., 2022), reinforce social inequalities (Sareen 2021; Sovacool et al., 2022), manifest

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incumbent structures (Loock 2020), and have ambivalent impacts on the diverse sustainability goals and indicators (Al Kez et al., 2022; Rohde et al., 2024). From a system-level perspective, there is a lack of conceptual clarity concerning the different ways in which digitalisation and sustainability transitions are coupled (Mäkitie et al., 2023). More specifically, this has led to calls in transitions research for studies that investigate how digitalisation is linked to the interplay between actors, technologies and institutions (Andersen et al., 2021). The main purpose of our paper is to conceptually contribute to this perspective.

Within ongoing transition dynamics, digital technologies appear to exert a qualitatively new force compared to existing, non-digital artefacts: Their ability to produce, analyse and act upon unprecedented amounts of data provides them with 'configurational' or 'transformative' (Hilty and Aebischer 2015a) potential because they integrate technological and human elements "into new context-specific configurations" (van Summeren et al., 2021, p. 3). The configurational power manifests itself, for instance, in the way existing, generic energy technologies operate, how intensively they are used, and to what extent control over these technologies is externalised. In this sense, digitalisation is often conceptualised as being "constitutive of transitions" (Sareen and Haarstad 2021, p. 94), and having "structural impacts" on transition processes (Townsend and Coroama 2018, p. 2). Here, studies pay attention to the particularities of digital technologies in sustainability transitions (Chen and Yu 2024) and highlight the pervasiveness, speed and scope with which digital technologies permeate socio-technical systems of various sectors (John et al., 2022; van Summeren et al., 2021; Kitchin 2023). At the same time, bi-directional, multi-system approaches are emerging. These approaches emphasise not only how digital technologies change socio-technical structures of sectors (van Summeren et al., 2021; Mäkitie et al., 2023) but also how existing sectoral regimes shape the development and diffusion of digital innovation (John et al., 2022). In their scoping review, Mouthaan et al. (2023, p. 11) note: "What unites most research on digitalization and sustainability is the traditional perspective taken on digital technologies as a set of artefacts, while largely ignoring the social and institutional embedding of such artefacts". The authors, hence, call for conceptual and empirical work that more strongly investigates the co-evolution of digitalisation and sustainability transitions (Mouthaan et al., 2023; Andersen et al., 2021). Our paper builds on these calls and proposes a novel perspective that combines concepts from sustainability transition studies with Science and Technologies Studies: This approach highlights how the development and implementation of digital technologies – as part of the digitalisation process – is deeply embedded in and therefore shaped by socio-technical system configurations.

Our approach is underlined by the notion that "technology is developed through a socio-political process which results in structures (rules and resources) being embedded within the technology" (Orlikowski 2000, p. 405). We understand digital technology development and implementation as embedded in energy transition processes, involving contestations and negotiations between heterogenous actors, technological conditions and requirements as well as diverse institutional settings. We expand these three core analytical dimensions in transition studies (Geels 2004) by ecological elements that also shape digital technology development (van der Jagt et al., 2020; Vermunt et al., 2020; Andersson et al., 2024). We therefore ask: *How do socio-technical-ecological configurations of sustainable energy transitions shape the development and implementation of digital technologies?*

To trace this relationship between digital technologies and socio-technical-ecological configurations, we develop a conceptual framework that combines the interplay of actors, institutions, technologies and ecological boundaries with the concept of scripts (Akrich 1992; Latour and Woolgar 1986) from Science and Technology Studies. We acknowledge the long history of research on the mutual shaping of technologies and their contexts (Bijker and Law 1992; Rip and Kemp 1998) and use scripts as an analytical lens to conceptualise how socio-technical-ecological configurations are inscribed and realised in digital technologies. This process of *in-scription* focuses on technology development and is complemented by processes of *de-scription* to account for the role of users and their power in interpreting and influencing the technological script during implementation (Akrich 1992; Fatimah et al., 2015). Investigating this interactive relationship between processes of in-scription, the script itself, and de-scription is vital for understanding how digital technologies are shaped by dynamic configurations of transitions. This, in turn, is a key prerequisite for grasping why and to what extent digital technologies may unfold their aspired transformational (Hilty and Aebischer 2015b) and configurational (van Summeren et al., 2021) potential.

Our paper is structured as follows: Building on current debates on digitalisation and digital technologies in the context of sustainable energy transitions (Section 2), we develop our conceptual framework (Section 3). We illustrate the framework with empirical insights from a case study on AI-based technologies for automated bird detection and curtailment of onshore wind power plants (Section 4) and reflect on the framework's applicability and the need for future research (Section 5).

2. Setting the scene: digitalisation and sustainability transitions

Our paper focuses on digitalisation in the context of sustainable energy transitions. While we also build on the literature on digitalisation and sustainability transitions more generally, we acknowledge the divergent roles, purposes, and challenges that come with digitalisation in different sectoral transition processes (John et al., 2022; Frenken and Schor 2017; Rijswijk et al., 2021). We start by reviewing existing research related to digitalisation and digital technologies in the energy sector (Section 2.1), as well as the interplay between digitalisation and sustainable energy transitions (Section 2.2).

2.1. Digitalisation and digital technologies in sustainable energy transitions

In the wider realm of the energy sector, digital technologies come in various forms, such as sensing and metering technologies, automation systems, cybersecurity, modelling or simulations, communication tools, or digital platforms (Ahmad et al., 2021). They consist of hardware and software and either directly constitute ICT or are enabled by them (Lyytinen et al., 2016). Often, they are developed and used in relation to existing energy technologies with the aim of making them 'smarter' – i.e., enabling communication between physical and human components (van Summeren et al., 2021), offering more energy and resource efficient solutions (Lange et al., 2020), or triggering new forms of sustainable patterns that existing innovations alone cannot achieve (Mäkitie et al., 2023). At first glance, these digital technologies may be viewed as 'add-ons', constituting additional layers to the existing socio-technical system (Geels et al., 2016). Yet, when considering digital technologies in the realm of digitalisation, they entail more profound changes. Understood as the real-time collection, analysis, and manipulation of data through digital technologies (Trittin-Ulbrich et al., 2021), digitalisation involves

> *"(…) the transformation of socio-technical structures that were previously mediated by non-digital artifacts or relationships into ones that are mediated by digitized artifacts and relationships. Digitalization goes beyond a mere technical process of encoding diverse types of analogue information in digital format (*i.e.*, 'digitization') and involves organizing new socio-technical structures with digitized artifacts as well as the changes in artifacts themselves*" (Yoo et al., 2010, p. 6*)*

The understanding that digitalisation impacts socio-technical systems is also reflected in existing notions within transitions studies. In their typology, Mäkitie et al. (2023) refer to the development, implementation, and usage of digital technologies that vary in their potential to affect and change socio-technical systems. Their concept of 'radical twin innovations' denotes a close coupling between digital innovations and sustainability pathways "lead[ing] to structural reconfigurations towards more sustainable *and* digital patterns of production and consumption" (Mäkitie et al., 2023, p. 4, emphasis in original). van Summeren et al. (2021, p. 3) understand ICT-based technologies as configurational because they integrate technological and human elements "into new context-specific configurations". The configurational power of ICT then manifests in, for instance, the way existing generic energy technologies operate, how intensively they are used, and to what extent control over these technologies is externalised. Coming from the information systems field, Hilty and Aebischer (2015a, p. 20) similarly conceptualise ICT as transformative technologies, "enabling more sustainable patterns of [energy] production and consumption". The related and currently emerging research field of *ICT for Sustainability* emphasises the dual potential of ICT in achieving direct resource and energy savings, such as through efficiency measures, and indirect savings through technological push-dynamics and substitutions towards more sustainable solutions (Townsend and Coroama 2018).

Taken together, digital technologies are assumed to offer new, unprecedented opportunities and challenges for sustainability transitions that set them apart from existing non-digital technologies and make them particularly relevant to study (Bailey et al., 2019): Because they are intelligent, these technologies 'act' autonomously and independently while significantly affecting the work of actors and organisations. They alter the way organisations collaborate, as well as the organisations' need for constant adaptation to evolving technological conditions, for example, evident in the development of smart grids (Paustian and Mattes 2024; Rohde and Hielscher 2021). Finally, by handling large amounts of data, digital technologies enable, but also require new forms of control and measurement in the energy sector.

2.2. Interdependence between digital technologies and sustainable energy transitions

While sustainable energy transitions and digitalisation can be viewed as socio-technical processes with their own inherent drivers and challenges (Bergman and Foxon 2023; Mäkitie et al., 2020), a growing body of literature has begun to foreground their dynamic interactions. Not only within transition studies but also in related fields – including ecological economics, organisation studies, and information systems research – the coupling between digitalisation and sustainable energy transitions is increasingly investigated. Accordingly, a diverse range of conceptual and empirical approaches has emerged. We broadly distinguish between two main directions: Research that investigates (i) the effects of digitalisation on energy use, natural resources, sustainability goals and indicators; and (ii) more structural impacts of digitalisation on socio-technical systems, including heterogenous actors, technologies, and institutions.

As arguably the most dominant research theme in this area so far, studies provide a rather ambivalent picture with respect to digitalisation's impact on energy and resource use. In recent years, hypes and expectations have surrounded the role of digital technologies in transitions towards sustainability (Sareen and Haarstad 2021; Soutar 2021). And indeed, ICT has the potential to decrease energy demand through efficiency measures (Lange et al., 2020), support the integration of renewable energy technologies through improved grid services (Al Kez et al., 2021), and enable more efficient and sustainable mobility systems through digital platforms (Noussan and Tagliapietra 2020). Yet, more and more findings raise concerns about the energy and resource consumption of both the ICT sector itself and the broader energy system (Lange et al., 2020; Al Kez et al., 2022), pointing to severe rebound effects (Galvin 2015) and even the creation of unsustainable consumption patterns (Frenken 2017). Scholars, therefore, propose greater conceptual clarity and differentiation between expected and actual (Piscicelli 2023), as well as intended and unintended (Bohnsack et al., 2022) effects of digitalisation on sustainable development, and they develop schemes for assessing digitalisation based on established sustainability criteria (Rohde et al., 2024).

A second research theme addresses the effects of digitalisation from a system-level perspective. In contrast to the former theme, studies explicitly relate to transition dynamics to analyse how digital technologies impact the interplay of actors, technologies, and institutions (Andersen et al., 2021). Here, effects on actors have been viewed in light of social (in)equality and actor empowerment, often with a focus on smart grids. Indeed, the use of 'smart' technologies can reinforce existing inequalities and forms of social exclusion (Sareen 2021), for instance, because the characteristics and requirements of ICT lead to unequal distributions of risks and benefits for local communities (Sovacool et al., 2022). Yet, actors also purposefully mobilise ICT which gives them agency to change the way existing technologies operate while providing them with opportunities to both stabilise and change institutional structures (van Summeren et al., 2021). Overall, the introduction of digital technologies into existing socio-technical energy systems brings about new roles and actor constellations (Erlinghagen and Markard 2012), which challenge the institutional settings of actors, leading them to actively pursue strategies for maintaining, creating, and disrupting institutions (Rohde and Hielscher 2021).

In sum, the studies reviewed above investigate how digitalisation affects actors, technologies, and institutions involved in pathways towards sustainable production and consumption – often in combination with an explicit emphasis on both intended and unintended ecological effects of digitalisation. Taken together, we notice a highly ambivalent role of digital technologies that is not detached from the complex socio-technical transitions happening in the energy sector. In this context, emerging bi-directional and multi-system approaches highlight not only how digital technologies transform sectoral structures but also how existing sectoral regimes shape digital innovation (John et al., 2022). Here, scholars call for further conceptual and empirical research on the co-evolution of digitalisation and sustainability transitions (Mouthaan et al., 2023; Andersen et al., 2021). Our paper responds to these calls by integrating insights from sustainability transition studies and Science and Technology Studies. It emphasises that digitalisation itself is deeply embedded in, and shaped by socio-technical system configurations.

On the one hand, our perspective on the interplay between digitalisation and sustainable energy transitions builds on information systems and organisation studies (Medaglia et al., 2022; Orlikowski 2010). It emphasises technology development as an emergent process involving dynamic interactions between (organisational) actors, institutional contexts, and socio-material artefacts, and seeks to portray "(…) how the particular interests and situated actions of multiple social groups shape[d] the designs, meanings and uses of new technologies over time" (Orlikowski 2010, p. 131). Studies from information systems research, therefore, acknowledge the organisational and institutional forces as well as exogenous contingencies, such as changes in regulations or industries, that influence digital technology development. Particularly in ICT- and AI-driven technological innovations, organisational actors determine and impact digitalisation processes while also being intertwined with the technological practices themselves (Barrett et al., 2012; Büchner 2018). Studies have also evaluated ex-post the actor constellations and power dynamics that surround ICT development and found that the particular rules, norms, and regulations embedded in the technology resemble those actors' interests and power relationships (Silva and Backhouse 2003; Backhouse et al., 2006; Medaglia et al., 2022).

On the other hand, the sustainability transition literature highlights how organisational actors play a crucial role in enacting couplings between digitalisation and sustainable energy transitions. This means that the activities of involved actors determine how digital technologies are designed and configured, and to what extent they reconfigure existing socio-technical systems (Mäkitie et al., 2023). As we discussed above, actors can purposively exploit digitalisation efforts to gain new forms of agency (van Summeren et al., 2021) while few powerful organisations can mobilise the potential of digital technologies to strengthen their incumbent positions in the system (Geels et al., 2021). Hence, the development and diffusion of digital technologies are assumed to be "driven by particular interests and the agency of incumbent actors" (Geels et al., 2021, p. 94), which may be impacted by actors' changing priorities (Mäkitie et al., 2023). This can ultimately determine how digital technologies are used to trigger change or induce stabilisation of the socio-technical system.

Taken together, insights from information systems and organisation studies constitute a fruitful rationale for our research perspective. Yet, at the same time, the sustainability transition literature highlights the development and implementation of digital technologies to be complex – and thus conceptually challenging: Not only heterogenous organisational actors at multiple levels and diverse institutional frameworks play a role in the development and implementation of digital technologies; also other existing technologies in the system as well as ecological boundaries shape these processes.

3. Conceptual framework: socio-technical-ecological scripts

Our framework situates the development and implementation of digital technologies *within* particular socio-technical-ecological configurations of transitions. We understand socio-technical-ecological configurations as the transition context in which digital technology development and implementation are embedded (Section 3.1). We introduce the concept of scripts as an analytical lens to trace how these socio-technical-ecological configurations manifest in digital technologies during processes of in-scription and de-scription (Section 3.2).

3.1. Socio-technical-ecological configurations

In transition studies, the development, diffusion and usage of technologies are understood through their entanglement with actors and institutions (Geels 2004; Markard et al., 2012). We, therefore, conceptualise technologies, actors, and institutions as heterogeneous elements that are closely linked to each other and that form socio-technical configurations (Geels 2002; 2018; Rip and Kemp 1998). Here, our work is based on a sociology of technology perspective, which also supports foundational research on sustainability transitions (Geels 2002; 2004): Technologies constitute 'configurations that work' (Rip and Kemp 1998), meaning an alignment of various elements that collectively fulfil a relevant societal function. Following this perspective, these configurations contextualise digital technology development: they both influence and are embedded in the technology. These manifestations of the socio-technical configurations in digital technology are then interpreted, negotiated, and modified by potential users based on their own embedding in the configurational setup.

So, how are these configurations made up? Technologies constitute "the structuring context for human action" (Geels 2004, p. 903). Thus, they are not neutral artefacts but impact actors' perceptions and activities. This means that the systemic characteristics of technologies in the energy sector can constrain or enable social practices (Svensson and Nikoleris 2018). At the same time, actors create, enact, and reproduce technological elements in their activities. Technologies are, therefore, understood as outcomes of societal negotiation and interaction processes (van Summeren et al., 2021; Pinch and Bijker 1984). Closely related is the idea that institutions –

in the form of rules, norms, or social practices – are embedded or inscribed in technologies during the development process (Akrich 1992; Hansen and Hauge 2017). Likewise, the durability and rigidity of technologies shape institutions in the form of social practices, norms, or regulations (Geels 2004). In this way, technological innovations have a 'reconfiguration capacity' (Fuenfschilling and Truffer 2016), as they challenge established practices and induce institutional change. However, technologies can also serve to maintain or stabilise socio-technical configurations when established institutions are embedded in technological artefacts (Andersson et al., 2018), leading to the manifestation of dominant regime structures.

For our conceptual framework, we expand the common notion of socio-technical configurations towards socio-technical-ecological configurations. We follow previous calls and efforts to consider ecological perspectives as an essential part of the socio-technical system (Foxon 2018; van der Jagt et al., 2020; Vermunt et al., 2020; Chlebna et al., 2023; Andersson et al., 2024; Andersen and Wicken 2021). Our decision to include ecological aspects is informed by recent developments in transition research. Scholars increasingly criticise transition studies for not explicitly accounting for interactions between socio-technical and ecological systems (Vermunt et al., 2020), which "so far, ha[ve] remained silent about 'nature' " (van der Jagt et al., 2020, p. 202). Traditionally, transition studies have implicitly considered environmental and ecological aspects. The assumption is that multi-actor and multi-level interactions in transition processes will ultimately lead to more sustainable technological innovations (sometimes labelled as 'green innovations'), which have the potential to overcome resource and ecological constraints (Dillman et al., 2023; Foxon 2018). Yet, this perspective suggests that transition studies need to explicitly consider whether and how innovations within transition processes reduce contemporary environmental pressures and how human activity affects planetary boundaries (Rockström et al., 2009). The transition literature, therefore, increasingly draws on notions of 'socio-ecological-technical systems' from related fields of socio-ecological systems (Markolf et al., 2018; McPhearson et al., 2022) to gain a better understanding of how the natural environment and ecological factors shape technological innovation (Ahlborg et al., 2019; Andersson et al., 2023) and transition dynamics (Vermunt et al., 2020). We build on these streams of literature and respond to calls for adopting socio-techno-ecological approaches to sustainability transitions (Andersson et al., 2024). We do so because, as discussed in Section 2, digitalisation brings ecological considerations to the forefront. Expectations surrounding digital technologies in the energy sector often relate to their potential to address ecological issues by enabling more energy and resource efficient solutions (Bergman and Foxon 2023) or facilitating new forms of sustainable production and consumption patterns (Mäkitie et al., 2023; Mäkitie et al., 2020). Building on the literature above, digital technology development is deeply intertwined with socio-technical-ecological configurations. Ecological factors impact the usability and persistence of knowledge in specific industry dynamics, shapes actor constellations and decision-making processes (Andersen and Wicken 2021). At the same time, institutions – in the form of natural rules and characteristics – are inscribed and realised in technological artefacts (Andersson et al., 2018). This implies that (digital) technologies can serve as instruments for shifting towards or maintaining ecological boundaries (van der Jagt et al., 2020). However, in practice, decisions regarding ecological exploitation in the course of digitalisation affect actors differently (Sovacool 2021; Sovacool et al., 2022). Technology can, thus, be viewed as mediating human-environment relationships as they reshape agency and redistribute sources of power (Ahlborg et al., 2019).

In the following section, we introduce the concept of scripts as an analytical lens to operationalise the role socio-technical-ecological configurations play in the development and implementation of digital technologies *within* ongoing sustainability transition dynamics.

3.2. Processes of in-scription and de-scription

The concept of scripts is closely linked to actor-network theory (Latour 1991) and describes how a variety of anticipations and visions regarding interests, values, and motives of future users are in-scribed into technological artefacts, and consequently shape technologies' use and practical application. In its original form, scripts attribute a crucial role to the designers of technologies:

> *"Designers thus define actors with specific tastes, competences, motives, aspirations, political prejudices, and the rest, and they assume that morality, technology, science, and economy will evolve in particular ways. A large part of the work of innovators is that of 'inscribing' this vision of (or prediction about) the world in the technical content of the new object." (Akrich 1992, p. 208)*

Much like a film script, Akrich's (1992) original conceptualisation denotes the accumulation of all the elements, considerations, and assumptions that are projected onto technologies during their development process. For our research purpose, we follow more recent empirical and transition-related studies that adopt scripts as an analytical method to study technology development processes as emergent and socio-technically embedded. These studies often highlight discrepancies between intended and actual design and usage of technologies (Hansen and Hauge 2017; Fatimah et al., 2015; Breukers et al., 2020). We develop a twofold operationalisation that builds on this notion of scripts to trace the recursive relationship between *processes of in-scription* and *de-scription* (Akrich 1992; Latour and Woolgar 1986; Hansen and Hauge 2017; Fatimah et al., 2015). *Processes of in-scription* refer to the complex social processes involved in the development of new technologies (Bijker and Law 1992; Pinch and Bijker 1984). *Processes of de-scription* pertain to aspects of technological implementation and cover how actors directly and indirectly affected by the new technology "respond to the technology's constraints and affordances, as well as to each other." (Leonardi and Barley 2010, p. 5). This notion of technological implementation covers actors' perceptions and interpretations of the technology's usefulness as well as processes of appropriation, i.e., the way in which users modify the technology by deviating from the designers' intended logics of how and where the technology is to be used. In this sense, scripts help operationalise the underlying notion of Rip and Kemp's (1998) 'configurations that work' by providing a lens to study the embeddedness of technology development and implementation. We now combine the concept of scripts with the socio-technical-ecological configurations elaborated in Section 3.1.

First, investigating *processes of in-scription* reveals developers' implicit and explicit assumptions about potential users and the

Table 1
Operationalising digital technology development and implementation within socio-technical-ecological configurations of transitions.

		In-scription Process in which developers anticipate needs of future users and fields of application for the digital technology.		**De-scription** Process in which various users interpret, negotiate and modify the digital technology.
Impact of socio-technical-ecological configurations	*Actors*	*Actors in the transition field that developers identify as potential users; actor constellations and conflicts that are sought to be mediated or altered by the digital technology*	*S C R I P T* *connecting in-scription and de-scription processes*	*Users that are directly or indirectly affected by the technology and actively interpret the usability and/or seek to modify the technology*
	Technology (technological context and interfaces)	*Expected technological and economic advancements due to the digital technology and expectations on optimization possibilities; interfaces with the digital technology*		*Issues, concerns or advocacy regarding the technological, economic feasibility and usability of the digital technology*
	Institutions	*Institutional arrangements that are embedded in/ compatible with the design and functionality of digital technology*		*Institutional arrangements that are endorsed, criticized or counteracted by users; new institutional settings that emerge through the digital technology*
	Ecology	*Ecological concerns related to the digital technology, reasons for including/excluding ecological considerations*		*Concerns or advocacy pointed towards the extent to which ecological concerns are incorporated by digital technology*

contextual environment in which the technology will be used (Jelsma 2003; Breukers et al., 2020). The socio-technical-ecological configurations of sustainable energy transitions, thus, form the context and the 'material substance' (Latour and Woolgar 1986) that is filtered by developers and in-scribed into the digital technology. Through this process, developers construct different societal, technological, institutional, and ecological issues as relevant. It acknowledges that designers' assumptions and choices do not exist in a vacuum but are significantly shaped by existing configurations of ongoing transition processes. Table 1 gives an overview of the operationalisation of the in-scription processes for digital technologies. Institutions – including existing standards, regulations or established forms of cooperation between actors in the energy sector – are considered by developers (Fatimah et al., 2015; Joerges 1999). Furthermore, actor constellations and existing power struggles between actors are often taken up and sought to be mediated or altered by the technology. For digital technologies that are developed to serve, improve or change the operation of 'generic', non-digital technologies (van Summeren et al., 2021; see also Section 2.1.), design choices are also impacted by considerations of the broader technological contexts – e.g., other existing technologies that the digital technology is meant to replace or integrate with (Sandén and Hillman 2011). Finally, the development process is impacted by the expected improvements or the potential to address and mediate ecological challenges. The elements decided upon in the in-scription process together form the script that is inserted into the digital technology and point to its resulting design and functionality. In the script, developers' choices are manifested in the form of concrete technological parameters and characteristics. It is, hence, the "material operation of inscribing" (Medaglia et al., 2022, p. 248; Latour and Woolgar 1986). This also acknowledges that not everything that is anticipated or pursued during the in-scription process can actually be realised and inscribed into the digital technology. Some visions may not be technically feasible, or trade-offs between ecological and technical concerns may arise.

Second, *processes of de-scription* refer to the role of users and their power in influencing the functionality of the digital technology (Akrich 1992). De-scription covers users' activities in interpreting the technology's functions, fields of application, and turning this interpretation into action (Fatimah et al., 2015). In sustainability transition contexts, this is compounded by the fact that digital technologies often do not only have conventional end-users but rather a diverse set of stakeholders that need to integrate the digital technology into their practices. These stakeholders may include policy-makers, grid operators, plant operators, consumers, local and national authorities, and civil society. Actors that are directly or indirectly affected by the digital technology actively interpret the usability, or seek to modify it. The script resulting from the in-scription process, thus, acts as a materialised connection and reference point between processes of in-scription and de-scription (see Table 1). Various user groups construct different ecological, institutional, or technical issues as relevant to their own frame of action. Users may have distinct perspectives on the technology compared to developers, which can result in divergences between 'designer logics' and 'user logics' (Breukers et al., 2020), and lead to under-utilisation, deviation, or modification of the technology (Fatimah et al., 2015; Breukers et al., 2020). For example, certain notions of control were in-scribed into the development of smart grid technologies by engineers and then de-scribed by citizens with alternative understandings of ‘control’, which ultimately shaped and redefined the technology’s usage (Hansen and Hauge 2017).

Our framework also accounts for how power and agency are constituted and reconfigured within and across processes of in-scription and de-scription. This aligns with recent contributions in Science and Technology Studies that propose to explicitly trace power and agency in scripts (Perret and Aradau 2024; Endter 2016). We build on existing conceptualisations in transitions and broadly refer to power as a social relation in which actors have varying capacities “to mobilize resources and institutions to achieve a goal” (Avelino 2017, p. 507). Following this notion, we account for the fact that actors involved in the development and/or implementation of a digital technology can mobilise different resources – ideas, concepts, practices, regulations, and technological artefacts – to influence the technological script. We, thus, view power as a key factor that inluences how and which elements of socio-technical-ecological configurations are in-scribed and de-scribed.

Processes of in-scription, the development of a script, and processes of de-scription are highly interactive and iterative (see Fig. 1). We follow Fatimah et al. (2015) in assuming that technology development and implementation within existing socio-technical systems involve *multiple* processes of in-scription and de-scription. Particularly in the development and pilot-testing phase of a technology, de-scription processes can trigger new in-scriptions. Additionally, user reactions (in de-scription processes) to technologies by early adopters may inform in-scription processes by subsequent developers. Also, the underlying socio-technical-ecological system itself is highly dynamic and configurations may shift over time. Therefore, an empirical analysis must iteratively move between designers’ intentions and anticipations and users’ interpretations and actions (Hansen and Hauge 2017). This is particularly relevant given digital technologies’ rapid evolution and deep integration into sectors which impacts existing socio-technical-ecological systems (Kitchin 2023; John et al., 2022).

4. Empirical illustration: automated bird detection and curtailment systems for wind power plants

We illustrate the applicability of our framework with a case study on a digital technology designed to be installed on or near onshore wind power plants with the aim of detecting avian species and curtailing wind turbines when protected birds are nearby and face imminent risk of collision. As outlined in more detail below, bird protection has been a significant obstacle to wind power expansion, and consequently, to the sustainable energy transition in Germany (Tucci 2022). Our analysis is based on a qualitative content analysis using 11 semi-structured interviews as well as related documents on the technology development and implementation process. Interview partners included technology developers of three innovating companies active on the German market that offer automated bird detection and curtailment systems, as well as actors from the wider wind energy field, including wind energy project planners and plant operators, government authorities, associations, and nature conservationists. The remainder of this section introduces the case background, the digital technology and lays out the methodological procedure. It then covers processes of in-scription and de-scription. The analytical dimensions (actors, technologies, institutions and ecological concerns) within processes of in-scription and de-scription are deeply intertwined. For clarity, each dimension is highlighted in bold to demonstrate consistency with our framework while we also tried our best to do justice to the complex dynamics of the case. Table 2 provides an overview of the main themes of the case covered by our framework.

4.1. *Case background and methodology*

Impacts of wind power plants on avian wildlife have been a controversial issue since the widespread diffusion of wind power in multiple countries worldwide (Sovacool 2012; Cohen et al., 2023; Katzner et al., 2019), including Germany (Grünkorn et al., 2016; Kiunke et al., 2022) – the focus of our case study. As various avian species, particularly birds of prey, are protected under EU and national law, potential collisions of birds with wind turbines are a critical factor in the permission process of wind power projects (Wulfert et al., 2022). The heated discussions surrounding this topic are intensified by scarce systematic data on bird fatalities (Grünkorn et al., 2016; Kuvlesky et al., 2007) as well as contestations over the effectiveness of available protection measures (Salomon et al., 2020; Reutter et al., 2024).

Amidst these complex socio-technical-ecological configurations, digital innovations have been increasingly gaining traction as a potential means to reconcile wind energy and nature conservation (Roddis 2018; McClure et al., 2021; BirdLife International, 2015). They are also discussed as a strategy to accelerate sustainable energy transitions by facilitating wind power expansion. Automated detection and curtailment systems are designed to reduce fatalities by i) detecting flight objects near wind power plants, ii) identifying protected avian species, and iii) temporarily curtailing turbines when birds are at risk of collision. A range of technologies is currently being developed for the German market; these differ significantly in both their development status and technological design (for a comprehensive overview, see KNE, 2022). An increasing number incorporate machine learning techniques, including deep learning and neural networks. The decision to curtail a turbine is based on algorithmic processing of various factors, including the bird’s proximity, flight path, and flight characteristics, as well as technical conditions such as the time span needed to slow down turbines into spinning mode (Ballester et al., 2024).

Through desk research, we identified core actors revolving around the automated detection and curtailment technologies: innovating companies, wind energy project planners and plant operators, governmental bodies, associations representing wind energy industry and nature conservation interests, and scientific institutes. We selected interview partners based on these insights and

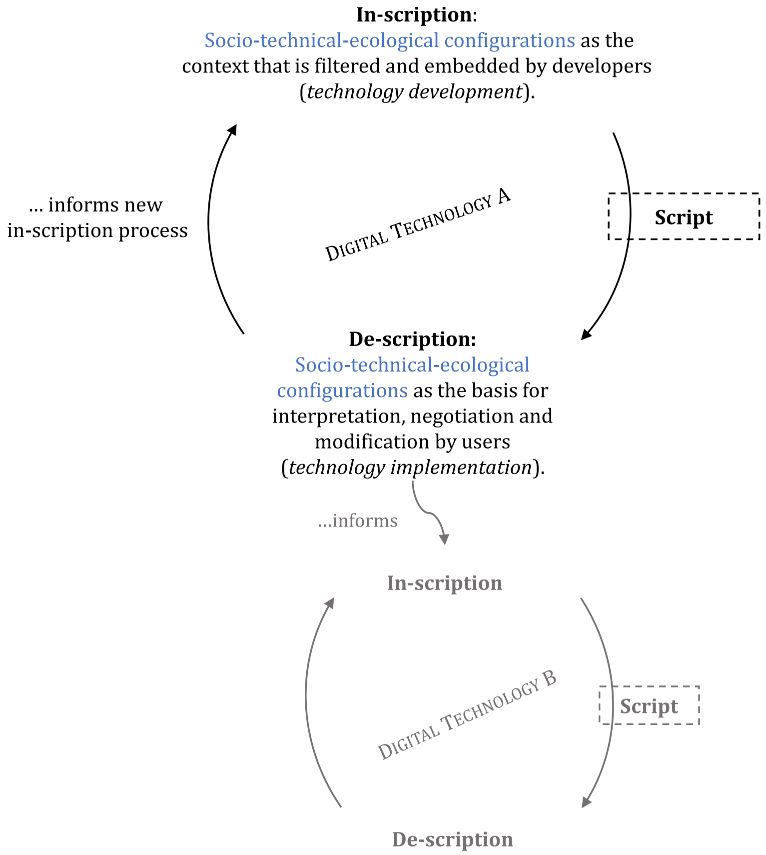

Fig. 1. Iterative processes of in-scription and de-scription.

employed the snowball sampling method, whereby interviewees suggested additional stakeholders. Given the exploratory nature of our research, we ensured that a diverse range of perspectives was covered[1]. We conducted all interviews in a semi-structured format. Our interview guide for the innovating companies covered questions about the anticipations and visions associated with the technologies' usability, possible users, field of application, and the resulting technological characteristics and parameters. The interview guide for all other interviewees focused on their perceptions, interpretations, and experiences with the digital technology. All interviews were audio-recorded, transcribed, and coded following the principles of qualitative content analysis using the software MAXQDA (Kuckartz and Rädiker 2023). We developed a coding scheme that we applied to all interview data and related documents, including policy briefs, association statements, and scientific reports. The coding scheme was primarily developed deductively based on our conceptual framework, but we also generated codes inductively to capture specific controversies within the case. The lead author and a research assistant co-coded the interview data. Throughout this process, discrepancies were systematically discussed, and codes refined to ensure high intercoder reliability. After coding all data, we cross-checked for coding overlaps to confirm that the codes were sufficiently distinct.

4.2. Processes of in-scription

The development process of the automated detection and curtailment systems has been shaped by a longstanding and seemingly irreconcilable relationship between the objectives and values of wind energy and species conservation actors. This has continually manifested in entrenched **actor** conflicts (Colell et al., 2022) and complex **institutional** arrangements (Wulfert et al., 2022). In Germany, wind power projects are subjected to significant legal checks and scientific assessments that evaluate the presence and potential impact on protected species near proposed plants. These regulatory and institutional frameworks frequently result in project delays, cancellations, or operational restrictions (Tucci 2022). Depending on the project site and the (expected and/or documented) presence of protected species, **ecological** considerations can lead to restrictions, including seasonal curtailments during the breeding

[1] Table A in the Appendix gives an overview of all interviews.

Table 2
Empirical illustration of our framework.

		In-scription Process in which developers anticipate needs of future users and fields of application for the digital technology.		**De-scription** Process in which various users interpret, negotiate and modify the digital technology.
Impact of socio-technical-ecological configurations	*Actors*	*Balancing the objectives and interests of conflicting actors including wind project developers, approval authorities, plant operators and conservationists* <u>*Result of in-scription*</u>*: Approval authorities considered as core customers as they are perceived to have the power of deciding upon the technologies' usability. Plant operators need to be on board*	*S C R I P T* *connecting in-scription and de-scription processes*	*Actors indirectly affected by the technology complicate implementation and usage* <u>*Result of de-scription*</u>*: Values and objectives of actors indirectly addressed by the technology clash with technology's script (maximising economic calculability of wind power plants vs ensuring species protection on a case-by-case level)*
	Technology (technological context and interfaces)	*Priority on the expected technological and economic advancements of wind power plants' operation due to targeted and selective shutdowns (as compared to generalised shutdowns during breeding season and agricultural works)* <u>*Result of in-scription*</u>*: Technology is optimised to minimise shutdowns by working towards a high detection rate of birds protected by law (as well as reductions of false-positive and false-negative curtailments)*		*The degree of interference with the operations of wind power plants and the resulting technological uncertainty remains unclear* <u>*Result of de-scription*</u>*: Missing empirical data on material fatigue of plants is demanded*
	Institutions	*Minding and adhering to existing regulations on species protection* <u>*Result of in-scription*</u>*: Technology is programmed to detect different target species, depending on the project site and the respective regulatory conditions*		*Contesting the strong embeddedness of the technologies in institutional regulations and emphasising its limits* <u>*Result of de-scription*</u>*: Vulnerability of technological implementation and usage to existing institutions*
	Ecology	*Addressing ecological challenges beyond existing regulatory limits* <u>*Result of in-scription*</u>*: Technology aims at protecting every individual bird, not aimed at the protection of species population as prior*		*Assessments of level of protection compared to other, existing and non-technical protection measures* <u>*Result of de-scription*</u>*: Other existing protection measures, like seasonal shutdowns appear back on the agenda for both wind industry actors and conservationists and are partly framed as superior*

season lasting several weeks, or curtailments in response to agricultural activities that attract birds near the plants. The tensions between those who interpret these restrictions as legitimate (Int6_Asso)[2] and those that consider them overly prohibitive (Int7_Wind; Int9_Wind) have been further intensified by inconsistencies in institutional regulations. Federal state guidelines and state-specific protection measures *"are quite different in each case (…) are often not detailed and elaborated, so that it can lead to lengthy negotiations with the authorisation authority."* (Int7_Wind). This challenge is further exacerbated by disputes over **ecological** concerns, particularly regarding when and under what conditions birds are actually at risk, as no quantifiable thresholds exist for assessing significantly increased risks for bird fatalities.

The development of automated detection and curtailment technologies has, thus, emerged as a response to these **institutional** obstacles, driven by the vision of mitigating regulatory hurdles while enabling wind power expansion. This vision has continuously served as the central rationale and starting point for **actors** involved in the technology development. It has been underpinned by the expectation that the digital technologies could *"render wind projects approvable"* (Int10_InnoC) while enhancing real-time and targeted species protection. Developers have perceived the technologies as a way to balance and unify both concerns (Int2_InnoA), fostering the prospect of a well-integrated socio-technical and ecological solution. To achieve this objective, aligning the digital technologies with existing socio-technical-ecological configurations has been recognised as a crucial requirement for ensuring its usability. Consequently, **institutional** arrangements have been continuously monitored and addressed throughout the technological development process:

> *"(…) this is government-related business in the form that authorities impose requirements and intervene deeply. The legislator makes the decision as to whether such an anti-collision system is bought or not. The customer won't buy it or not, so the requirement is coercive. (…) This is nothing new for us, but the decision-making processes were in the middle of the flow at the moment when we made our decision [to develop the technology], when Mr. Habeck and Mrs. Lemke [federal economics and environment ministers] overnight simply classified 13 bird species as endangered, for whatever reason." (Int8_InnoB)*

The technological development process has unfolded in parallel with ongoing changes in the socio-technical-ecological configurations. Developers have had to continuously adapt to these shifting conditions, as illustrated by the interviewee's account of how the programming team was subsequently instructed to design the technology to accommodate a wide range of target bird species, reflecting a parametrised approach in the script. The priority to align with **institutional** settings has also shaped how technology

[2] Codes denote the background of interviewees: Int_Sci (scientific institute); Int_InnoA/B/C (innovating company A/B/C); Int_Asso (association representing wind and/or nature conservation interests); Int_Gov (government authority); Int_Wind (wind project planning and operating firm).

developers have defined their technologies' core 'users': Authorities have been regarded as the most central **actors** in the configurations as they wield significant power in determining the technologies' applicability, possibilities and restrictions (Int2_InnoA; Int8_InnoB; Int10_InnoC). Also, by emphasising the technologies' embeddedness in existing institutional structures, innovating companies were able to avoid taking sides in the conflict between wind energy industry actors and nature conservation associations.

At the same time, the technologies have aimed to mediate these **actor** conflicts by embedding the interests and values of both camps into the technological script, see also Table 2. The automated detection and curtailment systems have been envisioned to significantly reduce shutdown times of wind power plants as compared to existing protection measures like seasonal curtailment or curtailment during agricultural works (Int1_Sci; Int2_InnoA; Int5_Gov; Int10_InnoC). Developers have based their assumptions on the estimation that selective and temporal shutdowns using these technologies would significantly lower wind power plants downtime because protected birds would only occasionally occur in the vicinity of plants (In8_InnoB; Int9_Wind; Int11_Sci). In the wind energy sector, plant downtimes can lead to significant economic losses. Thus, the digital technologies have been directly associated with both **economic and technological** progress in the wind power sector. Therefore, the technologies have been tweaked and optimised to minimise shutdowns while striving towards high detection rates of birds, simultaneously addressing **ecological** concerns.

However, as the legally required protective measures merely need to somewhat reduce a statistically increased risk of bird fatalities and do not need to protect every bird 100 per cent of the time (Int4_Asso), this **institutional** condition has influenced the technological development as well:

> *"At the reverse vending machine [for recyclable bottles], you as a customer expect 100 % of the bottle to be taken back, so a [detection] rate of 90 % is completely unacceptable (…) So now we have this detection and curtailment system and the first thing I was told is: 'No, we don't need 100 %'. Okay, why? 'Yes, it has been decided somewhere in some committees that there is no 100 %'. (…) which is of course a completely new situation." (Int8_InnoB)*

Our empirical data, thus, highlights the simultaneity of digital technology development (the in-scription process) and continuous reconfigurations of the existing socio-technical-ecological system. The need to couple the technological development with ongoing transition dynamics of the wind sector required developers to constantly monitor and update the technology based on current discourses and requirements (Int2_InnoA).

Ultimately, technology developers have had to navigate the challenge of developing a technologically optimised device while accommodating the interests of multiple **actors**. They have thereby aimed for a *"sweet spot"* (Int1_Sci) where the level of species protection is high and satisfies **ecological** concerns and existing **institutional** requirements while minimising economic burdens and **technological** uncertainties – specifically losses of revenues for wind project planners and operators. The parameters and characteristics have been in-scribed into the automated detection and curtailment systems accordingly. Yet, because these configurations needed to be transferred into concrete parameters of the digital technology – i.e., the script – the trade-off between ecological and economic/technical concerns has become particularly evident:

> *"(…) the anti-collision systems manufacturers, (..) some may not yet attach great importance to the technological side, they may prefer to switch off too much rather than too little, which is of course another economic factor. Every false-positive shutdown then costs money, which is not needed for species protection. You could say that this is great for every other bird that is protected. Of course, you can argue that. But then they would perhaps have worse conditions for future acceptance from the wind project developers' side." (Int1_Sci)*

4.3. Processes of de-scription

During the processes of de-scription, socio-technical-ecological configurations have formed the basis for various **actors** to interpret, negotiate and modify the automated detection and curtailment systems. This process has been closely interwoven with the processes of in-scription and started when the technological development of the automated detection and curtailment systems was still underway. Users' attention has been raised early on by several demonstration cases and research projects in which prototypes of the systems were involved. Furthermore, the novelty of the AI-based technologies and the high expectations associated with it arouse attention in the wind energy sector: "*Nobody was yet using the technology but everyone talked about it*" (Int7_Wind).

From the outset of the de-scription process, the technologies have had to demonstrate and prove their effectiveness compared to other, established protection measures, such as the establishment of designated protection areas or week-long shutdowns during breeding season. In the absence of any **institutionalised** criteria for assessing the technologies' effectiveness in detecting protected birds and curtailing plants, an association initiated the development of a standardised set of criteria. One involved **actor** pointed to the challenges of establishing what counts as effective without any "*empirical evidence yet*" (Int3_Asso). With the goal of legitimising their technologies for the German market, a handful of innovating companies undertook extensive performance tests ('Wirksamkeits-nachweis') following the established, preliminary criteria (Int3_Asso). The performance tests as well as the preceding processes aimed at achieving high performances can be interpreted as critical moments of negotiating the characteristics and functionality of the automated detection and curtailment systems. These processes have not only shaped the evolving understanding of the technologies but also led to concrete actions in terms of filling the **institutional** void, i.e., establishing practices on when and how to use the technologies. This highlights the relevance of adjusting usability conditions of the technologies to new requirements that emerge from the socio-technical-ecological configurations of ongoing transiton processes.

Despite the gradual increase in institutional clarity regarding the technologies' performance and functionality, controversies between involved **actors'** interpretations persisted and shifted over the course of the de-scription process. In the initial phases, wind project planners and operators viewed the technologies primarily as potential enablers and facilitators for securing approvals for wind energy projects (Int4_Asso; Int9_Wind). Over time, however, as discussions around the technologies intensified within the wind energy sector, they also voiced concerns related to the automated detection and curtailment systems' ability to interfere in the operations of the plants and the potential material fatigue of turbines **(technological context and interfaces)**. The empirical data illustrates how the focal points of discussion shifted: While initial discourse centred on the technologies' potential and enabling role when the first prototypes were installed and tested, economic and turbine-related concerns gradually gained prominence (Int1_Sci).

A major issue raised across industry **actors** has been the incalculability of shutdowns. This was mainly because curtailment induced by the digital technologies purely depends on the actual occurrence of protected birds near the power plants – without a quota to cap shutdowns per year. This has led banks – as core actors in the wind sector – to be hesitant or even reluctant to finance wind projects with a planned usage of automatic curtailment technologies as economic losses due to curtailments were difficult to calculate (Int1_Sci; Int4_Asso). As a consequence, generalised shutdowns during breeding season as alternative **ecological** protection measures have re-emerged as a feasible and more predictable measure on the agenda of project planners (Int7_Wind). The growing prominence of this issue also reveals underlying power dynamics: While innovating firms and environmentalists maintained that birds would most likely appear only occasionally – keeping shutdowns below the levels of generalised shutdowns (Int6_Asso; Int8_InnoB) – actors from the wind sector mobilised economic burdens and planning insecurity as influential resources to shift attention towards the technologies' reasonableness. This dynamic demonstrates how ecological elements embedded in the technological script have been consequently renegotiated during the de-scription process.

Interestingly, environmental associations and conservationists have also taken a rather hesitant stance; they have been rather concerned with the potential **institutional** scope that the digital technologies may unfold:

> "*And for the nature conservation side it was partly a sacrilege, [...] they [said] you are opening the gates to hell, [...] then there is no longer any reason to prohibit wind power plants, then you just attach a detection and curtailment system to it and declare it approvable.*" (Int3_Asso)

Furthermore, because the technologies' scripts have been deeply embedded in existing **institutional** settings, the technologies have been criticised for not protecting birds in general but only particular – legally defined – individual species:

> "*What if the technology is calibrated to protect red kites but then an eagle comes along and is struck (…) Other protection measures like designated protection areas are for all species, not just the ones that are protected by legislation requirements and thus covered [by the technology].*" (Int4_Asso)

Also uncertainties and disputes with regard to the significance of bird fatalities caused by wind power as well as the lack of comprehensive empirical evidence have been leveraged by several actors from the wind sector to interpret the digital technologies as unnecessary burdens for plant operators. This exercise of power, where actors have mobilised both ecological and economic uncertainties as core resources in the de-scription process, has led to severe insecurities among several innovating companies while some even scaled back their activities (Int3_Asso).

We, thus, observe discrepancies between the processes of in-scription and de-scription: The very way that has made the digital technologies effective and usable from the developers' perspective, and has been subsequently embedded in the technological script, has been re-interpreted by users who have been directly or indirectly affected by the digital technologies. Specifically, i) the reliable protection of birds (**ecological considerations**), which has been intended to be targeted and occurrence-based rather than generalised, has been interpreted as an economic and **technologically** incalculable risk; and ii) the short-term, temporal nature of plant curtailment, originally envisioned as a means to minimise economic losses, has been reframed as a **technological** uncertainty related to material fatigue.

In sum, these multiple, concurrent processes of de-scription illustrate the dynamic role of actors and their power in shaping the values associated with the technologies, as well as their applicability within existing socio-technical-ecological configurations. The case demonstrates the power of arguments emerging from the wind energy industry and associated institutions in potentially determining the applicability of the technologies: As concerns over incalculable curtailments have grown, both research (Int1_Sci; Int11_Sci) and industry (Int8_InnoB) have started to consider the introduction of caps or quotas to regulate the digital technologies' operations throughout a year. This, in turn, marks the emergence of a new in-scription process – one that actively incorporates these concerns into the technological development agenda (Int5_Gov; Int11_Sci).

5. Discussion and conclusion

Processes of digitalisation and processes of sustainable energy transitions are not separate developments but are deeply intertwined. While transition studies are starting to study the ambivalent role that digital technologies play in the progression of sustainable transition dynamics (Andersen et al., 2021; Mäkitie et al., 2023; Sareen and Haarstad 2021), there is still need to sharpen the conceptual understanding of the complex relationship between them (Mouthaan et al., 2023). Therefore, the core objective of this paper has been to disentangle the processes surrounding the development and implementation of digital technologies amidst ongoing transition processes. If we want to understand the conditions under which digital technologies can actually change, transform or reconfigure sustainability transitions (Hilty and Aebischer, 2015a; Townsend and Coroama 2018), we need to treat digital technologies as co-evolving with transition processes and, thus, as being shaped by the complex social, technical, institutional, and ecologic configurations of ongoing transitions.

The complexity of technology development and implementation processes, therefore, requires a conceptual embedding in transition dynamics. We, thus, combine the notion of scripts, a well-established concept for studying the mutual shaping of technology and society (Bijker and Law 1992; Akrich 1992; Latour and Woolgar 1986), with core concepts of transition studies. The resulting framework proposes a way to conceptually and empirically grasp how technology development and implementation are shaped by the peculiarities of transitions. While the original form of scripts places a strong emphasis on the role of actors – technology designers and users – and has been criticised for it (Verbeek 2011), our conceptual framework acknowledges how designers' and users' actions and interpretations are shaped and mediated by further elements, namely existing technologies, institutions and ecological elements. In line with existing studies (Fatimah et al., 2015; Jelsma 2003; Hansen and Hauge 2017), we thus expand the concept and its applicability to transition contexts. This follows a well-established tradition in transitions research as scripts and Science and Technology Studies have been constitutive for core transition concepts (Geels 2002; 2004). Given the increasing digitalisation and its entailed complexity, it is timely to further elaborate on their role and enhance our understanding of how actors, as well as related technologies, institutions and ecological considerations, determine and 'bring to life' couplings between sustainability transitions and digitalisation (Mäkitie et al., 2023; van Summeren et al., 2021).

The short empirical glimpses presented in this paper illustrate the applicability of our conceptual framework by showing how socio-technical-ecological configurations shape the development and implementation of automated bird detection and curtailment systems. The case demonstrates how concurrent socio-technical-ecological constellations are embedded in digital technologies: Technological requirements of wind power plants (compatibility of the digital technology with wind turbines; the need for economic planning security), institutional conditions (what counts as evidence for species harm; how is species protection regulated), and ecological considerations (how well are avian species protected as compared to using other protection measures) as well as the entrenched actor conflicts (incompatible motives and values of wind project developers, power plant operators, government authorities, and nature conservation associations) are all in-scribed into the technologies. The resulting scripts are not static, external entities but are instead interpreted, modified and applied in processes of de-scription: Users and other actors affected by the technologies evaluate and choose technological applications based on their respective socio-technical-ecological constellations. This results in a dynamic interplay between the development of digital technologies and the overall transition process. Our illustration demonstrates how automated detection and curtailment systems were initially considered an enabler for mediating between wind power expansion and species protection; yet, as part of the de-scription process, institutional efforts towards standardised performance tests and arguments mobilised regarding the technologies' economic viability have significantly hindered the usability of these technologies and consequently, its transformational capacity. Further conceptual and empirical research is needed to substantiate our framework as a fruitful approach for unravelling the relationship between digitalisation and sustainable energy transitions. In the following, we delineate four themes for future research.

a. Expanding the scope of technology development and implementation

A first potential enhancement of our conceptual framework relates to broadening the scope of technology development and implementation. In our framework, we apply a rather narrow focus and conceptualise digital technology development as a targeted endeavour within the energy sector, meaning we target digital technologies that are developed specifically for application in this field. While this certainly applies to many digital technologies in the energy sector – e.g. smart meters/grids or virtual power plants – a key characteristic of digital technologies is their broad applicability and flexibility (Mäkitie et al., 2023). Thus, it remains to be explored whether our framework needs to be conceptually enhanced to cover technologies like blockchain, which originated outside the energy sector and are influenced by different underlying values and objectives (Chen and Yu 2024). There is also scope for conceptual enhancements regarding the technology implementation phase. In our framework, processes of de-scription pertain to aspects of technological implementation and cover how actors directly and indirectly affected by the technology perceive and interpret the technologies' usefulness as well as processes of appropriations – i.e., the way in which users modify the technology by deviating from the designers' logics of how and where the technology is used. Yet, by definition, technological implementation also covers processes of 'enactment' – i.e., the way in which organisational practices emerge around the usage or non-usage of technologies – and 'alignment' – i.e., changing organisational structures due to technologies (Leonardi and Barley 2010). As this requires an organisational theory approach, it remains outside the scope of this paper, but presents a fruitful angle for future conceptual research anchored in transition studies. Empirically, more detailed case studies are necessary to refine the suggested framework and to further understand the processes of in-scription and de-scription. As the development and implementation of smart grids has been investigated through the lens of scripts in previous studies (Hansen and Hauge 2017; Breukers et al., 2020), it may be worthwhile applying our framework to such a well-studied technology. Evidently, it will be also vital to investigate cases of different technological applications and in different sectors.

b. Understanding the temporal dimension of in-scription and de-scription amidst sustainability transitions

As our conceptual framework embeds digital technology development and implementation within socio-technical-ecological configurations, it also relates to understanding how ongoing transition dynamics affect digitalisation efforts. While our empirical case has provided initial insights into how processes of in-scription and de-scription unfolded over time and interacted with changes in underlying socio-technical-ecological structures, further research is needed to explore their temporal dimensions in more depth. Specifically, further conceptual and empirical work can investigate how the continuous interaction between digital technologies and the transition process results in a reconfiguration or stabilisation of the existing socio-technical-ecological system. This means that when socio-technical-ecological configurations form the basis and are negotiated during processes of in-scription and de-scription, the eventual design and configuration of the technology can represent these configurations in different ways: It can reinforce the status quo and stabilise system configurations because the technology and its use manifest certain practices, actor constellations or technological monopolies in the system. Our empirical analysis provides some suggestions on how the technological regime 'wind power' in Germany along with its actors, technological and institutional structures and ecological traits restricted the applicability of the automated bird detection and curtailment systems by emphasising its technological uncertainty and economic burdens. At the same time, the technologies and its embedded script can also contribute to changing the system when new re-configurations are negotiated between designers and users. This implies that we essentially need to understand the mutual relationships between digital technology evolution and transition processes, and these involve concurrent dynamic feedback loops in both directions.

c. Power dynamics and digitalisation in sustainability transitions

The question of how digital technologies influence the agency of actor groups in transition processes (van Summeren et al., 2021), tackle social inequalities (Sareen 2021) or reinforce incumbent regime structures (Loock 2020) is increasingly becoming a central issue in the debate on digitalisation and sustainability transitions. Our framework addresses power dynamics and shifts in agency both during the development and the implementation of digital technologies. Our empirical illustration particularly shows how actors mobilise different resources to exert power during the process of de-scription as well as the resulting shift in agency between developers and 'users' of the technology. Still, a more systematic analysis of how power is constituted and distributed among those who are involved in technology development – i.e., during processes of in-scription – could enhance the framework's comprehensiveness and explanatory power. One approach would be to conceptually link the different resources used by actors to exercise power in social situations – e.g., ideas, beliefs, artefacts, natural and monetary resources (Avelino 2017) – to the core dimensions of our framework (actors, technology, institutions, ecological elements). This perspective would more strongly pronounce how digital technology development and implementation is not only shaped by the embedding socio-technical-ecological *systems*; it also emphasises how *agency* is constituted within and across these processes, for instance when actors strategically use resources of the socio-technical-ecological configurations. Taken together, addressing different forms of power could help unpack the broader implications of digitalisation for sustainability transitions (Sareen and Haarstad 2021). This could be done by investigating how actors contribute to manifesting existing institutions and structures within the technology or how they may instrumentalise digital technologies as new resources with the potential to alter existing agency and structures (Avelino 2017).

d. Transferability of the conceptual framework beyond digitalisation

The applicability of our framework to socio-technical-ecological configurations beyond digitalisation needs to be critically investigated. Given the widespread use of both the concept of scripts and socio-technical-ecological systems approaches, we believe the framework could be helpful for analysing various systems. This needs to be tested and validated with case studies addressing different technological, sectoral and geographical conditions. In line with Andersson et al. (2024), we propose to compare cases with varying relations to ecological concerns and dominance of existing technological regimes. For instance, while in our case ecological concerns (i.e., risks of bird strike) were mainly considered and addressed as side-effects of necessary technological developments (i.e., wind power expansion), other cases may feature them more explicitly as the core centre of attention. Depending on this, different elements of our framework will likely gain more prominence. A closer investigation could further advance our understanding of the role and significance ecological considerations play during (digital) technology development, and how these issues are being re-negotiated and modified during technology implementation. This can also help to identify trade-offs between ecological and technological and/ or institutional aspects in the script.

While the framework may well be applicable to contexts beyond the interplay between energy transitions and digitalisation, we believe that it continues to be particularly valuable for analysing the development and implementation of 'key enabling technologies' or 'general purpose technologies' (John et al., 2022; Bekar et al., 2018). Such technologies are characterised by a high degree of pervasiveness: While they may have originated in one field, they quickly spread to other sectors and are further developed and applied within ongoing transitions. They also show innovation complementarity, meaning they not only demand further technologies to function, but also themselves enable technological developments and involve unprecedented connectivity (Yoo et al., 2024). Given that the technological development and implementation of these technologies will likely have both beneficial and detrimental effects on sustainability transitions (John et al., 2022), our framework enables a structured analysis of these interdependencies and advances our understanding of 'twin transitions'.

CRediT authorship contribution statement

Ricarda Schmidt-Scheele: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – review & editing, Writing – original draft. **Jannika Mattes:** Writing – review & editing, Writing – original draft, Methodology, 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.

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Appendix A: Interviewees of the investigated case study

Table A: Interviews and background of the interviewees.

Background of interviewee	Interview conducted	Interview ID
Scientific institute	Onsite, Apr 2024	Int1_Sci
Innovating company A	Onsite, May 2024	Int2_InnoA
Association reconciling wind industry and nature conservation interests	Online, May 2024	Int3_Asso
Association representing wind industry	Online, May 2024	Int4_Asso
Federal ministry	Online, May 2024	Int5_Gov
Association representing nature conservation interests	Online, May 2024	Int6_Asso
Wind energy project planning and operating firm	Online, Jun 2024	Int7_Wind
Innovating company B	Online, Jun 2024	Int8_InnoB
Wind energy project planning and operating firm	Online, Jun 2024	Int9_Wind
Innovating company C	Online, Jun 2024	Int10_InnoC
Scientific institute	Online, Jun 2024	Int11_Sci

Data availability

The data that has been used is confidential.

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