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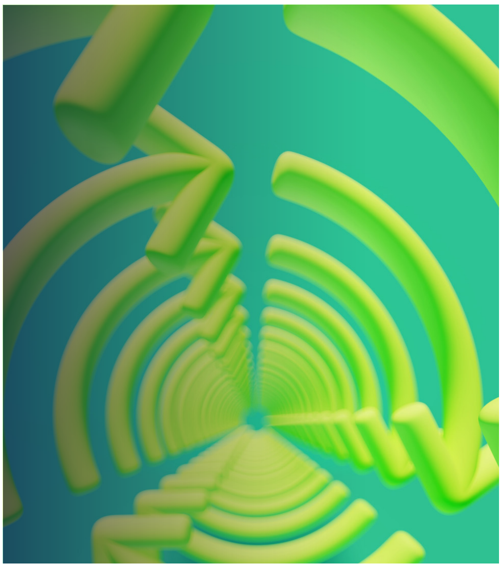
AMPLIFY

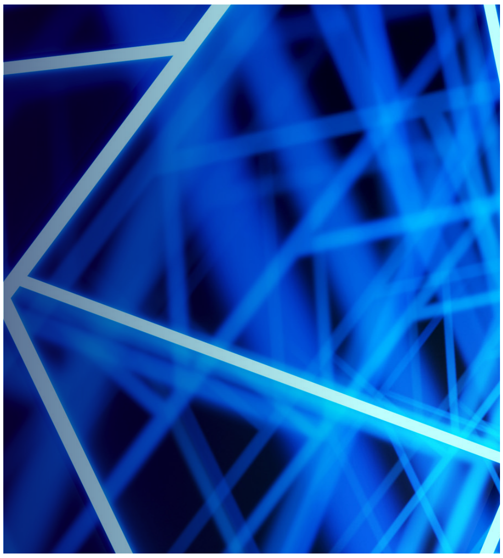
Vol. 37, No. 11, 2024

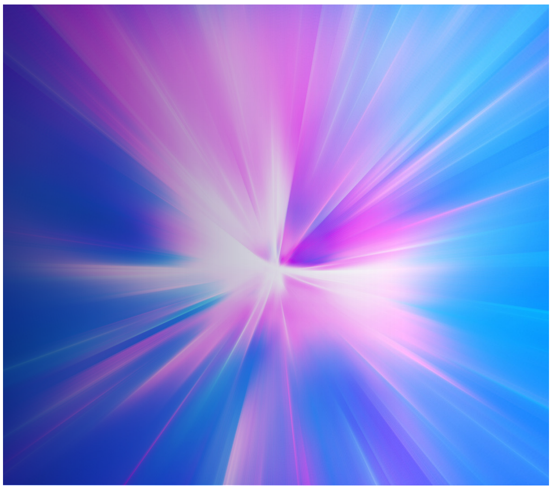
Anticipate, Innovate, Transform

Charting a Sustainable Future with Digital-First Solutions

CONTENT







CHARTING A SUSTAINABLE FUTURE WITH DIGITAL-FIRST SOLUTIONS

BY LUKAS FALCKE, GUEST EDITOR

Managing the twin transition — the digital transformation and decarbonization of our economy — is one of the greatest challenges business and policy leaders face today. As discussed in our first of this two-part *Amplify* series,[1] we cannot manage one (i.e., decarbonization) without the other (i.e., digital transformation) — and must leverage synergies.

For instance, AI offers many opportunities to optimize emission-intensive processes and reduce emissions, but its computational requirement leads to a sharp rise in energy demand for data centers. Similarly, smart sensors and drones can replace traditional carbon-intensive processes but can intensify demand for computer chips and rare materials.

This second *Amplify* installment builds on insights from academic research on digital sustainability. Much of the literature, including my work on digitally enabled and digital-first innovation for net zero published in the *Academy of Management Perspectives* (with Ann-Kristin Zobel, Youngjin Yoo, and Christopher Tucci),[2] highlights the potential of digital innovation for tackling climate change. However, more cautious voices are emerging. René Bohnsack, Christina M. Bidmon, and Jonatan Pinkse, contributors to our first issue, point to the unintended consequences of using digital innovation to tackle climate change.[3] Accordingly, they warn us to steer clear of unbridled tech optimism and the "butterfly effect" of AI.

However, the previous *Amplify* issue powerfully demonstrates that digital innovation, if managed correctly and with the right talent, can be the key to climate transformation. For instance, it is an important cornerstone for the e-mobility and energy transition and for implementing mission-driven policies. Given the potential for digital innovation to facilitate progress on climate change, the vast risks of unintended consequences, and the staggering energy demands of a digital sustainability approach, we need clear, actionable advice for managers and policymakers.

This issue offers another set of insightful articles from leading researchers and practitioners working on digital innovation for climate action. They reiterate the core message of this *Amplify* series: digital innovation can accelerate climate action if managed correctly. Of course, it will lead us directly to climate disaster if used irresponsibly. Applying the carefully crafted frameworks presented in this double issue can help us avoid the latter and enable the former.

IN THIS ISSUE

We begin with a deep dive into the potential of digital innovation to decarbonize one of the highest contributors to climate change: the construction industry. Diaa Shalghin, an emerging thought leader on building information management (BIM) in Germany and currently senior BIM manager at DEGES, teams up with Winfried Heusler of the Detmold School of Design, Germany, previously senior VP of engineering and building excellence at Schüco.

The authors apply a digitally enabled, digital-first framework to explore the opportunity of enhancing lifecycle assessment through digital innovation and present three takeaways: (1) implement a digital-first sustainability strategy for improved environmental simulation and modeling through BIM; (2) leverage digitally enabled sustainability for environmental data collection and analysis through the Internet of Things; and (3) combine digitally enabled and digital-first sustainability strategies for continuous optimization through AI.

> **DIGITAL INNOVATION CAN ACCELERATE CLIMATE ACTION IF MANAGED CORRECTLY**

These strategies allow companies to reduce their environmental footprint/costs and improve regulatory compliance and reporting. Importantly, this approach helps companies extend their lifecycle thinking beyond the operational phase, allowing end-of-life considerations. Industry practitioners will be happy to find a comprehensive overview of the challenges that emerge in their approach and a clear roadmap for overcoming them and "building" a sustainable future.

Our second article, from a high-profile research team at one of the world's leading universities in engineering and construction, TU Delft in the Netherlands, focuses on leveraging AI to create a circular built environment. Drawing from their rich expertise in real estate, housing management, urban planning, and innovation, Brian van Laar, Angela Greco, Hilde Remøy, Vincent Gruis, and Mohammad Hamida explore the concept of adaptive reuse, which involves repurposing buildings to extend their lifespan and can drastically cut emissions in the built environment.

However, implementing and scaling adaptive reuse is challenging. The decision-making process is often top-down and fails to capture relevant voices and make compromises acceptable to all stakeholders. AI might come to the rescue as it enables new visualization tools to unite stakeholders. AI visualization tools can accelerate the early design process in adaptive reuse projects. They also enhance stakeholder participation and allow teams to visualize potential pathways to align their wants and needs collaboratively. Finally, AI visualization tools help partners envision the future, quantify contradictions, and develop a more participatory and heuristic decision-making process for adaptive reuse projects that reduces human bias.

Next, Angela Greco, assistant professor of innovation management at TU Delft, and Andrea Kerstens, a TNO scientist and PhD candidate in innovation management at TU Delft, draw on their experience with Syn.ikia, an EU-funded Innovation Living Lab for positive-energy building districts that leverage energy efficiency and renewable energy sources. Digital innovations like digital twins have been essential to unlocking positive-energy districts. For instance, digital twins that combine physical models of buildings and AI models of user behavior allow building districts to predict and optimize usage of excess solar energy.

Their article presents three lessons learned from the project. First, ethical data management is key, as well as functioning AI prediction models (these need large amounts of personal user behavior data that can only be accessed if ethical data management procedures are in place). Second, even the most advanced AI models for digital twins are of limited use if the digital twins are not designed with the end user in mind. Finally, because the building industry is notoriously fragmented, digital twins must become real-time learning and collaboration tools to be value chain–proof.

Next, Armand Smits, an assistant professor of organizational change and design at Radboud University, the Netherlands, tackles one of the most pressing issues in digital sustainability: the rising energy and environmental cost of data centers. As illustrated by the first three articles, digital sustainability approaches and AI rely on large amounts of data that are increasing exponentially and must be stored and processed in data centers. Smits provides a deep dive into the Climate Neutral Data Centre Pact (CNDCP) to help managers and policymakers understand how to limit the environmental impact of data centers.

CNDCP focuses on target setting and monitoring of energy efficiency, clean energy, water, and the circular economy. However, this type of self-regulating pact can only be effective if it enables collective action and mandates three best practices. First, new relationships must be forged: the CNDCP emerged through a collaboration of the European Data Centre Association (EUDCA) and the Cloud Infrastructure Services Providers in Europe (CISPE). Second, it must leverage existing templates. CNDCP could, for example, build on the power-usage effective ratio to concretize the area of energy efficiency and many other environmental standards. Finally, it requires advanced, inclusive audit frameworks that incorporate the local climatic conditions in which data centers are built.

The issue closes with a fascinating story about the climate and digital transformation of a region traditionally reliant on coal. Led by Hamdy Abdelaty, a high-profile team of researchers at the Lusastia Energy Innovation Center (EIZ) at Brandenburg University of Technology, Cottbus-Senftenberg, Germany, shares insights about the role of digital innovation in facilitating energy innovation.

As part of EIZ's strategic focus on sector coupling (e.g., heat and electricity) and the intelligent digital operation of complex energy systems, the authors present five insights: (1) the power-to-X-to-power energy storage system requires advanced digital simulation to enable efficient carbon-free storage and renewable energy retrieval; (2) advanced stochastic models for real-time prediction of unsteady wind velocities can significantly enhance grid stability; (3) adaptive digital monitoring and control tools are essential for managing sector-coupled energy systems as they enable robust testing of solutions in real-world scenarios; (4) new technologies such as virtual reality offer immersive experiences that can significantly improve the acceptance of renewable energy transformations; and (5) transformative innovation projects like the EIZ require streamlined bureaucratic processes, funding agility, and collaborative frameworks.

The five articles in this issue deepen our understanding of digital innovation for climate action. They include three in-depth case studies, insights into managing the environmental impact of data centers through collective action, and an examination of how digital innovation can facilitate sustainability transformations of an entire region. Together with the first part of this *Amplify* series, these articles provide clear insights for managers and policymakers on successfully achieving the twin transition.

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BUILDING A SUSTAINABLE FUTURE IN CONSTRUCTION:

INTEGRATING DIGITAL INNOVATIONS & LIFECYCLE ASSESSMENT

Authors

Diaa Shalghin and Winfried Heusler

The construction industry is a significant contributor to climate change through emissions and extensive material usage due to its reliance on manual processes and physical materials.[1] However, digital innovations such as building information modeling (BIM), the Internet of Things (IoT), and AI are revolutionizing the way construction projects are planned, designed, constructed, and operated.[2] In the face of an accelerated climate crisis, these innovations present a unique opportunity to go beyond efficiency gains to tackle climate change.

Building on prior research on digital sustainability, industry experience, and empirical illustrations, this article explores how digital innovation can be harnessed to "build" a more sustainable construction industry.[3,4]

Using a digital-first and digitally enabled strategy, firms can leverage digital innovations to capture information about the physical world and physical processes, leading to optimization of physical structures and processes to reduce emissions.[5] This involves using digital models that leverage advanced algorithms and extensive databases to run iterative simulations and predictions in a low-cost, low-emissions digital world before turning the models into physical structures.

The article explores the integration of digital innovation and lifecycle assessment (LCA) to realize digitally enabled, digital-first sustainability strategies. After highlighting three important digital innovations in the construction industry and introducing LCA, we offer an integrated sustainability framework that lays out opportunities for integrating digital innovations into LCA. By integrating digital technologies with LCA, construction companies can make informed decisions that minimize environmental impact, reduce waste, and promote energy efficiency.

START WITH BIM

The key to digital transforming the construction industry is BIM, a comprehensive digital method that creates a digitally accessible model of a construction project.[6] It uses data exchange and standardized interfaces to allow stakeholders to easily collaborate, quickly identify potential conflicts, and optimize material use.

Drones, remote sensing, and IoT are also changing the construction industry by providing continuous streams of data on construction progress. Drones and laser scanners let companies (1) monitor progress and (2) compare the construction site with the planned BIM models to continuously update and improve it.

> **THE KEY TO DIGITAL TRANSFORMING THE CONSTRUCTION INDUSTRY IS BIM**

Sensors and smart meters provide real-time data on energy consumption, material use, and environmental conditions during the operation phase, turning BIMs into digital twins of an asset. The digital twin is an essential input for BIM-based construction projects across all phases, including design (as-planned model), construction (as-built model), and asset operations (extended digital twin). It can be used to improve models, optimize operations, identify inefficiencies, and implement energy-saving measures.

Finally, these models and data streams create conditions for AI use, including statistical learning algorithms that can analyze vast amounts of data to identify patterns, optimize processes, and predict outcomes. AI can dramatically improve asset planning, construction, and operations through predictions and optimization. In the next section, we show how digital innovations can lead to an advanced LCA process for climate mitigation.

LCA: FOUNDATION FOR A SUSTAINABLE FUTURE

LCA is a comprehensive methodology that evaluates the environmental impact of a product, construction asset, or system across its lifecycle.[7] This assessment spans every phase, from extraction of raw materials to manufacturing, transportation, construction, operation, and end-of-life disposal (or, preferably, recycling).

In the construction industry, LCA is critical for understanding the full scope of a project's environmental implications. By analyzing the entire lifecycle, it identifies stages where the environmental impact is most significant, whether that's energy-intensive material production, emissions generated during construction, or long-term energy use of an asset during its operational phase.

LCA allows construction companies to quantify environmental factors such as greenhouse gas emissions, energy consumption, water use, and waste generation across each project phase. This gives stakeholders a clear picture of the environmental footprint of a building or infrastructure project, helping them make informed decisions that minimize negative impacts. For instance, LCA might reveal that a particular type of concrete would result in higher emissions during production but lower energy consumption during an asset's operational life, helping to balance short-term and long-term environmental impacts.

An integral part of LCA is environmental product declarations (EPDs), which provide standardized documentation on the environmental impact of individual building materials or products. EPDs offer transparent, verified data on the carbon footprint, energy use, and resource depletion associated with a product. These declarations are essential for accurately assessing the environmental impact of the materials used in construction. When integrated into LCA, EPDs help construction companies make informed comparisons between materials and products so they can choose the ones with the least environmental impact.

OPPORTUNITIES FOR INTEGRATING DIGITAL INNOVATION & LCA

Digital innovations can enhance LCA practices in several ways (see Figure 1):[8]

- **Leverage digital-first sustainability for improved environmental simulation and modeling.** BIM is a powerful tool that creates detailed digital designs of buildings, enabling a digital-first approach in which various design scenarios and optimizations can be simulated at marginal cost. This lets architects and engineers

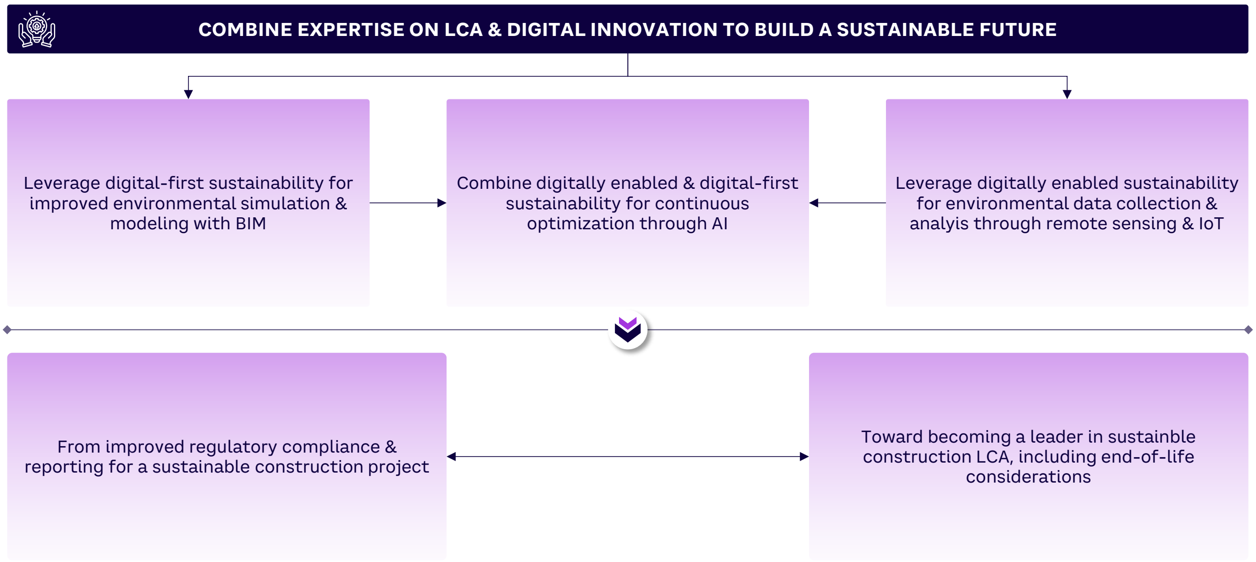

Figure 1. A framework for leveraging digital sustainability for construction

assess the environmental impacts of design choices before physical work begins. For example, BIM can model the energy performance of various window types, wall materials, or HVAC systems, helping project teams select options that reduce energy consumption and carbon emissions. It can also simulate how much the use of recycled or low-impact materials would lower the overall environmental footprint of the building.

- **Leverage digitally enabled sustainability for environmental data collection and analysis.** Drones, remote sensing, and IoT bring a new level of precision to LCA by enabling continuous monitoring of an asset's physical state. For example, drones and laser scanners help companies identify issues with insulation during construction. IoT sensors can be embedded in structures to track real-time data on energy consumption, water use, material wear, and environmental conditions such as temperature and humidity. This data collection is invaluable for LCA, enabling assessments based on operational performance rather than theoretical models or estimates. For instance, by monitoring energy use at different times of day and/or seasons, IoT devices reveal how building systems perform under varying conditions, leading to more accurate and dynamic LCA outcomes.

- **Combine digitally enabled and digital-first sustainability for continuous optimization.** AI plays a crucial role in analyzing the vast amounts of data generated by BIM, drones, remote sensors, and IoT devices. AI algorithms can identify patterns and trends that might not be immediately apparent and suggest optimizations that can significantly reduce environmental impacts. For example, AI can analyze LCA data to recommend alternative construction methods that use less material or generate less waste. Similarly, physical processes such as material transportation can be optimized, reducing fuel consumption and emissions. Finally, AI can help with predictive maintenance, identifying when equipment is likely to fail and suggesting repairs before breakdowns occur, minimizing downtime.

- **Improve regulatory compliance and reporting for more sustainable construction.** As sustainability regulations become stricter, LCA is the key to helping construction companies ensure compliance with stricter environmental laws and standards. BIM, IoT, and AI can automate environmental-impact tracking and reporting, making it easier to meet regulatory requirements and demonstrate sustainability credentials to stakeholders. This is particularly important for projects seeking certifications such as BREEAM (Building Research Establishment Environmental Assessment Method) or DGNB (German Sustainable Building Council), where detailed environmental reporting is mandatory.

- **Understand end-of-life considerations.** LCA does not stop at the construction or operational phases of an asset. It includes the end-of-life stage, which encompasses demolition, recycling, or repurposing of asset materials. Digital tools can assist in planning for an asset's end of life at the design stage. BIM can be used to design assets that are more easily deconstructed, allowing materials to be recycled or reused.

AI optimizes this process by analyzing the best ways to disassemble structures to recover the maximum amount of reusable material, reducing the need for new resources and lowering environmental impact.

3 EXAMPLES

The following three examples illustrate the application of digital innovation and LCA in the construction industry:

1. **Skanska's digital-first sustainability strategy using BIM-integrated LCA.** Skanska, a leading global construction and development company, is an interesting example of an incumbent construction firm that has successfully integrated BIM with LCA to assess the environmental impacts of their projects.[9] During the construction of Powerhouse One development in Trondheim, Norway, Skanska used BIM to model design options and their associated environmental impacts. This iterative, digital-first approach moved the assessment, experimentation, and reduction of environmental impact to the digital world, where iterations come with a marginal cost, allowing the company to select the most sustainable design before moving to the construction phase and reducing the building's carbon footprint.

2. **Integration of One Click LCA with Bentley System's iTwin platform to leverage IoT.** iTwin is a cloud-based solution that enables creation, visualization, and analysis of construction projects. The platform lets project teams incorporate real-time data from IoT devices such as sensors and drones. This provides a continuous, accurate reflection of an asset's current state that can feed into the LCA calculations of One Click LCA via integration with iTwin.[10,11] The information from the physical world comes first, and when captured and turned into a digital model through IoT, it improves the LCA of an asset that can be further optimized for sustainability.

3. **Combined digital-first and digitally enabled sustainability at Edge Technologies.** The Edge — located in the Zuidas business district of Amsterdam, the Netherlands, and developed by Edge Technologies — is one of the world's most innovative and sustainable office buildings.[12] A BIM guided the design of the building, leveraging digital-first predictions and iterations to maximize natural light. It includes a smart, comprehensive renewable energy system, including an array of photovoltaic solar panels, that provides sustainable electricity and thermal energy storage system for heating and cooling. These features earned The Edge the highest BREEAM rating for sustainability. The building follows a digitally enabled sustainability strategy to enhance sustainability and efficiency, using IoT sensors to monitor conditions like lighting, temperature, and occupancy in real time. This data is fed into AI algorithms to optimize energy use, resulting in 70% less electricity consumption than traditional office buildings of similar size and occupancy.

CHALLENGES TO LCA INTEGRATION

Digital innovation and LCA offer unique opportunities, but the challenges that forward-thinking construction companies face are significant. They include:

- **Lack of data integration and standardization.** The construction industry increasingly uses digital tools like BIM, remote sensing, IoT, and AI to improve project outcomes. These tools often operate on different platforms and use different data formats, making it difficult to integrate them into an LCA framework for digital sustainability. The lack of standardized data is a serious challenge to generating accurate, comprehensive environmental assessments.
- **Up-front costs and skills gaps.** Adopting advanced digital tools and comprehensive LCA practices requires substantial financial investment, including acquiring the necessary technology, training employees, and maintaining the required infrastructure. This leads to a "green premium" — higher short-term costs for a more sustainable outcome. Additionally, using these technologies demands specialized skills that many construction professionals do not possess. This gap poses a barrier to the widespread adoption of these innovations and digital sustainability strategies.
- **Complex regulations and lack of reporting standardization.** Although our digital sustainability approach allows companies to follow regulations, the construction industry has an increasingly complex landscape of environmental regulations that vary by region and are continuously evolving. Compliance requires continuous reassessment and improvement of firms' digital sustainability strategies to ensure a detailed and accurate LCA. Additionally, EPDs, which provide critical data on the environmental impact of building materials, currently lack standardization. Their inconsistent availability makes it difficult to compare materials, run realistic digital-first simulations, and ensure that projects meet all regulatory requirements.
- **Resistance to change and short-term focus.** The construction industry is slow to adopt new technologies, often due to cultural resistance to change and a preference for established methods. This is compounded by a focus on short-term financial gains rather than long-term sustainability. Many stakeholders prioritize immediate cost savings over potential long-term benefits, delaying digital tool implementation and hindering adoption of LCA practices essential for improving environmental performance through digital sustainability strategies.

A GUIDE TO REALIZING INTEGRATED DIGITAL SUSTAINABILITY

To overcome these challenges and work toward full realization of digital sustainability strategies, we recommend the following:

- **Invest in training and skill development.** Successful implementation of digital sustainability strategies that combine digital innovation and LCA requires a workforce and internal digital sustainability champions with expertise in both digital innovation and sustainability. Investing in training programs and continuous professional development is critical to ensure that employees are equipped to integrate digital innovations and LCA and navigate its associated challenges.
- **Promote industry collaboration.** Collaboration between construction companies, technology providers, and academic institutions can drive innovation and the development of standardized practices. Joint research initiatives and knowledge-sharing platforms can accelerate the adoption of digital technologies and LCA methodologies. Collaboration can help companies better understand and work within the existing regulatory environment or work toward improved conditions for digital sustainability.
- **Understand and tap into the regulatory environment.** Government policies and regulations can hinder digital sustainability strategies, but they can also support them. Firms need to understand the environment, face hurdles head-on, and seek out potential support. Incentives like tax breaks, grants, and subsidies for sustainable practices can encourage companies to invest in digital sustainability strategies.
- **Focus on long-term benefits.** Even with favorable regulatory conditions, initial investment in integrated digital innovations and LCA can be significant. Companies must convince their investors and stakeholders to take a long-term approach and factor in the potential for both environmental and economic benefits.
- **Leverage case studies and best practices.** To make their initial investment effective, firms should study successful case studies and best practices to discover insights and learn practical ways to implement digital innovations and LCA. Companies can adapt these strategies to their own situations to achieve similar benefits.

- **Adopt integrated digital platforms.** Following innovative case studies and standout sustainable construction projects allows firms to assess which tools and platforms they need to realize digital sustainability. Using integrated digital platforms that combine digital innovation and LCA (e.g., through APIs and extensions) is the basis for moving from strategizing to implementation.
- **Standardize data and methodologies.** These platforms and tools can only help companies realize the potential of digital first when firms use standardized data formats and LCA methodologies for consistency and comparability across projects. This standardization can facilitate better decision-making and sustainability performance benchmarking.

These guidelines are a set of recommendations intended to work together in continuous iterations. As companies integrate these strategies, the construction industry will begin to see the potential of digital innovation and LCA, paving the way for a more sustainable future.

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LEVERAGING AI TO CREATE A CIRCULAR BUILT ENVIRONMENT

Authors

Brian van Laar, Angela Greco, Hilde Remøy,
Vincent Gruis, and Mohammad Hamida

The built environment plays a crucial role in the ongoing challenge of climate change, primarily through resource consumption, energy use, and contributions to greenhouse gas (GHG) emissions. As urbanization accelerates, the environmental footprint of construction and building operations has grown significantly. Currently, buildings account for 40% of the world's waste, 40% of material resource use, and 33% of human-induced emissions.[1]

To mitigate these impacts, adopting circular economy principles that focus on material reuse, recycling, and regeneration is essential to foster a sustainable, closed-loop system.[2] This approach stands in stark contrast to the traditional linear economy, which operates on a take-make-dispose model, leading to excessive waste and resource depletion. In a circular economy, materials are kept in use for as long as possible by recycling, reusing, and remanufacturing.[3]

Among circular economy strategies, adaptive building reuse stands out. This approach involves repurposing buildings to extend their lifespan, conserve embodied energy, and minimize demolition waste.[4] Adaptive reuse reduces GHG emissions while conserving natural resources and revitalizing communities.[5]

Far from a new concept, adaptive reuse has been practiced for centuries. The conversion of buildings from one use to another has occurred in various contexts, at different scales, throughout history.[6] For example, in the Netherlands, many canal houses have been adapted and reused multiple times due to various causes of obsolescence, including changes in building regulations, shifts in the housing market, or evolving urban needs such as the diminished demand for warehouses in city centers.

However, the decision-making process involved in adaptive reuse is fraught with complexity and uncertainty.[7] Causes include the inherently slow pace of such projects, the lack of participatory engagement, and the struggles stakeholders face in envisioning future scenarios.[8-10] The process is often prolonged as stakeholders navigate regulatory frameworks, technical constraints, and diverse community needs.[11]

> **AMONG CIRCULAR ECONOMY STRATEGIES, ADAPTIVE BUILDING REUSE STANDS OUT**

The absence of sufficient participatory engagement means that the voices of key stakeholders, such as residents and local businesses, are often underrepresented. This lack of involvement can exacerbate tensions and contribute to polarized views on the future, as various groups struggle to align their visions with what is possible.[12] The difficulty in predicting future environmental, social, and economic conditions further complicates consensus building, often leading to decisions that are less sustainable and less beneficial to the community.[13]

Too often, polarized and contradictory views crop up among stakeholders, and each group clings to its perspective, sometimes at the expense of others.[14] This can skew decisions toward one dominant view, neglecting the broader range of possibilities and the needs of other stakeholders.[15]

To overcome this polarization, it is crucial to visualize these contradictions and make them explicit during the decision-making process.[16] By bringing differing views to the forefront, stakeholders can better understand the implications of each perspective and work toward more balanced, inclusive solutions.

TOO OFTEN, POLARIZED & CONTRADICTORY VIEWS CROP UP AMONG STAKEHOLDERS

AI is a powerful tool in this process. It can rapidly generate visual representations of adaptive reuse scenarios, enabling stakeholders to explore future conditions and see the potential effect of their decisions. The technology allows for a more collaborative approach, helping bridge the gap between opposing views and supporting the development of resilient, well-rounded adaptive reuse projects that are aligned with long-term community and environmental goals.

This article draws on the experience of Reincarnate, an EU-funded initiative aimed at increasing the use of construction and demolition waste while reducing buildings' CO_2 emissions. We illustrate how an AI-driven, process-oriented approach to forward-looking co-creation can significantly enhance stakeholder engagement, enable viable adaptive reuse projects, and accelerate the transition to a circular built environment (see Figure 1).

CHALLENGES

Construction is often regarded as a conservative industry, marked by a reluctance to adopt new technologies and innovations. Its decision-making tends to be top-down and fragmented across stages, leaving little room for iteration or flexibility.[17] In the context of adaptive reuse, decision-making is predominantly driven by economic considerations, with insufficient emphasis on participatory engagement.[18]

Local residents and stakeholders are frequently informed only after an initial direction has already been chosen rather than being involved from the outset. The design process is often linear, with architects adhering to top-down directives from the client, restricting design flexibility and limiting stakeholder input. This approach leads to conflicts and misalignment during initial strategy development, often prompting decision makers to opt for demolition and new construction to avoid challenges.[19]

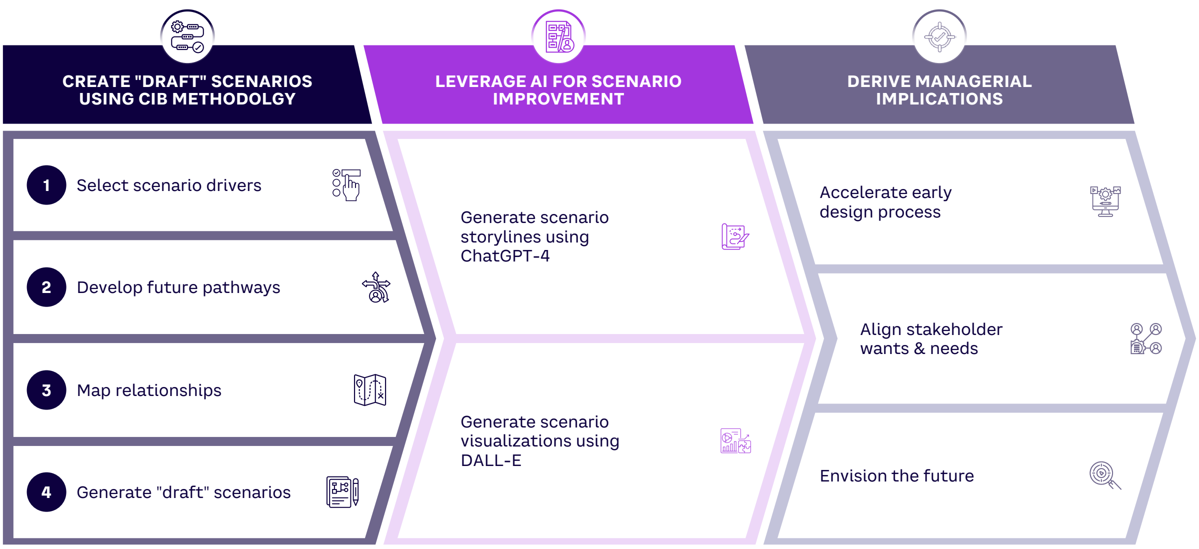

Figure 1. Summary of the research process

Their inherent complexities and uncertainties make adaptive reuse projects notorious for delays.[20] When strategizing collectively, we bring our own biases and tend to make choices based on established ways of working, following simple heuristics.[21] This can be a problem when decision-making involves complex and contradictory demands, as is the case of adaptive reuse projects.[22]

In construction projects, slow decision-making exacerbates the issue by driving a return to rigid, hierarchical structures, with the hope that this will streamline decisions. Paradoxically, it often makes the process even slower, as these structures fail to account for the nuanced (and often conflicting) requirements of complex projects. This rigidity ultimately hampers the ability to adapt effectively to specific project needs.

Overcoming these biases requires a shift toward collective, forward-looking co-creation in the decision-making process.[23] However, decision makers often struggle with this, particularly when long-term decisions have unforeseeable impacts.[24] The inability to envision future possibilities can lead to polarized views, resulting in decisions that disproportionately favor one perspective over others.[25]

Current approaches in the adaptive reuse decision-making literature tend to focus either on broad functional use or specific design options, which can limit decision effectiveness and quality.[26] Addressing this requires visualizing and explicitly acknowledging these contradictions, then exploring the wide range of future possibilities through collaborative action.[27]

> **GENAI OFFERS A FASTER, MORE SYSTEMATIC METHOD OF PRODUCING VISUAL & NARRATIVE OUTPUTS**

FUTURE-PROOFING ADAPTIVE REUSE

Scenario development addresses the challenges of adaptive reuse projects by providing a future-oriented perspective that assesses long-term sustainability and functionality. It allows stakeholders to consider various scenarios, which helps them anticipate shifts in environmental, social, and economic conditions and ensures that decisions are both adaptable and resilient. By highlighting the potential outcomes of various choices over a building's lifespan, scenario development fosters more sustainable and informed decision-making — crucial for projects that need to stay aligned with long-term community and environmental goals.

Traditionally, narrative and visual elements within scenarios have been crafted by local artists using techniques like visual harvesting, in which ideas are captured and represented in real time. This approach, although valuable for its human sensitivity and nuanced interpretation, can be time-consuming and reliant on artist availability and style.

Generative AI offers a faster, more systematic method of producing visual and narrative outputs. AI can incorporate a broader range of data and perspectives, ensuring consistency and reducing the risk of omitting contrasting scenarios that need to be considered. Rather than replacing the artistry and insight of handcrafted techniques, AI enhances the process, enabling a more inclusive representation of ideas and reducing the possibility of bias or oversight in the selection of information.[28]

This integration of scenario development and advanced visualization aligns well with the need for an iterative, flexible approach in adaptive reuse projects. By shifting toward forward-looking co-creation, decision makers can better navigate the complexities and uncertainties inherent in these projects, leading to decisions that are more inclusive, sustainable, and responsive (refer back to Figure 1).

LEVERAGING AI TO ACCELERATE ADAPTIVE REUSE DECISION-MAKING

AI has the potential to address challenges in adaptive reuse decision-making. As part of the Reincarnate project, we created desirable futures for the circular adaptive reuse of buildings through a series of scenarios. These scenarios contribute to Reincarnate's broader goal of developing technical and social strategies to create opportunities for buildings, construction products, and materials.

The scenario development process included a novel approach that combined traditional scenario methodology (cross-impact balance analysis) with participatory scenario-planning workshops. We used AI tools to collaboratively develop narrative and visual elements with stakeholders, which allowed us to better understand their benefits and how they can accelerate adaptive reuse decision-making.

The outcomes include 15 detailed scenarios that can guide stakeholders in exploring future pathways for circular adaptive reuse, with practical implications for policy and project implementation. These are "big picture" scenarios for adaptive reuse that represent hypothetical possibilities and are not related to specific projects.

Through this approach, we were able to consider a wide range of parameters that would be difficult to combine and analyze in a handcrafted scenario, ensuring a more comprehensive, data-driven outcome. This resulted in scenario scorecards like the one shown in Figure 2.

For 15 descriptors (e.g., political and community support, cost), three potential variants were drawn up:

1. **Strong** — descriptor's objective was reached (happy green emoticon)
2. **Medium** — descriptor's objective was partially reached (neutral yellow emoticon)
3. **Weak** — descriptor's objective was not reached (sad red emoticon)

The relationships between these descriptor variants were mapped during a workshop with adaptive reuse experts. An algorithm calculated consistent combinations of variants, which served as draft scenarios. For 15 consistent draft scenarios, ChatGPT-4 generated storylines based on the descriptions of the variants. DALL-E, an extension in ChatGPT-4, generated images from these textual descriptions.

SCENARIO NO. 24

Political & community support	Supportive hesitation	😐
Cost	Moderately costly	😐
Local economy	Local economic engine	🙂
Market potential	Sufficient market potential	😐
Social impact	Socially limited	☹
Accessibility	Inaccessible	☹
Building technology	Technologically adequate	😐
Environmental impact	Environmentally unfriendly	☹
Indoor environmental quality	Cold & loud	☹
Rules & regulations	Regulatory challenges	☹
Flexibility & adaptability	Flexible & adaptable	🙂
Quality & durability	Strong & durable	🙂
Physical characteristics	Spacious & versatile	🙂
Architectural value	Architectural beauty	🙂
Historic & cultural value	Preserving history	🙂

NAME SCENARIO: DIAMOND IN THE ROUGH

In a scenario where an iconic but no longer used building on the outskirts of the old city center is preparing for transformation, stakeholders navigate a landscape of cautious support and economic efficiency. Despite the hesitations of some key stakeholders **(supportive hesitation)** and the moderate costs **(moderately costly)** that slightly exceed the budget, this project promises to become a **(local economic engine)**, with an undeniable positive impact on the local economy. Creating jobs, stimulating local businesses, and improving public amenities are just some of the benefits the transformation will bring. With **(sufficient market potential)** located in a diverse and dynamic environment, the building is seen as attractive to a wide range of buyers and tenants, despite some financial risks. However, the project also faces its challenges. It confronts significant obstacles in terms of social impact **(socially limited)**, accessibility **(inaccessibility)**, and environmental impact **(environmentally unfriendly)**, with the current state described as "limited social," "limited accessibility," and "environmentally unfriendly." These shortcomings in the indoor environment **(cold & loud)**, technological limitations **(technologically adequate)**, and a strict regulatory environment **(regulatory challenges)** require a thoughtful approach to achieve the desired transformation. The heart of the transformation lies in the **(flexible & adaptable)** nature of the building, supported by **(strong & durable)** and spacious physical features **(spacious & versatile)** that enable the building to be redeveloped into a flexible, open, and multifunctional space. The architectural **(architectural beauty)** and historical value **(preserving history)** of the property is not only maintained but also celebrated, enriching the building and its surroundings. This transformation is driven by the vacancy of the building, the value of the location, and the desire to preserve a historical monument. With a project duration of approximately 3-4 years, the building will be transformed into a vibrant, multifunctional space that combines housing with other uses, making it accessible to the public and a valuable asset to the surrounding community. Inspiration for this project can be found in similar successful transformations, such as the Koepelgevangenis in Arnhem, the Werkspoorfabriek in Utrecht, and the Bijlmerbajes in Amsterdam. These examples show that with the right approach, vision, and collaboration, old buildings can be revitalized, ensuring they are preserved for future generations while also contributing to the livability and dynamism of urban environments.

Figure 2. Scenario scorecard created with DALL-E and ChatGPT-4

The scenario storylines served as input, accompanied by the prompt: "Create an image of an adaptive reuse scenario based on the scenario storyline above." DALL-E transformed the prompts into visual outputs, but refinement was needed to ensure the visualizations aligned more closely with specific expectations. Two images were generated: one from outside of the building and one from inside the building looking out.

The sections below describe the managerial implications of using AI tools in the early stages of adaptive reuse decision-making and how they can benefit practitioners.

ACCELERATING THE EARLY DESIGN PROCESS

Using AI visualization tools early in the design process has profound managerial implications. The traditional design process is lengthy and predominantly bottom-up: architects develop proposals for stakeholders to review and comment on. This sequential approach leads to delays and limited stakeholder engagement in the initial stages. By integrating AI visualization tools, stakeholders can be involved at the outset, collaboratively visualizing potential futures alongside architects.

This shift enables faster, more inclusive prototyping, allowing for iterative cycles in which scenarios are quickly explored, refined, or excluded based on collective input. The design process becomes more dynamic and responsive, reducing the time needed to arrive at an initial draft.

ALIGNING STAKEHOLDER WANTS & NEEDS

AI visualization tools can help align stakeholder wants and needs while enhancing their participation. In traditional design, differing stakeholder objectives lead to conflicting demands, making it hard to reach a consensus. AI visualization allows stakeholders to collaboratively visualize potential pathways, integrating these contradictory objectives in real time.

This approach accelerates the decision-making process and helps stakeholders see the tangible impact of their preferences and compromises, fostering a more inclusive and participatory environment. When integrated outcomes can be viewed early in the design process, managers can quickly identify and address potential conflicts, ensuring that the final design better reflects the collective vision of all parties.

ENVISIONING THE FUTURE

Traditionally, skilled architects produce renderings that resemble the final outcome, a time-consuming process that requires specialized expertise. Moreover, capturing the parametric complexity of early design stages is usually challenging. AI visualization tools streamline this process by making abstract concepts more tangible, allowing stakeholders to quickly grasp the potential impact of a scenario and reducing the need for multiple iterations.

Faster exclusion of unviable options helps surface the contradictions inherent in the design process. By making these tensions more visible and quantifiable, AI helps overcome human biases that often cloud judgment during abstract design phases. It acts as a heuristic tool, guiding stakeholders toward more concrete and balanced decisions, leading to more informed and efficient outcomes. These benefits are particularly valuable in complex projects where competing objectives must be balanced. AI enables a clearer understanding of trade-offs, helping managers "put their finger" on the magnitude of the contradictions and address them quickly and effectively.

LOOKING AHEAD

AI offers exciting opportunities to accelerate design processes and align stakeholder needs. It has the potential to enhance efficiency, empower individuals without traditional artistic skills, and drive sustainable innovation.

AI visualization tools do have drawbacks, including diminishing the role of human creativity in the early design process by giving non-creative individuals the ability to develop designs. It's important to develop AI-generated visualizations in collaboration with local artists or architects to ensure that human insight and creativity are maintained rather than replaced.

AI also contributes to the IT sector's increasing climate impact; the sector currently consumes nearly 10% of the world's energy.[29] In the project described above, a digital-first approach was adopted, using AI to visualize desirable futures for adaptive reuse. This approach leverages digital assets as the primary medium for experimentation and innovation, allowing firms to design, iterate, and optimize net zero solutions in the digital space before implementing them physically, which lowers emissions compared to traditional processes.[30]

We believe the future of AI lies in a digital-first approach, in which AI tools enhance decision-making at both management and individual levels. In particular, AI helps decision makers better understand circular scenarios, and it does so in a more iterative and participatory manner.

AI visualizations can inspire individuals by showing them a future they want to be part of (or one they want to avoid), encouraging them to embrace sustainable practices. Social barriers to adopting a circular economy, including resistance to change and perceptions of inconvenience, can be overcome by AI-powered visualizations that clearly represent the benefits of circular strategies.

By demonstrating how these approaches can reduce environmental impact, revitalize communities, and improve quality of life, AI can motivate individuals to embrace sustainable practices like adaptive reuse, making the transition to a circular economy achievable and personally rewarding.

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DIGITAL TWINS & SUSTAINABILITY:

A PATHWAY TO BUILDING POSITIVE-ENERGY DISTRICTS

Authors

Angela Greco and Andrea Kerstens

We are witnessing two pivotal transitions: the shift toward a low-carbon economy and the rapid digitization of our landscape. The first is progressing too slowly and needs to accelerate; the second is surging forward with unstoppable momentum, transforming our daily lives in unprecedented ways.

Given the contrasting paces of these transitions, failing to innovate solutions that harmonize both transitions while enhancing their synergies is a recipe for disaster. Sustainability-driven technologies are quickly becoming outdated, and organizations are experiencing lock-ins and innovation inertia, challenging their ability to reinvest and redesign and forcing them to reorganize at an unbearable pace.[1]

This phenomenon is already unfolding in the built environment. Construction companies are under pressure to lower their emissions. As they struggle to meet environmental targets like carbon and nitrogen reduction, the advent of digital twins offers the construction industry opportunities to manage buildings more efficiently throughout their lifecycle and beyond. Yet many struggle to embrace this shift: to digitize or not to digitize buildings?

> **CONSTRUCTION COMPANIES ARE UNDER PRESSURE TO LOWER THEIR EMISSIONS**

Although purposeful implementation of digital tools to achieve sustainability outcomes is promising, it may lead to unintended consequences.[2,3] In this article, we argue that if these undesirable consequences are not addressed from the outset, digital sustainability could undermine social and environmental outcomes rather than enhance them.

Below, we discuss the potential of digital twins and provide critical insights gleaned from a pilot project on digital twins for a positive-energy social housing district. These insights can help organizations responsibly implement digital twins.

DIGITAL TWINS FOR POSITIVE-ENERGY BUILDINGS

Globally, buildings are responsible for approximately 40% of total energy consumption and nearly 36% of CO_2 emissions. In comparison, industry accounts for around 26% of energy use. Shifting sustainability efforts from individual buildings to the neighborhood, district, and city levels is essential to effectively mitigate climate change and achieve the goals of the Paris Agreement.

Digital twins (dynamic digital representations of physical entities updated via Internet of Things [IoT] sensors, smart algorithms, machine learning, and cloud services) are crucial to this shift. They constitute a key technology that improves our ability to predict building demands in response to user needs and weather forecasts.[4] They also mitigate the risks of grid congestion resulting from peaks in energy consumption and surges in renewable energy production (solar and wind), currently a significant barrier to urban energy transitions.[5] This allows for more adaptive, efficient, and responsive energy use, improving comfort and overall quality of life within buildings. By leveraging digital twins, we can enhance energy efficiency at the building level and even across neighborhoods, creating favorable positive-energy districts that significantly contribute to climate mitigation efforts.

THE SYN.IKIA INNOVATION LIVING LAB

Syn.ikia, an initiative funded by the European Commission, aims to develop sustainable neighborhoods with surplus renewable energy across Europe. The name comes from the Greek words "syn" (συν), meaning "together" or "with," and "ikia" (οικία), meaning "house." This reflects the initiative's focus on collaboration and community-driven housing solutions. Its mission is to increase the number of neighborhoods that achieve surplus renewable energy while providing resilient, affordable living spaces across diverse contexts, climates, and markets in Europe.

The initiative includes 13 partners from six European countries. Together, they aim to increase the share of plus-energy houses in Europe by delivering a blueprint for sustainable plus-energy districts.

Syn.ikia has piloted four Sustainable Plus Energy Neighborhoods to demonstrate their functionality to European countries. These were tailored to four areas: Spain (Mediterranean climate), Austria (continental climate), the Netherlands (maritime climate), and Norway (subarctic climate). Built between 2020 and 2024, the neighborhoods serve as living labs for testing social and technological innovations.

Innovations include a participatory process for user-centric communities and social cohesion, advanced business models for positive-energy districts, implications for policy and financial instruments, and new ways to manage energy.[6-9] The latter includes complementary buildings consisting of edifices with different energy demands that can symbiotically share energy (e.g., an office that mainly needs energy during the day and a residential building that predominantly needs energy at night and on weekends).[10]

Digital twins are among the innovations being tested. In Uden, the Netherlands, the digital twin combines a virtual model for the building and its installations with an AI model that simulates user behavior and other dynamic factors (e.g., energy use, environmental conditions, and system performance).[11] Syn.ikia's partners are implementing this predictive twin in a model predictive controller to optimize excess on-site solar energy.

LESSONS LEARNED

Below are some key learnings from the Uden pilot. Some insights trace back to when the future inhabitants of the Uden neighborhood were first informed about the upcoming digital twin implementation. Others came later, when we cocreated possible approaches with project partners and present and future stakeholders to responsibly manage this technology at the intersection of digitization and sustainability.

ETHICAL DATA MANAGEMENT IS KEY

Imagine a winter day with a sudden drop of -10 degrees Celsius. You feel cold, reach for a blanket, and decide to increase your home's indoor temperature. When your home runs on gas boilers, you can turn on the heat by rotating a radiator valve or thermostat. You feel the radiator's warmth within minutes. If your home runs on sustainable energy and is heated through a geothermal heat pump, it may take hours to days to increase the temperature, depending on your system's capacity, your house's insulation, and the speed of the outside temperature drop.

DATA PROTECTION MUST BE A PRIORITY WHEN IMPLEMENTING A DIGITAL TWIN

If your home has a digital twin, you might not even realize the temperature had dropped and be surprised at how cold it is when you go outside. A predicting twin connected to a weather station knew there would be a temperature drop for a few days, and it slowly but steadily (hence, efficiently) heated your home to prepare for the temperature change. Digital twins can significantly reduce buildings' emissions by better preparing for future energy demands while ensuring comfort. The problem is that they need data (lots of data) to work.

Imagine you spend only a few hours at home and return home around the same time every day. Your digital twin knows you usually boil water at 6 pm, shower shortly after that, then turn on all the lights, the TV, the oven, and 60% of your other electrical devices. Knowing there will be a rise in energy demand coming from your apartment, the digital twin can prepare for your arrival while efficiently managing your energy demand and that of your neighbors. To do so, the digital twin needs to thoroughly understand the daily behaviors of those in the building.

Now imagine energy service companies have access to this data and are directly or indirectly managing the digital twin. These insights might impact energy pricing and energy contracts.[12] In a world run by renewables, where energy supply is sustainable but unstable, flexible energy pricing is becoming more common.[13]

Clearly, data protection must be a priority when implementing a digital twin, and the EU is working to ensure regulations keep pace with this fast-moving technology. But companies must also store and process data safely, something they are currently ill-incentivized and ill-equipped to do. As buildings become more digitized, there is a pressing need to protect users by making them aware of traceability risks and potential unethical implication, which leads to the next point.

DO NOT FORGET THE END USER!

User-centric design is not new. Over the past 50 years, design has become increasingly user-led, user-driven, and user-centric.[14] Architects and engineers have made significant strides in democratizing design, minimizing technocracy, and significantly reducing disempowering practices, something recognized as even more crucial to achieving sustainability outcomes in the built environment.[15] Nevertheless, digital twins may inherently limit user freedom by turning building management into an expert-only practice by sidelining nonexperts (i.e., disempowering them from engaging with and influencing the environments they inhabit).

Currently, digital twin developers are not framing this innovation as socio-technical, focusing instead on technical interactions. This is somewhat puzzling but not surprising. The advent of smart buildings (in which IoT sensors automate systems like HVAC, lighting, and security) led to many users expressing frustration about losing control over simple tasks like adjusting curtains or heating.[16] They are forced to rely on automated decisions made based on an average demographic that doesn't reflect individual preferences.

Digital twins still lack user-friendly interfaces. This may lead to users feeling alienated from their environments, reducing their sense of ownership and satisfaction. To truly empower users, digital twin development must prioritize intuitive interfaces and personalized control over automated systems. There's also a need to design platforms that foster community-driven solutions, empowering inhabitants while simplifying building management for all.[17] But this cannot be achieved by one actor alone and requires coordinated efforts across the entire building value chain.

MAKE IT VALUE CHAIN–PROOF

The building industry is notoriously fragmented.[18] Components, systems, and stakeholders often don't work together as smoothly as designs demand. This lack of integration can result in projects that seem patched together rather than cohesive solutions.[19] We might fix glaring short-term problems with minimal effort, but long-term issues like faulty installations or poor insulation could remain invisible for years, if not forever, negatively impacting the actual energy performance and CO2 emissions of buildings.

Unfortunately, learning from past mistakes isn't part of the industry's DNA. Companies in the construction sector rarely analyze what went wrong on previous projects, and even less frequently do they share feedback across teams, organizations, and stakeholders. In an industry driven by deadlines and budgets, solutions that could lead to better designs are often lost in the shuffle.[20] Without a feedback loop to improve on past experiences, digital twin technology risks reinforcing silos rather than breaking them down.

To make digital twins value chain–proof, they must become real-time learning and collaboration tools. They need to bring together all stakeholders (architects, contractors, engineers, users, and maintenance teams) to ensure everyone is reading from the same playbook. If we can close the feedback loop, we'll create systems that adapt and improve with every project, helping us spot potential failures before they happen and use data to guide better decision-making. Only then can digital twins benefit the entire value chain by fostering collaboration and continuous improvement (see Figure 1).

THE PATH FORWARD

For digital twins to deliver on their promise, we must focus on synergies rather than disjunction. This means creating a seamless flow between the technology, users, and the environment rather than introducing fragmented solutions that alienate one from the other. Architects, engineers, policymakers, and users must work together, learning from one another and feeding that knowledge back into the system. Without this, digital twins risk reinforcing the very silos they're meant to break.

And here's the reality: we may soon have no choice. As energy regulations tighten and sustainability targets become nonnegotiable, digital twins will move from a novel innovation to a necessary tool.

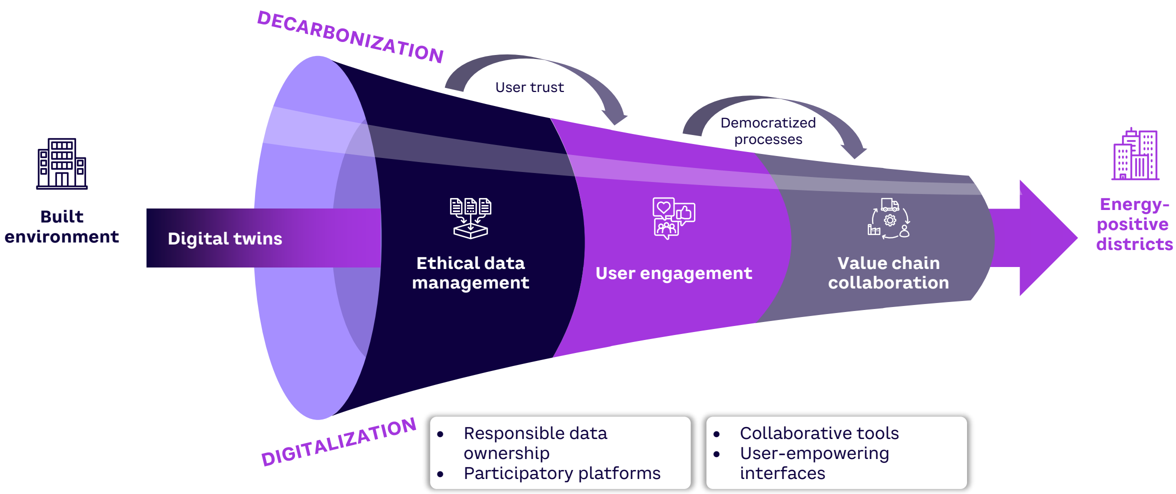

Figure 1. Digital twins benefit the entire value chain by fostering collaboration and continuous improvement

The question isn't whether you will adopt them but how prepared you'll be to make them work for you and your community.

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ESTABLISHING COLLECTIVE ENVIRONMENTAL SELF-REGULATION IN FRAGMENTED DIGITAL SPACES

Author

Armand Smits

Digital, cloud, and AI transformations are creating new offerings and business models. Fast-growing spaces and ecosystems are emerging at the intersection of existing industries. These transformations have been linked to a range of benefits for individuals, organizations, and societies.[1,2] At the same time, there have been calls to address their environmental impact.[3] A key example is the significant increase in energy consumption. Other developments include increased water use and the extraction of scarce minerals to support the cooling and constant renewal of the digital infrastructure that underpins these transformations.

Although environmental consequences are now on legislators' radar, the challenge of targeted and effective regulation in the digital age is significant.[4] Regulators often lack the skills and resources to effectively regulate and monitor the rapid and ongoing changes associated with digital and AI transformations. More participatory governance arrangements are needed, in which regulators engage in systematic dialogue with self-regulatory initiatives from the digital sector.

However, many digital fields are fragmented and still maturing. This can impede the collective action necessary for broader and more detailed self-regulatory initiatives to emerge. For instance, industry coordinating organizations are still inexperienced and may only represent firms from specific networks.

This article aims to help managers and policymakers understand how industrial players can overcome these difficulties. It draws on the Climate Neutral Data Centre Pact (CNDCP), which brought together a diverse group of data center operators to collaborate with the European Commission to limit the negative environmental impact of data centers,[5] and details three key practices used to develop the pact: forging new relationships, leveraging existing templates, and advancing inclusive audit frameworks.

CNDCP

The CNDCP, which was set up in close collaboration with the European Commission, pledged to achieve climate neutrality by 2030. Frans Timmermans, former executive VP of the European Commission for the European Green Deal, explicitly expressed his support:

> Today's pledge from important parts of the data industry constitutes a promise to society and offers a welcome first step toward achieving our common ambitions for a smart and sustainable future.[6]

> **MANY DIGITAL FIELDS ARE FRAGMENTED & STILL MATURING**

Pact members have committed to the European Green Deal, achieving greenhouse gas reductions that come with climate legislation, and leveraging technology to contribute to the ambitious goal of making Europe climate-neutral by 2050.

As is often the case in industry self-regulation,[7] increased attention to sector regulation at the European level was an important trigger for the pact. In 2019, the newly installed von der Leyen European Commission administration outlined an ambitious climate agenda that could lead to stricter regulation for data center operators. Although the field was not against regulation, there were concerns that new legislation would not be well adapted to the day-to-day operations of data centers. Data center operators wished to engage in further dialogue with the European Commission, and to do this more collectively, the pact was launched at the beginning of 2021.

CNDCP FOCAL AREAS

The pact comes with target setting, monitoring, and focal points for collaboration with legislators in several areas:[8]

- **Energy efficiency.** Digital services will continue to grow, but the impact of this growth on energy consumption will be determined by the pace of energy-efficiency gains. The pact commits to high standards of energy efficiency. Legislators are urged to reduce administrative barriers and facilitate cooperation toward more efficient information and communications technology (ICT) systems.
- **Clean energy.** The members of the pact are committed to meeting a significant proportion of the electricity needs of data centers with renewable energy. Members emphasize that the availability of renewable energy is a critical factor in realizing this goal.
- **Water.** Many data center operators use water for cooling. Recognizing that water is becoming scarce, the pact sets standards for water conservation.
- **Circular economy.** Data center operators plan to participate in the circular economy, an economic model that features prominently on political, governmental, and business agendas, particularly in Europe.[9,10] The circular economy promotes sharing, lending, reusing, repairing, upgrading, and recycling in a closed-loop system that aims to maintain the maximum utility and value of products, components, and materials in production and consumption. Pact members are committed to establishing, normalizing, and advancing circular economy business models and practices. The focus is on repairing and reusing equipment to reduce consumption. In this area, the pact calls on the EU to support policy frameworks that focus on and promote circular methods.
- **Circular energy.** Pact members agreed to explore the recovery and reuse of heat from new data centers. Heat recovery includes circular energy systems that use heat from a facility as a sustainable source for homes and buildings. Recovery can reduce emissions by displacing other energy sources used for heating and play a role in making Europe climate-neutral by 2050. However, optimizing heat recovery requires a policy framework that values the environmental benefits of recovered heat and reduces regulatory barriers to developing these projects.
- **Reporting/governance.** To increase transparency and support the quality of self-regulation,[11] the pact will meet with the European Commission twice annually to review its status. Furthermore, in its second year, an audit framework was developed, and participants are required to certify adherence.

To focus efforts, some targets (e.g., the ones for energy efficiency) were set right after the pact's initiation. Others, such as those on water use, were defined later or are still under development, including circular economy and circular energy.

3 KEY PRACTICES

Today, more than 100 operators have joined the pact. But how did this collective action take root given the fragmentation and dynamics in the field? Researching the pact yielded three supporting practices (see Figure 1) that are largely in the spirit of recombination, a mechanism designed to underpin a wide range of innovation processes.[12,13]

1. FORGE NEW RELATIONSHIPS

The intention of the European Green Deal was to understand the climate benefits of existing laws and introduce new legislation on the circular economy, building renovation, biodiversity, agriculture, and innovation.[14] The EU had already developed a code of conduct for data centers through its Joint Research Centre (in 2008). This voluntary code encouraged data center operators to use best

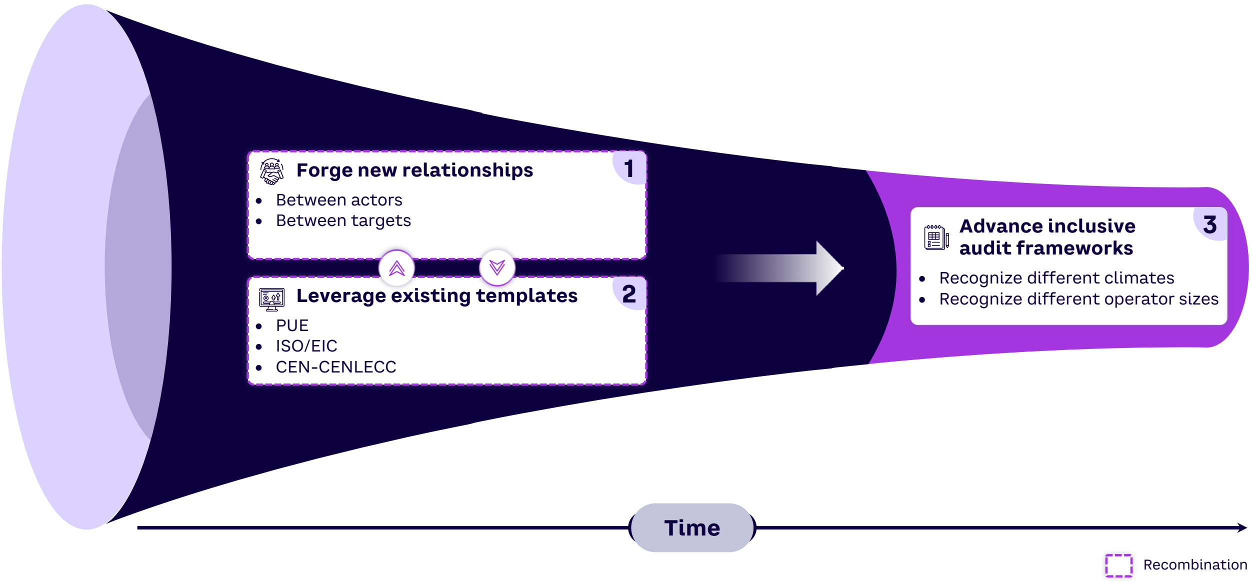

Figure 1. Three practices for setting up the Climate Neutral Data Centre Pact

practices to reduce energy consumption and promote sustainability. The industry feared that this code of conduct could become law under the Green Deal without sufficient input from the sector.

Two groups separately initiated a response and found each other at industry-wide events. The first was the European Data Centre Association (EUDCA), which predominantly represents industry participants with a co-location business model. The other group was CISPE (Cloud Infrastructure Services Providers in Europe), which represents companies with a cloud provider business model. They decided to work together to expand their reach, even though their business models compete with each other. The new relationship was formalized through the pact as a new organization run by representatives from both networks, which themselves had existed for less than a decade.

In addition to forging a relationship between the two networks, the pact also adjusted the industry's energy-efficiency target areas. The 2008 Data Centres Code of Conduct focused primarily on increasing energy consumption by data centers and the resulting environmental, economic, and energy security impacts.[15] The pact was the first to conflate this with a broader set of targets that became more prominent over time, such as water and circularity.

Addressing a broader set of issues supports the transition from carbon to climate neutrality but also complicates it, as targets can interact in non-synergistic ways. For example, some data centers evaporate water for cooling, and although removing it contributes to water targets, the energy for cooling must come from somewhere else, increasing energy use. These conflicts have been embraced and are now seen as targets for continuous innovation.

2. LEVERAGE EXISTING TEMPLATES

Institutional innovations such as the pact do not appear out of nowhere, and indeed, the pact appears to have drawn from several existing templates. For example, it used the power usage effectiveness (PUE) ratio to concretize the area of energy efficiency. PUE was introduced and promoted by The Green Grid, a nonprofit organization of IT professionals, beginning in 2007.[16] PUE is the ratio of the total energy consumed by a data center to the energy delivered to the computing equipment. The pact understands the limitations of PUE and is committed to helping develop a new efficiency metric, but it's using PUE for now because it is well-known in the IT infrastructure sector and thus makes it easier to get smaller players on board.

The pact also sought to align its auditing framework with existing international standards. The aim was to lower the cost of reporting by avoiding duplication and recognizing existing relevant certifications. The pact provided a comprehensive mapping of how its newly developed areas and targets correspond to a variety of partially overlapping European (CEN-CENLEC) and international (ISO/EIC) standards. This was further extended to US standards to accommodate operators with a global footprint.

3. ADVANCE INCLUSIVE AUDIT FRAMEWORKS

The pact also saw the wisdom of advancing inclusive audit frameworks, including recognizing the diversity of European climates in which data centers are built. Colder climates result in less need for cooling, which accounts for around 30% of the energy consumed by a data center. Therefore, it is easier to achieve better PUE levels in Finland than in Greece. Pact members agreed that by 2025, new data centers operating at full capacity in cool climates will have to meet an annual PUE target of 1.3, while those facing warmer outside temperatures will have to meet a PUE target of 1.4.

Pact members committed to meeting with the European Commission twice a year to review the initiative's status and introduced a performance assessment. To lower the threshold for participation and maintain inclusiveness, self-assessment was introduced for small data center operators. Large data center operators, which generally have more resources, must be assessed by an external assessor.

TAKEN TOGETHER

This article discussed collective self-regulation in the wake of Europe's push to combine digital and climate efforts. Collective action can be challenging for industry participants because digital spaces tend to be fragmented and complex. We zoomed in on the data center space to identify three practices that stand out in collectively setting up elaborate initiatives that go beyond broad codes of conduct and can therefore be better measured and monitored. This framework can easily be applied to initiatives in other digital spaces.

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GERMANY'S ENERGY INNOVATION HUB:

A CATALYST FOR CLIMATE NEUTRALITY

Authors

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Climate change will necessitate a profound transformation in economic structures, particularly global energy systems.[1] This transformation is more critical in regions historically dependent on fossil fuel industries — regions that have long served as the backbone of the global energy economy.[2] The imperative to change these areas from fossil-based energy production to sustainable alternatives presents a "wicked"[3] challenge.

The path to structural transformation is fraught with challenges, including entrenched economic interests, technological uncertainties, social resistance, and the potential for economic disruption in communities reliant on fossil fuel industries.[4] Technological change is often constrained by established systems, with high-margin incumbents reluctant to adopt low-margin, unproven alternatives, leading to a "lock-in" effect.[5,6]

Governments play a key role in fostering these changes, moving beyond regulatory frameworks to invest in high-risk, capital-intensive infrastructure projects and foundational research.[7] The private sector must then scale these innovations for broader adoption.[8]

This article focuses on Lusatia, a German region historically reliant on lignite (brown coal) for energy, and its ongoing transformation under Germany's ambitious Energiewende policy, which aims for climate neutrality by 2045. The transition involves closing all coal plants by 2038 and shifting to renewable energy. The region's transformation is guided by the Act to Reduce and End Coal-Fired Power Generation and the Structural Development Act, which provide financial and legal frameworks to support affected regions, including Lusatia.

The German government allocated €40 billion (US $43 billion) to support the transition, which includes infrastructure projects and job creation.[9] The Energy Innovation Center (EIZ) at Brandenburg University of Technology Cottbus-Senftenberg (BTU) is central to Lusatia's transformation, supporting innovation and technology development.

> **THE PATH TO STRUCTURAL TRANSFORMATION IS FRAUGHT WITH CHALLENGES**

EIZ: ENGINE OF STRUCTURAL CHANGE IN LUSATIA

EIZ was established in 2022 to drive the regional energy transition through research, entrepreneurship, technology transfer, and collaboration with industrial partners and other research institutes in the region. It is cofinanced with up to €102 million (US $112 million) for up to 10 years by the German Federal Ministry of Education and Research (BMBF) in partnership with the Investment Bank of the State of Brandenburg.

EIZ'S APPROACH TO RESEARCH & INNOVATION

The center comprises six interconnected and interdisciplinary research labs, each with a thematic focus (see Figure 1). With 15 professors, ~70 researchers and technicians at BTU, six project and innovation managers, and more than 50 additional partners from business and science, EIZ is ideally positioned for interdisciplinary research.

All EIZ research activities are dedicated to developing renewable energy technologies to replace Lusatia's lignite-based power production system. In a complementary approach, involved labs are developing novel solutions for establishing digital, intelligent, sector-coupled, secure, socially accepted, and sustainable energy system in collaboration with ecosystem partners in the region and beyond (see Figure 2).

EIZ is dedicated to product-oriented technology development and bridging the gap between research and Industry application through open innovation concepts. To enhance this approach, EIZ SPARK was formed in 2023 to act as an innovation and entrepreneurship center, where energy researchers and students drive the transition to a sustainable energy system by creating an open innovation ecosystem that accelerates knowledge and technology transfer from the labs to the marketplace.

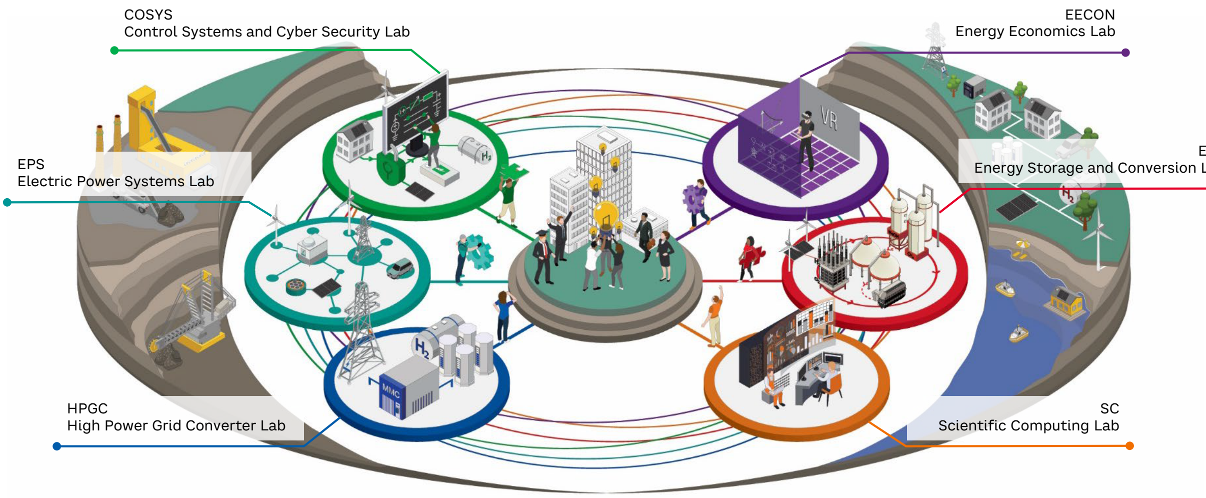


Figure 1. EIZ as a driver of Lusatia's energy transition

Figure 2. EIZ's components, technologies, and management structure

EIZ SPARK comprises entrepreneurs in residence and experts in energy technology, entrepreneurship, and innovation management to leverage both practical and conceptual expertise to achieve this mission. Unlike technology transfer centers that operate as independent entities across economic sectors, EIZ SPARK is closely integrated with EIZ research groups. This ensures ongoing interaction with researchers and emphasizes entrepreneurship and technology transfer.

EIZ's generous funding for basic research and infrastructure enabled the purchase of necessary lab equipment and the hiring of approximately 70 researchers. The project also gained considerable political backing, with high-profile visits from the German president, ministers, state secretaries, and international ambassadors that elevated the project's visibility.

The project quickly achieved significant academic success. Researchers presented their work at more than 40 global conferences and published more than 30 peer-reviewed articles within the first two years. The group participated in over 100 events, industrial fairs, and exhibitions, building partnerships with governmental and industrial organizations.

LOOKING TO THE FUTURE: EIZ'S TECHNOLOGICAL FOCUS

ENERGY STORAGE & CONVERSION TECHNOLOGIES

Power-to-X-to-power energy storage systems store surplus renewable energy in chemical energy carriers and release it during periods of low renewable energy generation. These storage systems are considered carbon-free because they recirculate carbon without emitting it into the atmosphere. They play a crucial role in the large-scale integration of wind and solar power into the energy market due to their high storage capacity, resilience, and potential for sector coupling.[10]

The Energy Storage and Conversion (ESC) Lab focuses on understanding fundamental processes within storage systems, enhancing process integration, and reducing costs for large-scale applications. This is accomplished by a multidisciplinary research team of engineers, physicists, and

EIZ BRIDGES THE GAP BETWEEN RESEARCH & INDUSTRY APPLICATION THROUGH OPEN INNOVATION CONCEPTS

chemists. Insights gained from experiments and field studies are shared with a team of computer scientists who drive the development of cutting-edge digital tools (see Figure 3).

The ESC Lab develops detailed simulation models for water electrolyzers, methane synthesis reactors, and combined heat and power plants, grounded in fundamental physical principles. These models are essential for determining fluid properties and calculating the dynamics of power-to-X-to-power energy storage systems. They enable virtual experiments that support deeper investigations and system optimization. Additionally, the data from these simulations is used to create data-driven metamodels and develop an advanced digital twin of the energy storage system.[11,12]

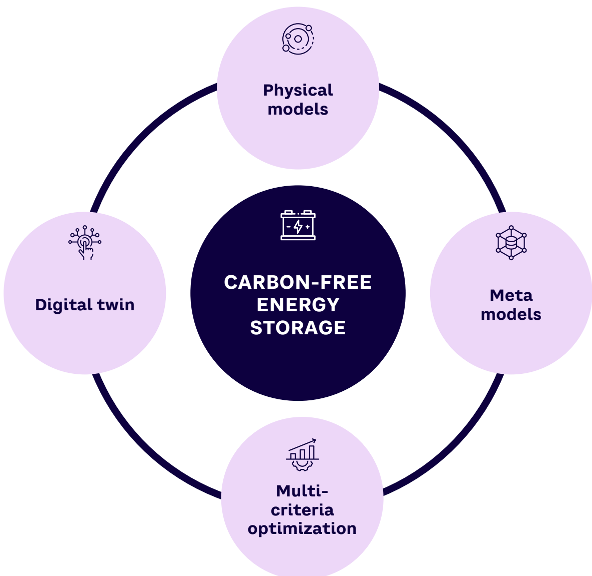


Figure 3. Innovative digital tools for carbon-free energy storage systems

Metamodels are developed from experimental and simulation data using statistical regression and machine learning algorithms. Although these models lack a physical foundation, they "learn" physical relationships from the data used in training. They effectively balance computational speed and accuracy, making them essential for multi-criteria optimization and digital twin development.

Physical models and metamodels enable virtual optimization of real processes, allowing the ESC group to identify operating parameters that maximize efficiency, minimize energy demand, or reduce operational costs. The group develops robust, reliable optimization methods capable of handling multiple objectives and a variety of optimization parameters. Multi-criteria optimization results are validated through energy system component test benches and a power-to-X-to-power energy storage system demonstrator.[13]

Digital twins leverage sensor data from the energy storage system, along with data from other sources (e.g., weather forecasts and energy markets), to create a virtual representation of the system. The goal is to predict the energy storage system's real-time behavior and provide feedback through multi-criteria decision-making. This allows the energy storage system to be automatically adjusted to changing conditions (e.g., weather, energy demand, electricity prices), ensuring optimal operation at all times.

STOCHASTIC & REDUCED-ORDER MODELS FOR MULTI-ENERGY SYSTEMS

The ability to "nowcast"[14] wind velocities is gaining importance as wind turbines are added to the power grid. Control is required to ascertain power grid stability so a control policy can generally benefit from more detailed knowledge of the wind velocity at a given site.

Available wind power P increases nonlinearly with the wind velocity v as $P = ½ \varrho Av3$, where ϱ is the mass density of air and A is the rotor area of the wind turbine, demonstrating that accurate wind-velocity predictions are crucial for substantial improvements in the estimation of the available wind power. Based on the established correlation between power output and wind velocity, it is worth noting that wind power fluctuations can be entirely attributed to fluctuations in genuinely unsteady wind fields.

To the best of our knowledge, standalone modeling tools for atmospheric flows under variable conditions do not exist, yielding a modeling gap for the operation of next-generation energy systems.

In addition, allocation of wind power sources is generally limited by the predictive capabilities and resolution of available models. It is too costly to select a numerical weather prediction (NWP) model for wind field predictions on different time and length scales, notwithstanding that NWP data has already been used for day-ahead forecasting of wind power ramps.[15] Another challenge is physically based modeling of wind-velocity profiles over a short time horizon, taking into account challenging atmospheric conditions.[16]

The team at the Scientific Computing Lab (SC) at EIZ explicitly addresses the challenge in wind power nowcasting for control applications, among other aspects of reduced-order modeling of multi-energy systems. It does this by developing and applying advanced stochastic tools for the standalone modeling of atmospheric wind-velocity profiles.

A one-dimensional stochastic model formulation is particularly well suited as it provides an almost ideal compromise between predictive capabilities, computational efficiency, and technical integrability.[17] The innovative feature is the use of nonlinear sampling that yields intermittent turbulent fluctuations as an emerging dynamical feature that results from energy-based modeling of turbulence in the atmospheric boundary layer. These stochastic models will contribute to a secure power grid operation that accommodates volatile sources. The main goal is to develop a stochastic tool that will enable nowcasts of the available wind power at the scale of an individual wind turbine.

MONITORING & OPERATIONAL TOOLS FOR SECTOR-COUPLED ENERGY SYSTEMS

Accurate monitoring and robust, efficient operation of an energy system undergoing transformative changes in production, transportation, consumption, and storage require novel and cyber-secure concepts for monitoring and control.[18] Future energy systems will seamlessly integrate optimally managed renewable energy assets through these advancements and accommodate new economic models for dynamic energy pricing.

This will occur in a context where demand response is prevalent and a stronger coupling exists through codesign and collaboration among various energy carriers, such as electricity and heating. Enabling these novel operating schemes is a challenging goal that requires decentralized (modular and scalable) adaptive modeling, monitoring, and cyber-secure control strategies for multi-energy systems.[19]

A holistic, structured, scalable approach to dynamic modeling and control has yet to be realized. Thus far, existing energy and demand management solutions are not robust enough to handle aggravating factors such as the presence of (model) uncertainties or unknown disturbances, including those originating from uncertain energy production or unpredictable fluctuating demand patterns.[20] Furthermore, increasingly complex energy systems that are increasingly exposed to the Internet may become the target of cyberattacks, jeopardizing the stability of energy networks and leading to the loss of private information.[21]

Consequently, the main goal of the interdisciplinary Control Systems and Cyber Security (COSYS) Lab of EIZ is to provide tested, cyber-secure schemes for operating and monitoring complex sector-coupled energy systems. This includes data-centric modeling and safety assessment algorithms for networked dynamical systems.

> **A HOLISTIC, STRUCTURED, SCALABLE APPROACH TO DYNAMIC MODELING & CONTROL HAS YET TO BE REALIZED**

Key objectives also include the development of methods/tools for explainable and interpretable attack and anomaly detection in digitally connected energy systems and research/evaluation of end-user privacy-protection techniques.

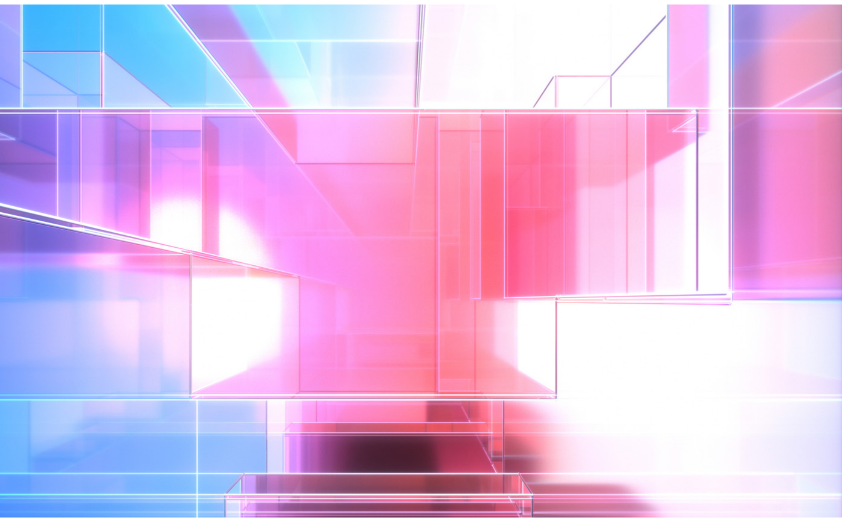
COSYS is also working to validate theoretical developments by commissioning a state-of-the-art hardware-in-the-loop laboratory. This facility also supports prototype testing and the demonstration of system-wide and component solutions. Such efforts are essential for promoting knowledge transfer to the region through active collaboration with local stakeholders, creating an incubation hub for new ideas, technologies, and products.

STUDYING THE PUBLIC ACCEPTANCE OF SUSTAINABLE INFRASTRUCTURES

To achieve climate neutrality by 2045, Germany's energy system must undergo significant changes, including expanding solar panels, wind parks, hydrogen infrastructure, and carbon-capture storage.[22] These changes traditionally face low social acceptance, which can slow down the transformation process.[23]

The Energy Economics (EECON) Lab at the EIZ studies the factors influencing social acceptance of energy infrastructure projects. People from all social groups in the Lusatia area are invited to participate in a two-part study.

Participants first experience a virtual reality (VR) scenario that simulates the impact of energy infrastructure, including wind turbines, solar panels, direct reduction plants for steel decarbonization, and railway transport for carbon-capture storage. The information in the VR scenario varies between groups to analyze its effect on social acceptance. (VR is used because it creates immersion among the participants and effectively conveys information about new technologies, making them more understandable.[24])



Next, participants take part in a laboratory experiment, where they make financially consequential decisions about energy infrastructure. For instance, they might decide to expand solar energy projects or provide financial support for green hydrogen projects. By focusing on consequential decisions, researchers can measure revealed preferences instead of stated preferences (the latter is hypothetical and hard to take at face value).[25,26]

Policymakers can use the study outcomes to accelerate the energy system transformation. For example, the results show which types of information or participation processes (procedural, financial) may be most effective in increasing public acceptance of the energy transition.

KEY INSIGHTS

The focus of the EIZ on sector coupling and the intelligent digital operation/optimization of complex energy systems leads to five key insights:

1. **Power-to-X-to-power energy storage systems, supported by advanced simulation and digital twin technologies, enable efficient, carbon-free storage and renewable energy retrieval.** Using virtual optimization and real-time system adjustments, these tools enhance storage performance, reduce operational costs, and facilitate reliable integration of renewables into the energy market.
2. **Advanced stochastic models for nowcasting of unsteady wind velocities offer an efficient, scalable solution for more accurately predicting wind power at individual turbine sites.** These models provide means for extended predesign studies and enhanced grid stability through precise short-term forecasts that account for turbulent atmospheric fluctuations, thus contributing to improved control strategies and integration of wind energy into the power grid.
3. **Cyber-secure, adaptive monitoring and control tools are essential for managing and protecting complex, sector-coupled energy systems.** These tools help practitioners ensure stable operations, respond to unpredictable energy demands, and defend against cyber threats, while a hardware-in-the-loop lab offers a practical environment for testing and demonstrating robust solutions in real-world scenarios.
4. **Engaging the public through immersive experiences like VR and using real financial decision-making scenarios can significantly improve the understanding and acceptance of energy projects.** These insights can guide practitioners in designing targeted, effective communication and compensation strategies that build trust and facilitate smoother project implementation in local communities.
5. **Successful implementation of transformative innovation projects like the EIZ requires streamlining bureaucratic processes, enhancing funding agility, and building collaborative frameworks from the start.** A specific focus must be put on reducing administrative barriers, enabling faster hiring and procurement, and fostering strong partnerships among academic, industrial, and regional stakeholders.

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