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Special Session: Digital Technologies for Sustainability— Research Challenges and Opportunities

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ABSTRACT

This paper presents an integrative exploration of key digital technologies instrumental in enabling the global green transition. In view of ambitious climate neutrality targets, it underscores the complex interplay between these technologies, policy implications, research challenges, and real-world applications in building a sustainable, low-carbon solutions. From a policy perspective, the paper delves into the systemic opportunities and challenges, providing valuable insights for various stakeholders. The discussion also encompasses pivotal research areas necessitated by the convergence of digital technologies and sustainable practices, emphasizing the need for a multi-disciplinary approach. Further, the paper identifies the practical applications of digital technologies across a range of sectors, highlighting several illustrative case studies, drawing lessons for future implementations. It concludes with forward-looking recommendations, stressing the significance of coherent policy coordination, public engagement, and global cooperation in furthering the digital-led green transition.

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1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC), a leading international body that has played a crucial role in shaping our understanding of the urgency and magnitude of the climate challenge, emphasizes the need for ambitious and coordinated policy responses. Zero-emission policies have been launched globally to achieve low-emission targets set by the Paris Agreement. In Europe, the *European Green Deal* aims to transform the region into a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases (GHG) by 2050 and where economic growth is decoupled from resource use. The deal encourages the adoption of digital technologies that can contribute to energy efficiency and smarter resource use, including those deployed in the manufacturing sector. Moreover, it underlines the role of robust policies in steering the transition towards a sustainable economic model.

Similarly, in the United States, the Biden administration's plan, often referred to as the *Biden Green Deal*, aims to put the U.S. on an irreversible path to achieve net-zero emissions by 2050. The plan also envisions the creation of millions of sustainable jobs in clean energy sectors, including digital industries. It highlights the importance of upgrading infrastructure, investing in clean energy, and using science and innovation to address the climate crisis.

These and other similar sustainability-focused initiatives are being pursued in other regions worldwide, underscoring policies' crucial role in facilitating the transition towards sustainable economic models. They acknowledge the potential of digital technologies in achieving these goals and highlight the need for ongoing research to address the challenges and maximize the potential of these technologies for sustainability.

These initiatives require a radical reimagining of our current systems. Among the promising avenues for achieving this ambitious goal are *Key Digital Technologies* (KDT), which are poised to play a pivotal role in catalyzing the green transition and fostering a circular economy. KDT carry immense potential to serve as a lynchpin in the shift towards a low carbon circular economy. Current digital consumption accounts for an estimated 2.3% of global CO2 emissions, amounting to 1.25 gigatons (Gt) of CO2. However, the transformative power of KDT presents an opportunity to offset this footprint significantly, potentially saving a staggering 12.08 Gt of CO2 by the end of this decade [1]. KDT contributes to enhanced energy efficiency, thereby driving a substantial reduction in overall energy use and GHG emissions [1].

1.1 Key Digital Technologies

We use the KDT definition from [5]: KDT consist of *cyber-physical systems* (integration of computation, networking, and physical processes, where embedded systems and networks monitor and control the physical elements [3]), edge computing, AI, architectures, design

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processes, methods and tools, connectivity, and smart components and systems.

Edge Computing is a key digital technology that revolves around the principle of conducting data processing near the source of the data, rather than relying on a distant centralized data center. This approach enables significant improvements in latency, bandwidth, and energy consumption. It leverages diverse, specialized processing architectures, including CPUs, embedded GPUs, and various accelerators, making it a dependable and efficient solution. Importantly, edge computing accommodates the use of Artificial Intelligence (AI), allowing devices to interpret and respond to their environment swiftly and intelligently. This combination of edge computing with AI, often referred to as Edge AI, contributes to automating complex tasks, thereby driving forward digital transformation across various application domains.

Artificial Intelligence (AI), empowered by advancements in machine learning, is a pivotal technology for tasks such as image recognition, natural language understanding, and complex process optimization. It necessitates vast amounts of data and sophisticated computational capabilities, with recent improvements reducing its resource needs, enabling complex tasks to be executed on local devices. AI is increasingly embedded within network nodes, including at the edge, optimizing distributed system operations. It enhances edge computing's efficiency, allowing local data processing, reducing necessary data transmission, and adapting to the environment through self-learning. Its development continues to focus on reducing memory size, processing time, and energy consumption, making it a cornerstone for Edge Computing.

Connectivity encompasses an array of systems that enable information exchange across various networks. It extends beyond traditional 5G, diving into early 6G investigations, and includes low power wide area networks like narrow band IoT and LTE, as well as non-cellular technologies such as SigFox and LoRa. Low power short-range connectivity is also covered, primarily through wireless technologies, both existing ones like Bluetooth and WiFi, and innovative ones. High-speed connectivity involves advanced wireless systems, including point to point mmW and satellite communication. This broad spectrum of connectivity technologies plays a crucial role in our digital infrastructure, facilitating communication, information exchange, and improved interoperability between different applications and systems.

A critical factor for successful transformation of innovative concepts into high-value applications is the utilization of robust platforms, which integrate effective architectures, structured design methodologies, and efficient engineering tools. Future systems-of-systems are projected to be intelligent, autonomous, and capable of evolving over time. These advanced systems will interact with each other and the cloud, and their functionality will primarily be implemented through software, running on high-performance specialized hardware. This necessitates innovations, improvements, and expansions in *architectures*, *design processes*, and corresponding *methods and tools* that facilitate the creation of these future applications. Such applications have requisite quality attributes such as *safety*, *reliability*, *cybersecurity*, and *trustworthiness*.

In addition, smart components, modules, and systems play a crucial role in bridging the gap between fundamental technologies like semiconductors and interconnection, and key applications. Smart components integrate intelligence, sensing, communication, and control functionalities. They are developed in parallel with other KDT.

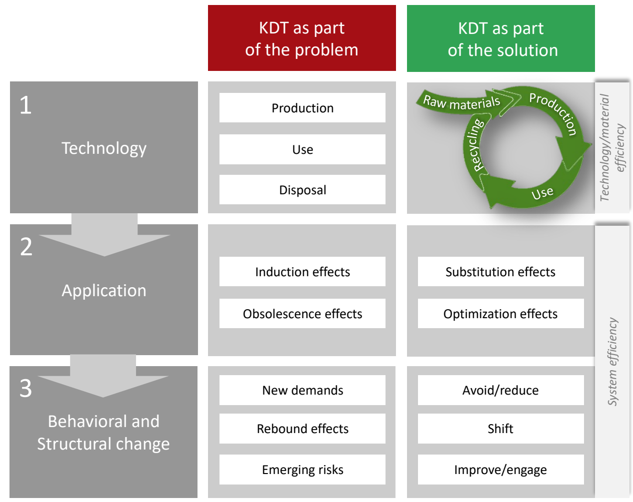

Figure 1: Key Digital Technologies for sustainability, adapted from [2].

1.2 KDT for Sustainability

The challenge with KDT for sustainability is that it can both be part of the solution, or it can be part of the problem, see the illustration in Fig. 1, adapted from [2]. According to [2], KDT can significantly contribute to sustainability by replacing and reducing resource use, and by catalyzing sustainable socio-economic transformations. KDT can enable resource substitution and optimization (Level 2 in Fig. 1). For instance, digital documents can replace paper, reducing deforestation (substitution effect). Similarly, smart grids can optimize electricity use, conserving energy (optimization effect). At a systemic level, ICT can drive long-term socio-economic shifts. For example, teleconferencing can reduce emissions from travel. Also, digital marketplaces can promote a circular economy, enhancing resource efficiency (Level 3).

Although there has been a lot of work to assess the benefits of KDT for sustainability, there are still several challenges, as identified by [7]. Often, the baseline for comparison is not adequately discussed, and the underlying hypotheses may be implicit or insufficiently explored. Structural impacts are frequently overlooked and difficult (if not impossible) to predict, and the expected benefits might be minor. Compatibility issues between different solutions and negative interactions can also reduce effectiveness. Furthermore, the quality of input data and the propagation of corresponding uncertainties are often not properly addressed, leading to potential inaccuracies in the evaluation.

Careful management of KDT is necessary to mitigate potential negative impacts, including both direct (such as increased energy consumption from digital devices) and indirect effects at the system level due to application and behavioral and structural changes, see Fig 1. The induction effect, where KDT induces consumption and increases demands for energy and materials, can be seen in hybrid work models. For example, online meetings and cloud computing enable remote work, but people moved further away from the city in search for bigger houses, increasing the energy use and commuting distance (albeit less frequent) and thus CO_2 emissions. Another example is the obsolescence effect, where KDT shortens resource's useful life due to incompatibility. Last but not least, rebound effects can offset KDT's efficiency gains, and new risks can emerge from, e.g., network vulnerabilities. We first showcase the opportunities for sustainability with KDT (Sect. 2) and then identify the main research challenges that have to be addressed to successfully use KDT for sustainability (Sect. 3). We discuss the policy implications in Sect. 4, considering also the potential negative impacts of KDT [2]. An overview on how to mitigate the KDT's effects in data centers is presented in [8].

2 OPPORTUNITIES FOR SUSTAINABILITY

The strong potential of KDT use for sustainability has been put forward in several sectors [1, 2, 9]. We start by discussing how KDT are used in the main sectors[1] and then exemplify with several use cases.

KTD in *digital manufacturing* offer significant sustainability benefits—2.7Gt CO2 potential reduction in the manufacturing sector (see the caveat in the footnote on these numbers, which should be taken as an indication). By enabling material and energy efficiency, they contribute to reducing carbon emissions and reinforcing the manufacturing sector's leadership. Examples include transforming steel plant carbon emissions into usable fuels and plastics, utilizing edge computing for analytics-driven optimizations that enable energy savings in factories, optimizing energy consumption in products, facilitating data-driven recycling, and employing cloud applications to calculate product carbon footprints. These technologies drive resource efficiency, waste reduction, and carbon footprint reduction.

KDT in the *energy sector* offer significant sustainability benefits, resulting in a potential reduction of 1.8Gt of CO2 emissions. By enabling intelligent electricity networks, these technologies lead to more efficient, flexible, and resilient grids with seamless integration of renewable energy. Advanced digital control and data analytics models reduce operational costs and outages. Specific energy use cases include boosting wind farm productivity through digitalization platforms and optimizing wind energy distribution using AI. Additionally, these technologies can facilitate demand management, district heating, and seamless integration of renewables with other energy sources, further enhancing sustainability in the energy sector.

Using KDT in the *transport* sector brings significant sustainability benefits (potential 3.6Gt CO2 reduction). Through digitization, logistics can be optimized, resulting in reduced emissions. Driverless and connected cars, flexible charging services, and mobility-as-a-service (MaaS) solutions promise to contribute also to further CO2 reductions in the transport sector. Without policy interventions towards sustainable paths, however, MaaS could also induce more demand, reduces occupancy, and increase "empty" miles that increase the overall emissions. Digital technologies also enable smart ports, 5G-powered sustainable growth, digitally-predicted trajectories for aviation decarbonization, and 5G-enabled corridors promoting green driving.

The same is true for the *agricultural* (potential reduction of 2.07Gt of CO2 emissions) and *construction* sectors. For example, advanced livestock monitoring enables targeted resource administration, optimizing water usage, preventing pollution, and achieving energy savings. This, along with IoT and data analytics for helps with higher crop yields, reduced pesticides, and optimized resource utilization. Remote monitoring tools also enable scalable and sustainable agriculture practices. In the construction sector, CO2 reduction is achieved via the creation of sustainable buildings that are net-zero, ultra-efficient, and environmentally friendly. By embracing digital tools, construction companies can develop digitally-enabled, decentralized, and decarbonized city infrastructure, contributing to a greener and more sustainable urban environment.

2.1 Example solutions

Danfoss Drives, a division of the larger Danfoss Group, has been designing and constructing AC Drives[2] since 1968. A central tenet of their approach has always been a robust emphasis on energy efficiency. Initially, energy efficiency served primarily as a competitive advantage since more efficient drives are cost-effective. However, more recently, it has emerged as a crucial digital component of that can support the green transition.

AC Drives are commonplace in modern society, regulating various sectors from industrial processes and power conversion in power grids, to HVAC systems on different scales, and pumps in water and wastewater systems. Consequently, leveraging these devices in the green transition can impact numerous domains. Early iterations of AC Drives were purely power electronics devices. However, modern AC Drives are evolving into increasingly digital entities, equipped with comprehensive software stacks that facilitate high-level programming, data processing, edge computing, and general integration into complex digital ICT systems.

There are already straightforward solutions that demonstrate the potential of digital technologies for sustainability. Since 2010, Aarhus Water[3] and water environment consultants have collaborated intensively to enhance the energy balance for the Marselisborg wastewater treatment plant. This plant serves roughly 200,000 people. As part of this endeavor, over 100 modern AC drives were installed to regulate all functions at the treatment plant, alongside an array of real-time sensors. This resulted in an remarkably optimized control of the plant, culminating in one of the most energy-efficient wastewater treatment plants in Denmark[13].

Moreover, the plant also generates energy from the biogas produced from household wastewater. Sludge is extracted from the wastewater and pumped into digesters, which yield biogas—primarily methane. This methane is then combusted to generate heat and electricity. As a result, since 2016, the Marselisborg plant has been producing about 100% more energy than needed to treat wastewater. The plant now generates sufficient energy to meet the entire water

[1]The numbers on CO2 emission reductions are from [1] and should be taken only as an indication of the potential.

[2]Also known as adjustable speed or frequency drives,variable speed or frequency converters, inverters, and power converters.

[3]A Danish public limited company owned by Aarhus Municipality

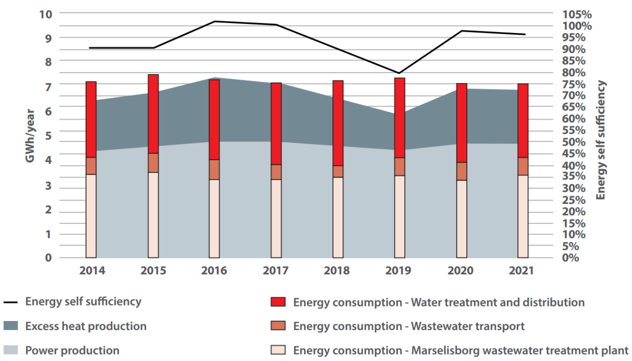

Figure 2: Energy consumption and production at Marselisborg.

cycle needs of the entire catchment area, including both drinking water and wastewater, effectively decoupling water from energy. It is estimated that process optimization and digitization contributed to 70% of these improvements.

While Marselisborg's case employed relatively simple digital technology, that is, local and small-scale digitization, it exemplifies how smarter process control can yield substantial results. Two key technologies that could facilitate intelligent control across multiple domains are digital twins and edge computing, both independently and collaboratively. The digital twin—a digital replica of a system—enables real-time simulation and testing under various conditions for highly efficient and optimized control. This predictive capability of digital twins facilitates proactive maintenance and error detection, reducing downtime and waste while improving system resilience and reliability. This proves particularly valuable in energy-demanding systems or those managing critical infrastructure.

Edge computing allows real-time data processing, which promotes swift response and control of AC Drive systems. It decreases the control loop latency, enabling instant drive operation adjustments based on current conditions. It also reduces the dependence on bandwidth, as less data needs to be transmitted to a central location for processing. Combined, digital twins and edge computing provide a potent control mechanism for AC Drive systems. The digital twin offers a highly detailed model of the system and its environment, while edge computing enables instantaneous, local decision-making based on real-time data from the system and its digital twin.

These technologies are actively being developed by Danfoss across multiple projects and collaborative efforts. One such initiative is the Water Living Lab project[4], which includes a large-scale simulation model of an entire water supply grid. It also includes experiments in local, edge-enabled data analytics of pressure spike phenomena in the supply grid, prototyped with high-fidelity digital twins of AC Drives.

As these technologies are still undergoing active development, they have not seen widespread adoption in the markets yet. However, solutions like those employed at the Marselisborg treatment plant can yield significant benefits. As we expect that new digital technology will revolutionize many industries, the solutions of today can already push us far along the green transition. For instance, at the Okocim Brewery in Brzesko, owned by the Carlsberg group, dedicated control for ventilation and water pressure systems led to a 50% reduction in electricity bills [11]. Similarly, improved control and newer AC drives installed at the Jersey Water desalination plant improved energy efficiency between 36 and 38% [12].

To maximize the benefits of digital technologies for sustainability across various domains and industries, it is essential that data is shared, control schemes are participated in, and protocols are kept open. As AC Drives and most components of cyber-physical systems are, to some extent, standardized products, it must always adapt to whatever context the customer requires. As we progress towards a highly digital society, this adaptability will become more critical than ever. To function in complex smart manufacturing, devices will need to output, and in many cases, input and process relevant data, while responding appropriately to a myriad of different and complex control schemes. In the future, we might imagine that in addition to declaring physical characteristics such as voltage, devices will need to disclose their digital characteristics, including what data they can output, process, and which control schemes they can participate in.

3 MAIN RESEARCH CHALLENGES IN KDT FOR SUSTAINABILITY

There have been several research "agendas" and "roadmaps" that identify research challenges related to key digital technologies [5]. We have listed them in our proposed "Industrial IoT RoadMap" for the green transition [10]. In this section, we identify the main *research challenges* in relation to sustainability with KDT (including circularity).

Edge Computing: In addressing the limitations of both embedded systems and cloud computing, edge computing may take the form of for example cloudlets or telco edge, to provide localized computing while reducing the potentially very large amounts of data that would otherwise need to be transferred to the cloud [3]. This involves processing data where it is generated and co-designing algorithms, hardware, software, and topologies to optimize energy use, reflecting the essence of sustainable computing. Edge computing also addresses the complexity of systems, for example by opening up for a new emphasis on distributed architectures, where the main highly configurable functionality will reside in edge servers, complemented with I/O devices. Edge computing systems should be able to balance performance with interoperability and achieving self-optimization, reconfiguration, and self-management, assisted by AI. Such optimization strategies can potentially streamline resource usage. Additionally, increasing the lifespan of devices and systems through hardware that supports software upgradability, improved interoperability, and the promotion of a second life for components is essential. These strategies align with the circular economy principles, advocating for resource reuse and reduction of waste. Finally, ensuring sustainability in the design of embedded architectures, emphasizing open-source hardware and engineering support for sustainable AI and edge computing are essential.

[4]https://lighthousewatertech.dk/projekt-waterlivinglab/

Embedded AI: The most important challenge is related to enhancing the energy efficiency of AI. This needs innovative hardware architectures, techniques to avoid moving large amounts of data, such as sparse data coding, federated learning, and processing at the data source, and the pursuit of interoperability among various applications. Federated learning can enhance privacy and integrity while reducing the energy needed for data transfer. Embedded AI should be scalable and modular across the distributed chain, increasing flexibility, resilience, and compatibility. Managing the complexity of these systems is vital, with a focus on developing trustworthy AI, facilitating easy adaptation of models, and introducing standardized interfaces for hardware and software tool chains. To support the increasing lifespan of devices and systems, the realization of self-learning mechanisms (unsupervised learning, transfer learning, etc.) and continuous update mechanisms are key. Such strategies align with sustainability goals, reducing resource consumption and waste. Lastly, the challenge of ensuring sustainability in AI involves the cultivation of diverse skillsets and adherence to ethical principles, transforming innovations into commercial successes, and enhancing the resilience of the embedded AI ecosystem.

Connectivity: To minimize the energy footprint, advancements in ultra-low power transceivers, high-frequency antenna design, and energy-efficient materials are imperative. Exploring new spectrums and mediums for connectivity, along with harnessing edge AI, could lead to more efficient and adaptable networks, thereby reducing environmental impact. Additionally, achieving autonomous interoperability—translating communication protocols, data encoding, and security semantics—could streamline system interactions, conserving energy. Moreover, the co-design of applications with the platforms and networks is essential to minimize communications, transferring mainly what is relevant from the application's perspective. Also, the advancement of scalable, secure, and adaptable IoT systems, as well as the implementation of network virtualization across various platforms like 5G and 6G, holds promise for more energy-efficient data processing and transfer. A pressing challenge is to address the high energy consumption associated with advanced connectivity technologies like 5G and 6G, improving the energy efficiency of these networks to mitigate their environmental impact.

Platforms, processes, methods and tools: We need robust development processes that can handle complex, interconnected, intelligent systems. This includes expanding these processes to manage the full lifecycle of a product from design to decommissioning, reducing waste, and enhancing the adaptability of systems. By creating systems capable of evolution and updates, we can increase the useful life of products and reduce the electronic waste footprint. The safety, security, and trust have to be integrated into the design of future systems. By ensuring the resilience of systems, we can help prevent failures and the corresponding resource waste. Secure and reliable systems are essential to support clean and efficient infrastructures, such as smart grids, where failures or attacks can lead to significant energy losses. The increasing complexity of systems and SoS requires the development of efficient design and validation tools, but also requires specific emphasis on run-time monitoring and error handling to deal with unknowns and anomalies. Such tools and mechanisms would allow for energy and resource conservation by making the design process more efficient, reducing the need for physical prototypes, and by creating systems that perform their tasks more efficiently, reducing operational energy consumption. Another challenge relates to the management of the diversity inherent in system designs. By ensuring bi-directional connectivity between the virtual and physical world, we can create efficient systems that optimally utilize resources. Advanced modeling and simulation can result in designs that require less physical testing, further reducing environmental impact.

4 REFLECTIONS ON POLICIES FOR THE TWIN TRANSITIONS

As the world grapples with the monumental task of mitigating climate change while fostering economic growth, policy implications for sustainability and the role of policies in driving the green transition come to the forefront. For example, the European Union is advocating for policies related to Industry 5.0, which is incorporating environmental and social sustainability that are missing from the Industry 4.0 paradigm [6]. The transition towards a sustainable energy system necessitates a system perspective, acknowledging the interconnectedness of technical, economic, and social domains.

While KDT has the potential to significantly contribute to sustainability goals, it is important to acknowledge the existence of various *barriers* that may hinder the successful application of these technologies towards sustainability. Some of these barriers encompass legacy and traditions that present socio-technical challenges to shifting to new, sustainable technologies. At the managerial level, lack of adequate competence or insight into KDT and sustainable practices may also pose significant obstacles. In addition, innovation and changes in business models, often involving transformations in entire supply chains, are required but can be challenging to implement. In the academic sphere, multidisciplinary research, despite being crucial to the integration of KDT and sustainability, is generally less rewarded compared to traditional disciplinary research. This creates a lack of incentive for KDT researchers to apply their knowledge to sustainability issues and to collaborate across different disciplines. To overcome these barriers, incentives could be put in place to encourage cross-disciplinary research and application of KDT to sustainability. Moreover, legislative barriers may exist that prevent or slow the integration of KDT into sustainable practices. Overcoming these challenges calls for active policy interventions, regulatory updates, and strong governmental support.

The integration of digital technologies into the sustainability agenda presents a range of opportunities and challenges for *policy*. It is essential to acknowledge the need for specific considerations when formulating policies that address the intersection of sustainability and digital technologies. Policymakers are responsible for ensuring that KDT are harnessed as part of the solution. There is an urgent need for coherence and coordination of policies, with an emphasis on multidisciplinary research and collaboration. This necessitates the development of regulatory frameworks that encourage the integration of sustainable practices within KDT and foster innovation in this field. Further, the establishment of public-private partnerships can enable the creation of sustainable digital ecosystems that address complex sustainability challenges. We offer some reflections on suitable policies, requirements, and implications that can guide future research and policy development.

Policy Frameworks and Incentives: It is crucial to develop policy frameworks that recognize the transformative potential of digital technologies in promoting sustainable systems. These frameworks should encompass a holistic approach, considering various aspects such as data privacy and security, interoperability, and technology standards. Policy incentives can play a significant role in fostering the adoption and deployment of digital technologies in various sectors. These incentives may include financial support, regulatory measures, and market mechanisms to encourage innovation, collaboration, and investment in digital solutions.

Collaboration and Stakeholder Engagement: Effective policy development requires collaboration and engagement with a diverse set of stakeholders, including policymakers, industry experts, researchers, and technology providers. This can help identify the specific needs and challenges related to policy and digital technologies, ensuring that policy measures are relevant, practical, and aligned with the goals of sustainability.

Capacity Building and Knowledge Sharing: Enhancing the capacity of policymakers and practitioners in understanding digital technologies is crucial for informed decision-making. This can be achieved through targeted training programs, workshops, and knowledge-sharing platforms that facilitate the exchange of best practices and lessons learned.

Flexibility and Adaptability: Policy should be designed to be flexible and adaptable to accommodate the rapidly evolving landscape of digital technologies. Policymakers should anticipate advancements and potential disruptions, enabling timely adjustments to policy frameworks and regulatory mechanisms.

Monitoring, Evaluation, and Learning: Establishing robust monitoring and evaluation mechanisms is essential to assess the effectiveness of policies targeting digital technologies. Regular review and analysis of policy outcomes can provide valuable insights for policy refinement, identifying successful approaches, and addressing any unintended consequences.

While these reflections provide a starting point for policy considerations, further research and collaboration between policy experts and digital technology specialists are needed to develop more nuanced and context-specific policy frameworks. Future studies should delve deeper into the specific requirements, challenges, and opportunities that arise when integrating digital technologies into policy, thereby enabling evidence-based decision-making and promoting sustainability.

By addressing these research challenges and opportunities, policymakers, researchers, and practitioners can collectively contribute to shaping a future where digital technologies play a pivotal role in advancing sustainable systems.

The role of policies in driving this transition cannot be overstated. They serve as the guiding force in creating the conditions necessary for KDT to contribute positively to sustainability goals. Policymakers should prioritize research and development (R&D) programs that focus on the research challenges and potential solutions for the twin green and digital transitions. These programs should also aim to overcome barriers to the needed transitions, including the development of suitable incentives to drive transformation. Additionally, such programs should support the development of open testbeds for controlled experiments, both on enabling KDT and its applications in various sectors. Open testbeds present a valuable opportunity to explore new solutions, foster new collaborations, and generate open data that can further fuel innovation and progress.

In parallel, to ensure a future workforce equipped with the necessary skills, universities should focus on training students in both digitalization and the green transition. Furthermore, there is a need to incorporate life-long learning opportunities. These can take forms such as modular university courses for practicing engineers and other professionals, fostering collaboration in education delivery. Life-long learning is crucial to keep up with the pace of technological and environmental changes [4]. Ultimately, such proactive policy measures will be instrumental in maintaining the positive role of trustworthy KDT in enabling the transition to a more sustainable future.

REFERENCES

[1] Global e-Sustainability Initiative (GeSI) and Accenture, *#SMARTer2030: ICT Solutions for 21st Century Challenges*, Global e-Sustainability Initiative, 2015. [Online]. Available: http://smarter2030.gesi.org/
[2] L. M. Hilty and B. Aebischer, *ICT Innovations for Sustainability*, Vol. 310, Springer, 2015.
[3] M. Törngren et al., "Industrial Edge-based CPS—Application Needs and Concerns for Realization", *IEEE/ACM SEC*, 2021.
[4] M. Törngren. et al., "The Role of Competence Networks in the Era of Cyber-Physical Systems—Promoting Knowledge Sharing and Knowledge Exchange", *IEEE Design & Test*, 37(6), 2020, pp. 8-15.
[5] AENEAS, EPoSS, and Inside associations, *Electronic Components and Systems Strategic Research and Innovation Agenda*, 2023.
[6] D. Renda, A.S. Serger, S. Tataj, D. Hidalgo, C. Giovannini, E. Huang, A. Isaksson, "Industry 5.0, a transformative vision for Europe", *ESIR Policy Brief No.3*, Publications Office of the European Union, 2022.
[7] A. Rasoldier et al., "How realistic are claims about the benefits of using digital technologies for GHG emissions mitigation?", *Proc. of the 8th Workshop of Computing within Limits*, 2022.
[8] X. E. Ouvrard, M. Peon-Quiros, and D. Atienza, "Challenges and Opportunities for Sustainable Multi-Scale Computing Systems", *Submitted to CODES+ISSS*, 2023.
[9] DigitalEurope. *Digital action = Climate action: Ideas to accelerate the twin transition*, 2021.
[10] P. Pop and M. Törngren, *Nordic Industrial IoT Roadmap: Research And Innovation For The Green Transition*, 2021.
[11] Danfoss *How did Carlsberg reduce power costs by 50%?* [Online]. Available: https://www.danfoss.com/en/service-and-support/case-stories/dds/carlsberg-brewery-drives-down-energy-consumption/
[12] Danfoss *Jersey Water desalination plant boosts efficiency by 38%* [Online]. Available: https://www.danfoss.com/en/service-and-support/case-stories/dds/jersey-water-desalination-plant-boosts-efficency-by-38/
[13] Danfoss *Marselisborg: pathway to a energy-neutral water sector* [Online]. Available: https://www.danfoss.com/en/markets/water-and-wastewater/dcs/waste-water/