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Digital innovation's contribution to sustainability transitions

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ABSTRACT

Digital innovation is increasingly mentioned as a potential key contributor to sustainability transitions. However, there has been little theoretical discussion of this topic. In this conceptual paper, the authors draw on literature on both sustainability transition studies and innovation studies to explore critically the contribution of digital innovation in sustainability transitions. They conceptualize transitions as fundamental changes in patterns of production and consumption, such as those relating to energy. Radical innovation leads to changes in the structure of socio-technical systems underlying such patterns, while incremental innovation contributes to maintaining the structure and current patterns. The authors suggest that digital innovations may contribute positively to sustainability transitions through couplings with sustainable innovations. They propose the following typology of such couplings: incremental twin innovations, sustainability supported digital innovations, digitally supported sustainable innovations, and radical twin innovations. Radical twin innovations may possess the greatest potential for sustainability transitions, as they are linked to structural change and thus open new pathways for sustainability transitions, whereas incremental twin innovations merely optimize current unsustainable systems. The typology is illustrated with examples from shipping and from electricity systems, and some of the complexities of twin transitions encountered by researchers and practitioners alike are discussed.

1. Introduction

Couplings between digitalization and sustainability transitions are emerging as a notable topic in socio-technical transitions research [1–4]. Moreover, policymakers, industry actors, and researchers alike have articulated expectations that digitalization may contribute to sustainability transitions [5] – what has been named as twin transitions. For example, an EU Ministerial Declaration states that 'smart use of clean digital technologies can serve as a key enabler for climate action, environmental sustainability, and reaching the UN Sustainable Development Goals' [6].

However, there is still a striking lack of conceptual clarity concerning the content and dynamics of twin transitions, and more generally how digital technologies may contribute to sustainability transitions. Commonly, authors who have adopted the use of the concept of twin transitions have merely pointed to a connection between digitalization and sustainability [7–9]. Therefore, it is necessary to explore further the underlying conceptual assumptions about twin transitions.

It is increasingly clear that not all digital innovations contribute to increased sustainability. For example, data centres produce large amounts of carbon emissions and have significant water and land footprints [10], and emissions generated by the use of cryptocurrencies are notable [11]. Moreover, the effect of digital innovations in mobility (e.g. automated vehicles) on energy demand depends on how such innovations are used [12]. Similar observations have been made in the case of e-materialization, such as e-publications and e-music in comparisons with physical books and records [13]. Thus, the sustainability of digital technologies is dependent on how actors use the technologies to satisfy their social needs. Additionally, the uptake of digital technologies may entrench existing social inequalities [14,15]. Therefore, we need more knowledge about when, how, and in what situations digital innovations may contribute to sustainability transitions.

Moreover, it is necessary to discuss further the concept of sustainability and/or green transitions in the context of twin transitions. In the literature, sustainability transitions [16] are seen as fundamental changes in the patterns of production and consumption of socio-technical systems, such as those relating to energy [17]. With this systemic perspective on transitions, it becomes clearer that the potential sustainability effects of digital innovations (e.g. for optimizing current production and consumption patterns, some of which are inherently unsustainable) do not necessarily drive sustainability *transitions* (i.e. reconfiguration of the structure of socio-technical systems towards

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sustainability) [18,19]. Nevertheless, there is a need for such structural changes, for example to meet the Paris Agreement goal of limiting global warming to 1.5 °C. While digital innovations that merely increase the efficiency of current industrial processes based on fossil fuels [20] can reduce emissions to some extent, they are insufficient for net-zero carbon emissions to be achieved by 2050. Therefore, it is necessary to explore further the role of digital innovations in creating structural change towards sustainability in socio-technical systems.

In this paper, we seek to strengthen the theoretical understanding of the issues highlighted above. We contribute to the literature on sustainability transitions and twin transitions [1,2,16,18] by proposing a typology of couplings between digital innovation and sustainable innovation, and how such couplings may contribute to sustainability transitions. In so doing, we draw on the concept of incremental and radical innovation in the innovation studies literature [21,22] and on the concept of socio-technical system change in the sustainability transitions literature [17,23]. We understand incremental innovations as innovations that optimize current system configurations and production and consumption patterns [24], while radical innovations lead to reconfigurations of the structure of socio-technical systems [21,22]. Thus, only radical innovations have the potential to create the substantial structural changes in production and consumption patterns necessary to reach urgent sustainability goals. We aim to provide a conceptualization that allows for critical examination of the potential positive interactions between digital innovation and sustainability transitions. We do not undertake a general exploration of the relationship between digital technologies and sustainability (see e.g. Ref. [25], but instead we focus on digital innovation's potential or lack or potential to contribute to structural change towards sustainability in socio-technical systems.

We understand digital innovation as the development, deployment, and use of electronic systems, devices, tools, and resources that generate, store, and process data [26]. We consider digitalization as follows:

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 [27].: 6).

Yoo et al.'s definition of digitalization highlights how transformation is contingent upon the extent to which digitized artifacts can contribute to socio-technical change. In other words, digital innovations may differ in their capacity to transform socio-technical systems. While incremental innovation may lead to digitization and efficiency gains, radical innovation may contribute to a broader digitalization: reconfiguring the structure and practices of socio-technical systems [28,29]. At the same time, it is not given that digital innovation will contribute to structural change towards sustainability; rather it will merely increase digitization or digitalization.

In this paper, we argue that digital innovations may contribute to sustainability transitions through couplings with sustainable innovation. To explore this topic of couplings between radical and incremental sustainable and digital innovations, we draw on examples from energy transitions. Our research question is: *How do incremental and radical digital innovations differ in the way they couple with sustainable innovations and contribute to sustainability transitions?*

The paper proceeds as follows. Section 2 reviews existing perspectives on socio-technical change in sustainability transitions and presents the concepts of incremental and radical innovation. The latter concepts are discussed with reference to existing literature on digital innovations. Section 3 synthesizes the insights into a typology of couplings between incremental and radical digital and sustainable innovation. Section 4 illustrates the typology with examples of innovations in shipping and electricity systems. Section 5 discusses some of the complexities related to the role of digital innovation in sustainability transitions, and finally, our conclusions are presented in Section 6.

2. Perspectives on digital innovation in sustainability transitions

2.1. Socio-technical system transitions

As suggested by the definitions presented in Section 1, both sustainability transitions and digitalization point to structural changes in the patterns of production and consumption of socio-technical systems, albeit in different, yet parallel, dimensions [17,30]. Researchers have used multilevel perspectives in their theorizing and analyses of socio-technical systems change [23] in sustainability transitions studies [17,31].

Socio-technical systems consist of networks of actors, institutions, and technologies that, through their interlinkages, fulfil the function of the system, such as supply and use of energy, transport, and food. The prevailing configurations of these elements form the structure of socio-technical systems that underlie the established patterns of production and consumption (e.g. supply and use of fossil fuels in the energy system) [32]. The structural elements and prevailing production and consumption patterns are reproduced and enacted by actors [33]. Key actors in a system include companies, public authorities, users, social movements, and research organizations, each with their interests and preferences, and they are coupled together through various types of dependencies and interactions [32,34,35]. Institutions include prevailing regulations, norms, values, and cognitions of socio-technical systems [32,36]. Technologies are the artifacts, knowledge, and infrastructure used to fulfil the system's function. Together, the prevailing configurations of these structural elements favour certain types of production and consumption patterns (e.g. mobility through privately owned and petroleum-fuelled private cars), while they may hinder other patterns unsuited to them (e.g. shared hydrogen vehicles) [32]. Since the structural elements of socio-technical systems are interdependent, it is challenging to change individual elements.

The socio-technical systems and their structure are dynamically stable, meaning that they usually undergo only minor changes and adjustments. They typically evolve over many decades into stable structural configurations of prevailing actors, institutions, and technologies. These configurations are strengthened and solidified by incremental and path-dependent improvements. However, the systems may occasionally experience periods of reconfiguration and fundamental change. Historical examples of such transitions are the transition from sailing ships to steamships [23] and from horse-drawn carriages to automobiles [37]. Such processes of socio-technical system reconfigurations can be understood through interactions between three analytical levels: regime, niche, and landscape [23,38]. The stability of the socio-technical system structure is upheld by the regime, 'the semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce' the prevailing structural configurations [39]: 27). This stability is upheld by lock-ins, such as techno-economic, cognitive, and institutional lock-ins [40]. However, the regime may be destabilized by increasing pressure from the landscape: the wider context of socio-technical systems, consisting of, for example, demographic, political, and macro-economic patterns, as well as the material and technical framework conditions for the system. Changing conditions and external events at the landscape level (e.g. public demand for climate-change related action, wars, pandemics) may put pressure on the prevailing regime for change if the current configuration of the socio-technical system is unsuited to the new conditions (e.g. due to the increasing importance of energy security). Such pressures may open windows of opportunities for radical innovations that until now have not fitted with the prevailing socio-technical configuration. Such radical innovations are developed and matured in niche spaces (e.g. living labs and small market niches), 'where users have special demands and are willing to support emerging innovations' [39]: 27). Thus, niches provide protective spaces outside mainstream selection environments [41]. If radical innovations are sufficiently mature when a window of opportunity opens up, they may break into the mainstream through the agency of actors and over time lead to a reconfiguration of the socio-technical structure [39].

The above-described process suggests that innovations differ in how they affect socio-technical transitions. In the following sections (2.2 and 2.3), we discuss the incremental and radical modes of innovation [21,22,42].

2.2. Incremental innovation

Incremental innovation enhances the performance and value of technologies. It maintains current knowledge and competencies, and it mitigates problems in prevailing technologies, for example by improving energy efficiency and design. Such changes make current technologies and practices more attractive, consequently raising barriers for alternative technologies [21,42]. For incumbent actors, incremental innovations involve relatively limited risk, in the sense that they mainly sustain and improve the current technologies and solutions of socio-technical systems, rather than leading to the implementation of entirely new technologies [22,29,43]. Therefore, incremental innovation can be seen as optimizing current system configurations [24].

In the context of energy transitions, incremental sustainable innovations can be related to energy efficiency, such as improved insulation of houses and reduced fuel consumption of cars. However, mere efficiency improvement does not end current energy systems' high reliance on fossil fuel based patterns of supply and use. With regard to digital technologies, incremental digital innovations can be seen as minor improvements to current socio-technical systems (e.g. new design, add-ons and new features of existing digital tools), as well as digitization of physical processes and products (e.g. digital command, information and control tools). Such digital innovations optimize the current configurations of actors, institutions, and technologies in socio-technical systems (Fig. 1). An example of such optimization is smart heating control [44], which may contribute to reduced energy consumption through better control of living space heating, but does not involve a broader change in the heating system (e.g. how and by whom heat is produced).

2.3. Radical innovation

Radical innovation enables change that is more fundamental. Radical innovation disrupts patterns of production and consumption, and it may render existing technologies and practices obsolete [42]. The 'creative destruction' of radical innovations gives rise to the need for new knowledge and competences, and may lead to the formation of new industries and actors [45]. In other words, rather than optimizing the existing structure, radical innovations lead to reconfigurations of socio-technical systems [21,22], also described as systemic transitions towards fundamentally new patterns of production and consumption [24]. Such radical innovations are characterized by uncertainty, including competition with other emerging innovations (e.g. hydrogen versus electric vehicles), novel technology's poor economic performance in the early phase of innovation, and cognitive and social uncertainties (e.g. acceptance) [46].

Thus, radical innovation is linked to institutional change, novel collaboration patterns, and the entry of new actors and reorientation of established actors [47,48]. Long periods of mismatch between new technologies and established socio-technical structures, such as institutions, can be expected [49]. Moreover, such 'competence destroying' innovations may put pressure on incumbent firms [50], as well as on established sectors and their associated socio-technical systems [32]. However, incumbents may take proactive roles [35,51,52], and lead in the development of discontinuous technologies through 'creative accumulation' [53]. For instance, digital incumbents that use smart grid technology have brought in enormous resources that can make significant differences to further development and alter sector structures [54].

Radical innovation depends on actors in terms of both development and adoption. Also, the substantial degree of change makes radical innovation challenging for actors because it differs from 'normal' incremental innovation and routines [55] and rather requires innovation processes such as second-order learning, articulation of expectations and visions, and building of new social networks [56]. Radical innovations are often associated with large investments and risks, and are inherently linked to resistance and scepticism, possibly due to users having limited understanding of their benefits [57]. Consequently, firms that have well-developed innovation capabilities in existing markets are still challenged when attempting to pursue unfamiliar new markets or the use of new technologies [58,59]. Uncertainties related to radical innovation grow in the presence of multiple competing radical innovations

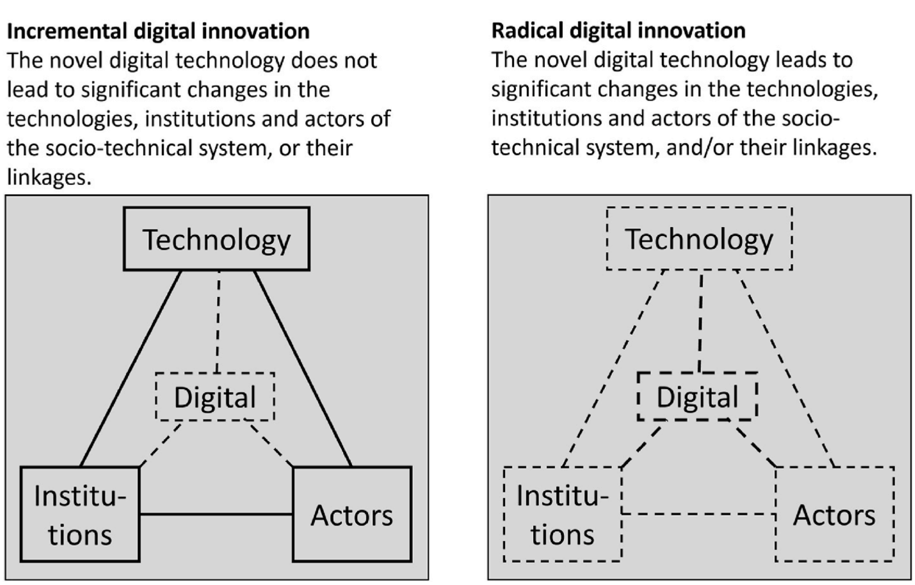

Fig. 1. Radical and incremental digital innovation in socio-technical systems change. Dashed lines indicate structural change, solid lines indicate unchanged structure.

[60]. Such situations may lead to waiting games, which in turn slow down innovation [61]. Risks and uncertainties are exacerbated by possible failures in developing or commercializing radical innovations [62,63]. Radical innovation may thus face a variety of barriers, originating both at the actor level (e.g. insufficient resources, lack of competences, internal resistance to radical innovations, conservative decision-making) and in actors' environment (e.g. customer resistance, competitors, lack of public support and financing) [62].

It is important to note that a given innovation's radicalness is context-dependent: innovations can be radical in one context, but not in others [48]. This is influenced by how actors empower innovations, either to 'fit-and-conform' with the existing socio-technical structures and practices or to 'stretch-and-transform' them [41,64]. In other words, actors may use innovations to maintain socio-technical structures or to reconfigure them. Agency is thus of central importance for driving both innovation and transition processes [33]. Therefore, determining whether a given innovation is radical or incremental is an empirical task.

In sustainability transitions, radical sustainable innovations (e.g. renewable energy technologies and electric vehicles) cause changes to the prevailing actor networks, institutions, and technologies of socio-technical systems. They enable decarbonization by causing a change in the regime of energy systems from fossil fuels to renewable energy. However, such processes face several systemic barriers, including carbon lock-in Ref. [65] and resistance from incumbent actors such as fossil fuel producers [66,67].

In the context of digitalization, examples of potentially radical digital innovations are digital platforms (e.g. Facebook, AirBnB, Uber) [68,69], sharing economy platforms [70], autonomous systems (e.g. self-driving cars) [71,72], and blockchains (e.g. Bitcoin) [73]. Such innovations may shake the prevailing ways of doing things, for example in hospitality, transport, energy, and financial systems [30] (see Fig. 1).

Finally, radical innovation may provide novel linkages *between* socio-technical systems [28] and can thus spur change both within systems (Fig. 1) and across systems (Fig. 2). Unlike incremental innovations, radical digital innovation enables novel ways of coupling socio-technical systems. For example, blockchain technology may enable peer-to-peer trading within energy communities, thereby integrating the production, distribution, and use of electricity in new ways [73]. In the electricity sector, digital technologies may reduce the need for non-local centralized physical infrastructure and thereby create new opportunities for distribution organizations, including improved local control and decentralized electricity generation [74]. Lastly, digital platforms may reorganize production networks [75], for example towards production and consumption systems that seek to eliminate waste (i.e. a circular economy) [76]. Digital platforms may act as 'circularity brokers' that establish connections between waste generators and potential receivers of waste, thus enabling the recovery of waste back to production processes or to consumption. In the case of food waste, digital platforms may lower barriers for higher circularity, for example by connecting organizations with food surpluses with those willing to take the surpluses [77].

3. Typology: couplings between sustainable and digital innovation

In this section we use the modes of innovation presented in Section 2 to conceptualize how digital innovation may couple with sustainable innovation and contribute to sustainability transitions. Fig. 3 shows our proposed typology of four ways that digital innovation may couple with sustainable innovation in the context of sustainability transitions: incremental twin innovation, digitally supported sustainable innovation, sustainability supported digital innovation, and radical twin innovation.

Incremental twin innovation, meaning the couplings between incremental digital innovation and incremental sustainable innovation, is the least transformative digital innovation in the context of sustainability transitions. These are innovations that do not cause fundamental change, towards either more sustainable patterns or to digital patterns, but rather strengthen, improve, and adapt the existing structural configurations of socio-technical systems against pressures such as those posed by climate change concerns. They may improve the sustainability effect of existing production and consumption patterns with the help of digital means, for example by increasing efficiency. However, even though an incremental twin innovation may have sustainability effects in the short term, they may work against a sustainability *transition* by making existing patterns (i.e. fundamentally unsustainable patterns) of production and consumption more resilient to pressures, therefore raising the bar for more radical innovations to outcompete them [21,24,42]. An example of incremental twin innovation is optimization of existing industrial production processes through, for example, machine learning or artificial intelligence, potentially leading to reduced costs and environmental footprint per produced goods [20].

Digitally supported *sustainable innovations* are those innovations that cause structural reconfiguration towards more sustainable patterns of production and consumption but do not lead to major changes in digital patterns. As general-purpose technologies, digital technologies (both hardware and software) are essential for most contemporary technologies, such as renewable energy technologies, and electric vehicles. Incremental digital innovations thus enable the basic functioning (e.g. through digitization) of sustainable technologies, but do not directly cause significant changes to socio-technical systems. For example, digital innovation can help to improve solar tracking systems that enable solar photovoltaics (PV) installations to follow movements of the sun, which in turn increases efficiency and electricity generation from PV [78]. Such digital innovation thus enhances the functionality of a radical sustainable innovation (solar PV).

Sustainability supported *digital innovation* refers to radical digital innovations that do not foster structural change towards more sustainable structural configurations but do lead to structural change towards digital patterns. This type of innovation may thus cause a socio-technical transition whereby digital innovations reconfigure the system structure, while also potentially having some positive environmental effects (through incremental sustainable innovation). Such effects can be highlighted by actors to frame also digital innovations as sustainable, seeking to increase their legitimacy. However, once again, the incremental sustainability innovation does not lead to a sustainability *transition*. For example, some of the sharing economy platforms, such as AirBnB and Uber, were originally seen to promote economic, social, and environmental sustainability, while in reality they have not led to more sustainable structural reconfigurations, but have instead led platform corporations to become digital giants [79–81]. In other words, arguments regarding potential sustainability benefits may be used to support the digital innovation, yet the impact in terms of socio-technical reconfigurations towards more sustainable production and consumption patterns remains limited.

Radical twin innovations lead to structural reconfigurations towards more sustainable *and* digital patterns of production and consumption. They are couplings between digital and sustainable innovations that are particularly interesting from the perspective of sustainability transitions, and indeed, twin transitions. This is because radical digital innovation may enable new kinds of socio-technical change that radical sustainable innovation alone cannot produce. In other words, when coupled with sustainable innovation, radical digital innovation may open new pathways for sustainability transitions through means of digital system reconfiguration. For example, blockchain may enable peer-to-peer trading in community-based initiatives, and thus enrol broader sets of actors in the energy transition [82]. Such digitally enabled energy communities are an alternative to, for example, centralized power production controlled by large utilities [54].

Such alternative pathways caused by radical twin innovation can be particularly visible when analysing sustainability transitions as multi-system phenomena. Besides being linked to reconfigurations within a socio-technical system, digital technologies may also lead to changes in

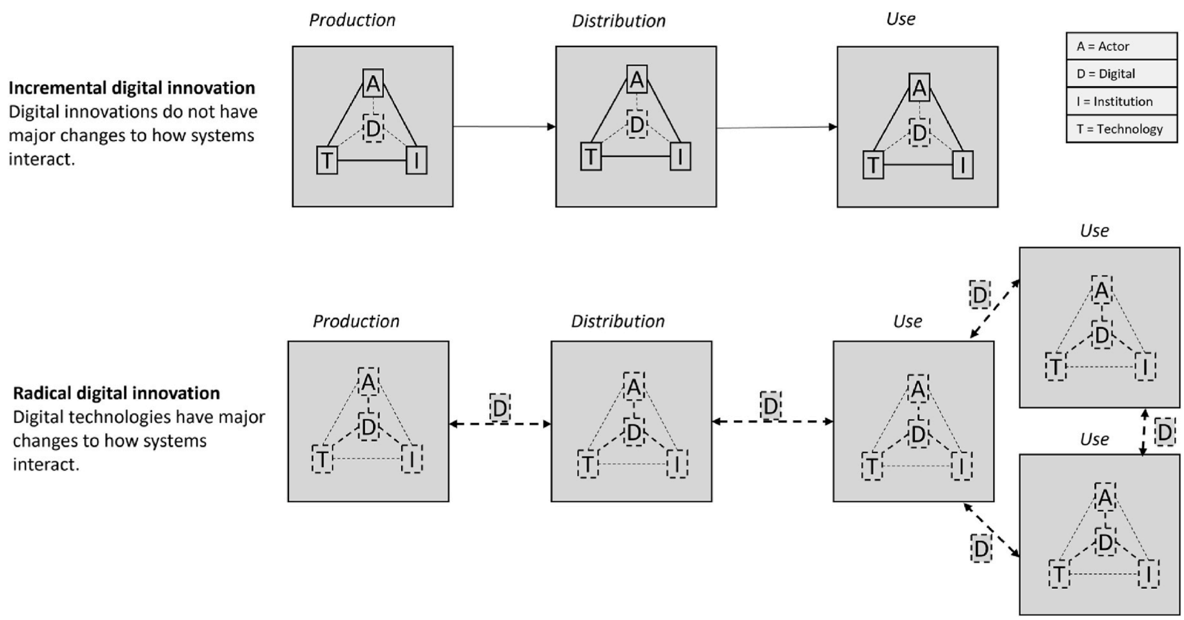

Fig. 2. Incremental and radical digital innovation and interaction between socio-technical systems. Dashed lines indicate substantial changes in structural elements and interactions, solid lines indicate unchanged ones.

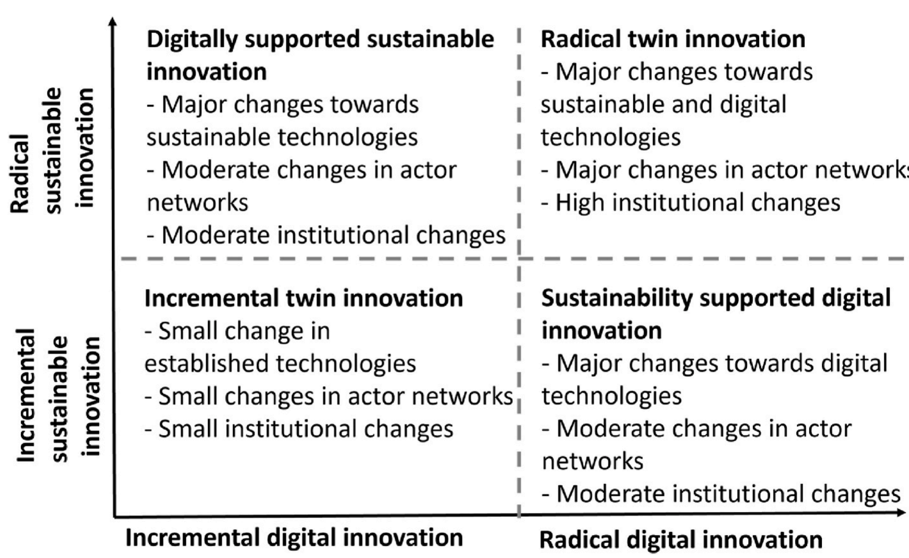

Fig. 3. Couplings between incremental and radical sustainable and digital innovation in sustainability transitions.

interactions between systems, such as transport, energy, and housing. For example, digital technologies such as blockchain, Internet of Things, and digital platforms may facilitate the creation and enhancement of novel circular supply chains between, for example, waste management and manufacturing [83–85].

4. Empirical illustrations: emerging energy transitions in shipping and electricity systems

We illustrate the typology proposed in Section 3 by using emerging innovations in shipping and electricity as examples of possible different types of couplings between radical and incremental sustainable and digital innovation (Figs. 4 and 5).[1]

Shipping is one of the most energy-efficient modes of freight transportation and is the backbone of international trade [86]. However, it is

[1] As the radicalness of innovation is dependent on agency over time, it is not possible to determine fully whether or not the emerging innovations will actually create the structural change necessary for socio-technical transitions. The examples in this section are thus illustrative in nature, based on current expectations of their potential. Their actual degree of radicalness remains an empirical research topic for future studies.

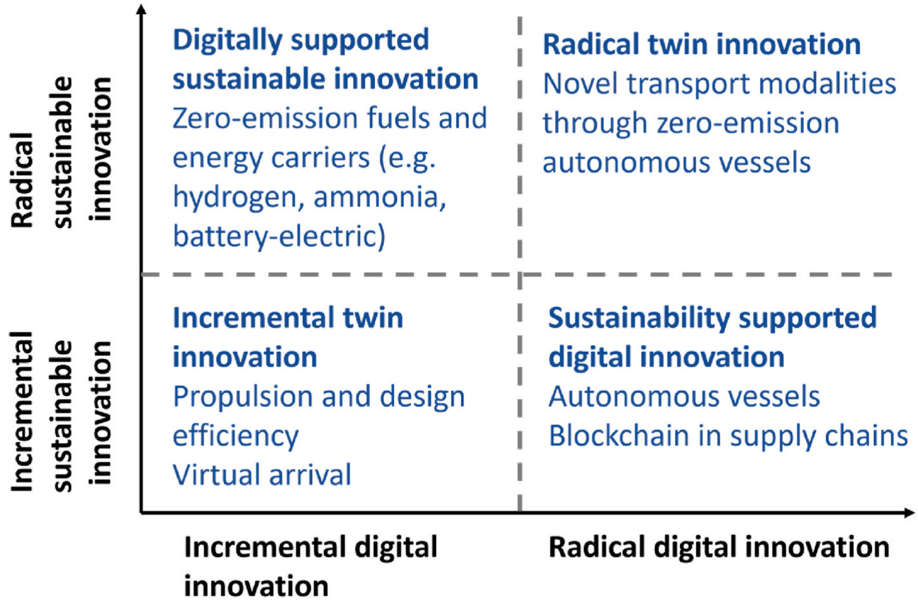

Fig. 4. Examples of couplings between digital and sustainable innovations in the shipping sector.

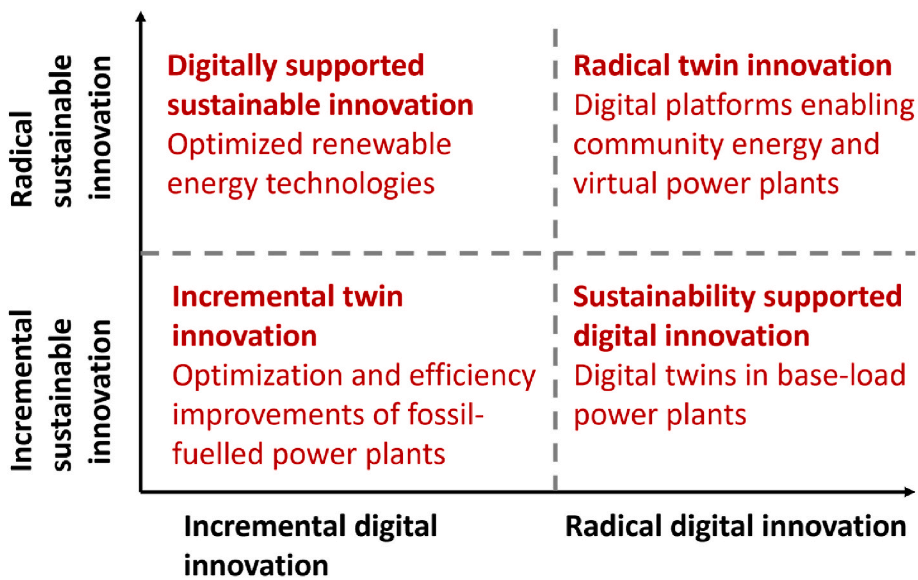

Fig. 5. Examples of couplings between digital and sustainable innovations in the electricity sector.

heavily dependent on fossil fuels and is under growing pressure to decarbonize [87,88]. Globally, the shipping industry accounts for approximately 3% of total emissions, and the International Maritime Organization (IMO) has set out a pathway to decrease CO_2 emissions per transport work (carbon intensity) by at least 40% by 2030 and total annual GHG emissions by at least 50% by 2050, compared with 2008 [89].

In the meantime, electricity and heat production are the biggest cause of carbon pollution worldwide. However, a transition towards renewable energy is emerging with technologies such as wind power and solar PV. The electricity transition is thus moving from the development of renewable energy technologies to a new phase of rapid deployment. This raises novel challenges, such as the need to handle the intermittency of renewable energy by means of distribution and transmission (e.g. smart grids and demand-side management) and energy conversion (e.g. power-to-X) [90].

4.1. *Incremental twin innovation*

Shipping is a 'hard-to-adopt' sector in which sustainable innovation has until recently been incremental in nature and focusing on, for example, energy efficiency [91] and virtual arrival [92,93]. Incremental improvements in ship design and equipment have been promoted by regulations, with the IMO's Energy Efficiency Design Index (IDEE) and Ship Energy Efficiency Management Plan (SEEMP). Incremental energy efficiency is partly enabled by novel digital technologies, such as sensors that measure vessel performance, as well as data analytics that can be used for optimizing, for example, vessel design, performance, virtual arrival, and route selection [20,94–96]. They are thus examples of coupled incremental sustainable and digital innovation, without major changes to the structure of the shipping system. While energy efficiency innovations and related regulations reduce emissions to some extent, they do not make substantial changes to the structure of shipping based on combustion of fossil fuels, such as heavy fuel oil, marine gas oil, and marine diesel oil.

In the electricity sector, digitization of generation assets represents a further example of incremental digital and environmental innovation. Sensors and supporting software are widely available and can provide data and analytics to support and improve operations in power plants, and thereby help to reduce costs. For example, sensors may provide real-time information on the state of components, as well as input flows such as those relating to fuel. Data and analytics then provide opportunities for reduced operation and maintenance costs, thereby minimizing outages and increasing efficiency. Optimization of fuel use is associated with efficiency gains in terms of less fuel consumption and emission reductions per unit of output, for example in coal plants [97,98].

When incremental digital innovations are used in existing assets, it cannot be expected that they will radically change system structures, but rather they will serve to solidify and increase performance, much like the sailing ship effect, in which improvements contribute to maintain an existing socio-technical system [23]. Concerns have been raised about how incremental improvements, such as increased efficiencies and reduced costs in fossil generation assets, make them more competitive vis-à-vis renewable energy [97], which may slow down sustainability transitions.

4.2. Digitally supported sustainable innovation

In terms of radical sustainable innovations, zero-emission fuels and energy carriers such as ammonia, hydrogen, biofuels, and electrification offer opportunities for significant emission reductions in shipping. The introduction of such low and zero-emission fuels are still in its infancy, as there are several barriers to overcome [87,99]. However, electrification of vessels (mostly hybrids) has emerged in recent years in some shipping segments, such as passenger vessels, but due to the short range resulting from the use of batteries, electrification is mainly limited to short-distance vessels and hybrids. As radical innovations, zero-carbon technologies require significant reconfigurations of infrastructure (production and bunkering of novel fuels, shore power connectors), technologies (new propulsion systems), institutions (expectations, regulations, standardization), and actors (new technology suppliers), both in shipping itself and in the technology value chains of new fuels [100,101]. Hence, their adoption by shipowners is only just emerging [102,103]. As with other novel contemporary technologies, digital technologies are of central importance for the development and functioning of zero-carbon technologies, such as in redesigning and reoptimizing vessels and propulsion systems to match the requirements of novel energy sources. For example, with electric propulsion of vessels, digital technologies can optimize the performance of ‘smart’ energy storage, allowing for closer to optimal use of energy [104]. Moreover, new wind-assisted propulsion systems, such as the ECO FLETTNER rotor, coupled with various sensors and data analytics for gathering wind and navigation data, help to optimize route selection and the use of wind conditions [105]. Novel zero-emission fuels and energy carriers can thus be seen as an example of sustainable radical innovation assisted by incremental digital innovation.

In the electricity sector, renewable energy technologies such as wind turbines and solar PV panels represent radical sustainable innovations. Incremental digital innovations can augment and strengthen renewable energy niches in terms of functionality and operation, but in themselves they do not contribute to a major change in system structures. In the case of wind turbines, digital solutions contribute to monitoring, controlling and optimizing power flows in variable speed generators, which in turn can support efficient production scheduling [106]. Further examples include digitally supported weather forecasting for wind farm management. Data from sensors can provide forecasts for optimal timing of maintenance and downtime of wind turbines. This in turn may contribute to reductions in operation and maintenance costs, which could amount to 25–35% of the total levelized cost of wind energy [107]. Similarly, in the case of solar PV, the use of sensors, data, and algorithms underlies monitoring and fault detection systems, which in turn enhances the performance and reliability of installations. Such monitoring systems can, for example, compare actual data with forecasts [108].

4.3. Sustainability supported digital innovation

Both partly and fully autonomous vessels are currently being developed. Such vessels are operated by a digital control system with either minimal or no crew on-board, with onshore control and monitoring by humans [109]. The operation of autonomous vessels is enabled by multiple new types of subtechnologies, such as edge computing, environmental sensing devices, and machine learning. Edge computing assists in faster computing of navigational routes and decisions, whereas environmental-sensing and machine learning are used to collect real-time data relating to, for example, environmental conditions, wind, temperature, and emissions [104]. Autonomous vessels may thus improve safety by not exposing human lives to sometimes dangerous sea conditions. They may also reduce costs by having fewer crew on-board, and by increasing efficiency and carrying capacity. However, they may also make some aspects of seafaring competences obsolete, thus potentially leading to the need for retraining, among other changes.

Fully autonomous vessels allow for more flexible operations, including lower speeds and operation at night and weekends. Thus, autonomous vessels potentially represent a radical digital innovation in shipping, as they may cause notable changes to the structure and practices (e.g. types of competences needed, lack of on-board crew, regulations allowing for autonomous and/or remotely controlled vessels, new ship design due the lack of need to accommodate crew on-board, new ways of using ships), and how shipping interacts with, for example, land-based transport. They have the potential to enable new types of transport patterns, including increasing multimodality (increasingly moving transport from roads to waterways) on short-sea voyages [20,95]. For example, by becoming more cost-efficient, shipping can compete better with heavy land transport, potentially increasing safety, and reducing congestion and local emissions on roads. As most shipping accidents are caused by human error, autonomy also has the potential to reduce accidents. In sum, autonomous vessels are often framed as having sustainability benefits, as they may allow also for more optimal and effective routing and energy use [20,94,95].

Another example of a potentially radical digital innovation is the introduction of blockchain technology in the shipping sector. Applications include tracking of cargo transportation, optimizing supply chains, and simplification of maritime logistics [110]. Blockchain technologies can minimize human intervention in logistic processes, and therefore they can change the relationship between different actors in shipping [111].

In the electricity sector, digital twins [112], artificial intelligence, and machine learning [113] are examples of radical digital innovations in the sense that they enable change from fixed to flexible electricity generation patterns for plants traditionally designed to provide base-load power. Power plants, such as coal-fired plants, traditionally have been operated by providing fixed amounts of electricity (base-load) to the grid. Digital innovation can enable a more flexible production profile for such plants, and thereby contribute to those plants taking on a new role in the electricity system by operating in load-following mode, depending on demand fluctuations [113]. Digital twins can model and forecast the state of assets and improve performance and efficiency, thereby changing the ways how, for example, fossil energy assets can be managed [98,114]. Digital twins can also help to improve fuel efficiency and maintain economic competitiveness (fuel costs typically represent a large share – 60–70% – of operational costs of coal plants), with a further benefit of emissions reduction [112] due to more efficient fuel use.

4.4. Radical twin innovation

While not yet realized, combining zero-emission fuels and energy carriers with autonomous vessel innovation is of potential interest for the energy transition in shipping. The first autonomous zero-emission vessel, container transport vessel MV *Yara Birkeland*, started operating in Oslofjord in Norway in 2022 [115]. Zero-emission autonomous vessels offer opportunities to reorganize how goods transport is carried out, in turn enabling new application opportunities for zero-emission technologies. For example, as shipping companies would not be limited by salary costs and working hours on-board, they might find it more acceptable to lower vessel speeds (and hence energy consumption), and to operate more flexibly at any given time. Lower energy needs can be important for battery-electric and hydrogen solutions, which have lower volumetric energy densities than fossil fuels, thus limiting the range and speed of vessels. Moreover, as there would not be any need to build facilities for the crew (e.g. accommodation and leisure spaces, sanitation), the weight of the vessels would be reduced, which again would reduce energy needs. Autonomy could thus alleviate some of the challenges related to alternative fuels, and thus open more application possibilities for such fuels. However, the challenge of dual structural changes to shipping (e.g. new propulsion systems and energy supply chains, and new control and operational practices relating to autonomy) would also increase the overall level of uncertainties and complexity for shipowners, due to multiple parallel radical innovations.

In the electricity sector, renewable energy technologies are currently diffusing rapidly, which in turn is leading to radical changes in socio-technical systems [90]. Distributed renewables, such as wind and solar, challenge prevailing systems because they differ from established centralized generation assets in terms of generation patterns (intermittency) and associated concerns for grid stability. Digital platforms such as community energy solutions and virtual power plants may alleviate such challenges to large-scale deployment of renewable energy by offering new ways to manage the production and consumption of renewable electricity. In the case of the virtual power plant, the digital control system may align the dispersed renewable energy with the system based on centralized generation, and as such facilitate particular interactions between electricity supply and electricity distribution systems [64]. Hence, virtual power plants may enable a novel way to organize the interaction between renewable energy production and distribution.

As another example, novel energy management systems enable shared energy storage solutions in communities. Such digitally enabled energy storage solutions have been labelled a missing link in energy transitions, as they contribute to making system integration of intermittent renewables more effective, while empowering local communities through more democratic ways of energy provision and management [116]. Furthermore, such innovations may create novel roles for citizens, such as energy citizenship [117].

Also, blockchains may be used to create new ways to trade, sell, and use electricity by enabling consumer-oriented electricity trading and microgrids, and thus facilitate easier transactions between electricity producers and consumers [118].

5. Discussion: tackling the complexities of twin transitions

Differentiating innovations according to the extent of structural change they cause in socio-technical systems allows for evaluation of their relevance for transitions towards more sustainable patterns of production and consumption, such as the fundamental system change required to reach net-zero emissions by 2050. Our proposed typology thus provides, we argue, a fruitful conceptualization of the contribution of digital innovations to sustainability transitions, providing insights that lead to a better understanding of twin transitions. We contribute by discerning between those digital innovations that may trigger profound change in socio-technical systems and those that mainly spur incremental change by maintaining or improving the current unsustainable socio-technical structures. Our typology suggests two main ways that digital innovations may contribute to sustainability transitions: (1) through digitally supported sustainable innovation (i.e. when a digital innovation supports the functioning of a radical sustainable innovation), and (2) through radical twin innovations (i.e. when a digital innovation couples with radical sustainable innovation and causes structural reconfigurations towards sustainability and digital patterns). We suggest that the latter type is particularly interesting because it may open alternative pathways for fundamental transitions towards sustainability, either through changes to the structure and practices of a single socio-technical system or by changing interactions between socio-technical systems.

Our conceptual exploration has also revealed multiple kinds of complexities, which so far have received only limited attention in the sustainability transition literature [1,16]. In this section we describe and unpack some of these complexities from the perspectives of research and governance of twin transitions.

5.1. Complexities in researching twin transitions

First, our paper suggests that while some digital innovations (radical) may contribute to sustainability transitions (understood as reconfigurations of the structure of socio-technical systems towards sustainability), others (incremental) may primarily strengthen the established and potentially unsustainable patterns, and thus ultimately hinder sustainability transitions [21,22,24,29,42,43]. Considering that digital innovations may also have outright negative effects on sustainability, such as more carbon emissions [11] and entrenched social inequalities [15], this challenges analysts to evaluate critically digital innovations' potential to contribute to sustainability transitions, such as those required by the current climate crisis. It is particularly important to differentiate between sustainability supported digital innovations and radical twin innovations. While the former may contribute some sustainability benefits (e.g. increased energy efficiency), the latter type of innovations may contribute to more fundamental transitions needed to solve some of the key sustainability challenges of our time. Twin transitions research should therefore pay more attention to digital innovation's foreseen degree (minor or major) and direction (towards mainly digitalization and/or sustainability) of structural change in socio-technical systems.

Second, the radicalness of digital innovation is context-dependent, and shaped by the activities of actors. Actors may empower innovations to either fit and conform to the current structural configurations of systems or aim to stretch and transform them [41]. From the perspective of socio-technical transitions, a given digital technology (e.g. machine learning or blockchain) is thus neither radical nor incremental by default, but the 'radicalness' of the innovation is dependent on whether actors use the technologies to trigger turbulence and change in socio-technical systems. While the potential of an innovation to create structural change can be speculated upon a priori, its impact as either an incremental or radical innovation over time remains an analytical question. Moreover, the empowerment of actors may also change over time, turning some radical innovations into incremental ones, or vice versa, as a result of changing priorities, behaviour, and action among key actors [119]. Assessment of twin innovations in terms of their radicalness should therefore follow a longitudinal process approach.

Third, the delineation between incremental and radical modes of innovation acts as a heuristic analytical model rather than an unambiguous reflection of reality. Indeed, incrementality and radicalness are two opposite ends of a continuous scale, on which most innovations are located somewhere in between the extremes. For example, the incremental innovations described in Section 4 can be expected to have some effects on the structure of shipping and electricity systems (e.g. introduction of some new technology providers, development or adaptation of certifications, changing practices), while not all structural elements can be expected to be reconfigured due to the introduction of innovations exemplified as radical.

5.2. Complexities in governing and managing twin transitions

As already noted, radical twin innovations are particularly interesting from the point of view of sustainability transitions. However, they also face policymakers and managers with several complexities.

First, radical twin innovations imply simultaneous change in the structural configurations of socio-technical systems in two differing dimensions, namely towards more sustainable and more digital patterns of production and consumption. This increases the uncertainties related to radical innovation, which are already notable in 'single' radical innovations, due to, for example, changing knowledge bases, networks, and institutions [46,55]. Additionally, there are often multiple competing sustainable radical innovations emerging in parallel. For instance, in shipping, several emerging alternative fuels are currently being explored to reduce maritime emissions, leading to uncertainty regarding which of them will prevail, which will be suited for what shipping segments (e.g. deep-sea cargo shipping, passenger vessels), and when the supply chains of different alternative fuels will evolve [100–102]. Such uncertainties create challenges for firms [55] and policymakers [120,121]. In the case of radical twin innovations, the uncertainties for practitioners may grow exponentially. For example, shipowners may need to decide which alternative fuels (e.g. electrification, hydrogen, liquefied biogas, ammonia) and, for example, which kind of autonomy (e.g. partly or fully autonomous) to invest in, but they may also seek to understand which kind of combinations of different sustainable and digital technologies can be optimal in which type of use [95,101]. Thus, actors need to deal with new knowledge bases and structural change in both sustainable and digital dimensions, but also to understand the possible implications of the coupling of the two. This may increase uncertainty and lead to further waiting games, thereby slowing down transitions (cf [61]. Moreover, designing technology-specific innovation policies – often considered a necessary policy strategy to accelerate radical sustainable innovations [122,123] – may become increasingly complex due to increased technological alternatives [121]. Hence, experimentation will become an even more crucial vehicle for reducing uncertainty, thus highlighting the importance of, for example, early movers, the availability of funding for demonstration and pilot projects, and public procurement for innovation to create early niche markets.

Second, practitioners must consider the mode of digital innovation (incremental versus radical). As already discussed, incremental digital innovation may help to optimize and improve sustainable technologies, while radical digital innovation may open new pathways for sustainability transitions when coupled with radical sustainable innovation. However, incremental innovation in established solutions may raise barriers to radical innovations to outcompete them, potentially slowing down transitions. As the degree of radicalness depends on context and agency, practitioners who seek to pursue sustainability transitions should also seek to promote the empowerment of digital innovations towards sustainable structural change, rather than assume that all digital innovations are beneficial for sustainability transitions. One approach to address this could be to define societal problems as the scoping devices of digital innovation policy [124].

Third, it is important to keep in mind that structural reconfigurations induced by radical digital innovations alone are not necessarily inherently sustainable, and may also, for example, strengthen social inequalities [14,15]. Indeed, in the context of evaluating the role of digital innovation in sustainability transition it is worth bearing in mind that the guiding logics of digital and sustainable innovation may have differing, implicit, or explicit starting points. For instance, sustainable innovations have often had a clear intrinsic goal of contributing to meeting the United Nations' Sustainable Development Goals, while this is not given in the case of digital innovation. Therefore, the two different dimensions of innovations may fall naturally under different frames and goals of innovation policy, namely (1) fostering economic growth and addressing market failures, (2) stimulating innovation systems, and/or (3) pursuing transformative change towards, for example, sustainability [125]. With an explicit aim to contribute to sustainability transitions, radical twin innovations are most relevant in the latter of the three framings, while fostering digital innovation alone could be justified for in any of the three framings. Recognition of such potential differences in understanding the purpose and empowerment of innovation – innovation as a goal in itself (as a means to generate economic growth and improve competitiveness) or rather as means to solve societal problems – is thus an important prerequisite for effective governance of digital innovation towards sustainability goals.

Fourth, novel policy paradigms, such as those linked to addressing societal challenges, tend to be associated with struggles, contestation, uncertainty, and directionality. As a result, different groups may have competing interests and narratives to influence policy [126,127]. Our typology may serve as initial steps to aid practitioners in distinguishing between innovations linked to development paths that merely optimize established (unsustainable) structures, and those that hold the potential for more profound change.

6. Conclusions

This conceptual paper contributes to the literature on twin transitions and sustainability transitions by discussing couplings between incremental and radical sustainable and digital innovation, aiming for better understanding of the contribution of digital innovation to sustainability transitions. Based on existing literature on innovation and sustainability transition studies, we have built a typology of such couplings and illustrated them with examples from shipping and electricity systems. We argue that couplings between radical sustainable and digital innovation – radical twin innovations – are particularly interesting in the context of sustainability transitions. Examples include community energy storages, virtual power plants, and autonomous zero-emission ships. In such innovations, new digital technologies and practices may create new ways for actors to create structural reconfigurations in socio-technical systems towards more sustainable patterns of production and consumption, thereby creating novel pathways for sustainability transitions. Meanwhile, even though incremental twin innovations and sustainability supported digital innovations may contribute to, for example, emission reduction, they may also merely increase the lock-in in current unsustainable patterns. Thus, researchers and practitioners alike must consider critically the different modes of digital innovation and their role in contributing to a structural reconfiguration of socio-technical system towards sustainability.

The growing discussion and expectations regarding the potential of digital innovation requires researchers to explore further the features and conditions for twin transition. Our paper has only scratched the surface in this respect, and it has a number of limitations, which also open opportunities for further research.

First, our empirical discussion has been illustrative in nature, basing on existing literature. Moreover, we have focused on energy examples. Further empirical investigations are needed, for example in food and mobility systems, and circular economy. Second, we have elaborated little on the role of agency in pursuing couplings between radical sustainable and digital innovation, and empowerment of digital innovations towards fit-and-conform and stretch-and-transform patterns (i.e. how and when actors use innovations to uphold or reconfigure socio-technical systems). Further theoretical and empirical work should investigate this crucial dimension of *enacting* twin transitions. Third, twin transitions are a major managerial and policy challenge, and more knowledge is needed regarding how their complexities can be tackled. Fourth, due to the focus of our paper, we have elaborated little on the potential negative effects of digital innovation on sustainability transitions. As digital innovation gains momentum, this topic will become increasingly important for researchers. Fifth, and finally, our paper does not elaborate on the operationalization of our proposed framework into empirical analysis, and indeed the methodology of assessing the degree and mode of digital innovation in creating structural change. Further methodological development regarding the analysis of twin transitions is thus needed.

Author statement

Tuukka Mäkitie: Conceptualization; Investigation; Visualization; Writing – original draft; Writing-review & editing, Jens Hanson: Conceptualization; Investigation; Visualization; Writing – original draft; Writing-review & editing, Sigrid Damman: Funding acquisition; Investigation; Writing – original draft. Mari Wardeberg: Investigation; Writing – original draft.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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