

Building Twin Transitions: Colliding Digital and Sustainable Paths for Positive Energy Districts.

Abstract

Angela Greco and Andrea Kerstens look at the opportunities and risks of implementing digital twins to accelerate the effectiveness of Positive Energy Districts. Digital twins can potentially facilitate user comfort, energy management, and energy savings in the built environment. However, they can also result in unintended consequences, undermining both environmental and social outcomes. Drawing on insights from Syn.ikia —an initiative funded by the European Commission to develop, test, and implement innovations for Positive Energy Districts— they reflect on the potential unintended consequences of digital twins and provide recommendations for companies considering their implementations.

Introduction

We are witnessing two pivotal transitions: the shift towards a low-carbon economy and the rapid digitalization of our landscape. While 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 different paces of these transitions, failing to innovate symbiotic solutions that harmonize both transitions while enhancing their generative 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 Sustainability-driven technologies are quickly becoming outdated, and organizations are experiencing lock-ins and innovation inertia, challenging their ability to reinvest and redesign, requiring them to reorganize at an unbearable pace.¹

We are already observing this phenomenon unfolding in the energy transition and digitalization of the built environment. Construction companies are under pressure to lower their emissions. As they grapple with meeting environmental targets like carbon and nitrogen reductions, the advent of Digital Twins offers the construction industry new opportunities to manage buildings more efficiently throughout their lifecycle and beyond. Yet, many still struggle to embrace this digital innovation shift: to digitalize or not digitalize buildings?

While the purposeful implementation of digital tools to achieve sustainability outcomes is promising,² it may also lead to unintended consequences.³ In what follows, we argue that if these potential consequences are not addressed from the outset, digital sustainability could undermine social and environmental outcomes rather than enhance them.

Below, we introduce the potential of digital twins and provide critical insights we learned from a pilot project on digital twins for a positive-energy social housing district. These insights can aid organizations working to innovate and implement digital twins responsibly.

Why digital twins for positive-energy buildings?

Globally, buildings are responsible for approximately 40% of total energy consumption and nearly 36% of CO₂ 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 for effectively mitigating climate change and achieving the goals of the Paris Agreement.

Digital twins – dynamic digital representations of physical entities updated via IoT sensors, smart algorithms, machine learning, and cloud services – are crucial in enabling this shift. They constitute a key enabling technology that improves the prediction of buildings' demands in response to users' needs and weather forecasts.⁴ They also mitigate the risks of grid congestions resulting from peaks in energy use and renewable production, which is currently a significant barrier to urban energy transitions.⁵ This allows for more adaptive, efficient, and responsive energy use, improving comfort and societal well-being within buildings. By leveraging digital twins, we can enhance energy efficiency at the building level and across entire neighborhoods and districts, creating favorable positive energy districts that significantly contribute to climate mitigation efforts.

A pilot project within Syn.ikia

Syn.ikia' is an initiative funded by the European Commission to develop sustainable neighborhoods with surplus renewable energy across Europe. The name comes from two Greek words: 'Syn' (συν), meaning 'together' or 'with,' and 'Ikiá' (οικία), meaning 'house.' This reflects the initiative's focus on collaboration and community-driven housing solutions and its mission to increase the share of sustainable neighborhoods with surplus renewable energy and resilient and affordable living places in different contexts, climates, and markets in Europe. This innovation initiative brings together 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. Throughout the initiative, Syn.ikia piloted four real-life Sustainable Plus Energy Neighborhoods to demonstrate their functionality to European countries. These have been tailored to four European climatic zones, contexts, and markets, namely in Spain (Mediterranean climate), Austria (Continental climate), The Netherlands (Maritime climate), and Norway (Subarctic climate). Built between 2020 and 2024, these neighborhoods now serve as living labs for testing new social and technological innovations. Examples of innovations include a new participatory process for user-centric communities and social cohesion,⁶ new business models for positive-energy districts,⁷ implications for policy⁸ and financial instruments,⁹ and new ways to manage energy, for example, through complementary buildings consisting of edifices with different energy demands that can share energy symbiotically¹⁰ (e.g., an office needing energy during the day and housing predominantly needing it during the night or weekend).

One of the innovations being tested is the digital twin. In the pilot case in Uden, the Netherlands, the digital twin combines a physical model for the building and its installations with an AI model that describes user behavior.¹¹ Syn.ikia's partners are implementing this predictive twin in a model predictive controller (MPC) to optimize the temporary excess capacity of on-site solar energy. In what follows, we shared some key learnings deriving from this pilot. Some of our learnings trace back to when we informed the future inhabitants of the neighborhood in Uden about the upcoming digital twin implementation and when we co-created possible approaches with various project partners and stakeholders to responsibly manage this technology at the intersection of digitalization and sustainability.

Lesson Learned

Ethical Data Management is Key

Imagine a cold winter day with a sudden drop of -10 degrees Celsius. You feel cold, reach out for a blanket, and want to increase your home's indoor temperature. When your home runs on gas boilers, you can turn on the heating by rotating your radiator valve or thermostat. You can feel the radiators' warmth –and dry indoor air – within minutes. But, if your home is running on sustainable energy and

is heated through a geothermal heat pump, it may take several hours to days to increase the temperature, depending on your system's capacity, your house's insulation, and the speed of outside temperature drop. But if your home has a digital twin, you might not even realize a sudden temperature drop and be surprised by how cold it is outside when walking out the door. A predicting twin connected to a weather station knew already there would be a temperature drop for a few days, and slowly but steadily – hence efficiently – heated up your home to prepare for this sudden drop. Digital twins can significantly reduce buildings' emissions by better preparing for future energy demands while ensuring comfort. The problem? They need data. Lots of data to make it work.

For example, imagine you spend only a few hours at home and return home roughly around the same time every day. Your digital twin knows you will boil water at 6 p.m. every day, shower shortly after, and turn on all the lights, your TV, the oven, and 60% of your other electrical devices. The digital twin can prepare for your arrival, knowing there will be a pick in energy demands coming from your apartment, and manage efficiently the energy and comfort for you and your neighbors simultaneously. To do so, the digital twin needs to learn well about your daily behavior and those of your neighbors. That's what we want and need from an energy-efficiency perspective.

But imagine if energy service companies were to have access to these data and perhaps be the ones to, one day, directly or indirectly be involved in managing digital twins. 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

Data protection must be a priority if you consider implementing a digital twin. Current EU legal frameworks are trying to keep pace with these fast developments. Still, companies must also store and process data safely –something they are currently ill-incentivized and equipped to ensure. With the digitalization of buildings –including digital building logbooks and passports – there is a pressing need to protect users and make them aware of traceability risks and potential unethical implications.

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 to democratize design, minimize technocracy, and significantly reduce disempowering practices. Something recognized as even more crucial to achieving sustainability outcomes in the built environment.¹⁵ Yet, digital twins may inherently limit user freedom by turning building management into an expert-only practice. This risks sidelining non-experts, effectively disempowering them from engaging with and influencing the environments they inhabit. Currently, digital twin development is not framing this innovation as socio-technical, focusing instead on technical interactions and overlooking the social dimensions. This is puzzling but not surprising. Learning from the advent of smart buildings—where IoT sensors automate systems like HVAC, lighting, and security—many users expressed frustration at losing control over simple tasks like adjusting curtains or heating.¹⁶ Instead, they must rely on automated decisions made for an average demographic that doesn't reflect individual preferences.

The development of digital twins still lacks user-friendly interfaces. As a result, a possible unintended consequence of digital twins is that they can disempower users and make them feel 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. This also presents an opportunity to design platforms that foster community-driven solutions, empowering inhabitants while simplifying building management for all.¹⁷

Make it value-chain proof

The building industry is notoriously fragmented.¹⁸ Different components, systems, and stakeholders often don't work together as smoothly as the design would demand. This lack of integration can result in projects that seem like patchwork rather than cohesive solutions.¹⁹ And while we might fix glaring short-term problems with quick, minimal effort, long-term issues like faulty installations or poor insulation may remain invisible for years, if not forever.

A significant problem is that 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 rush.²⁰ Without a feedback loop to improve on past experiences, digital twin technology risks reinforcing these 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 works from the same playbook. If we can close the feedback loop, we'll create systems that adapt and improve with every project, allowing us to spot potential failures before they happen and use data to guide better decision-making. Only then can digital twins become a valuable opportunity to benefit the entire value chain by fostering collaboration and continuous improvement.

Conclusion: The Path Forward for Digital Twins

For digital twins to deliver on their promise, we must collectively 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. It's not just about technical innovation—collaborative effort is essential. 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: soon, you might have no choice. As energy regulations tighten and sustainability targets become non-negotiable, digital twins will move from a novel innovation to a necessary tool. The question isn't whether you will adopt them but how prepared you'll be to make them work for you and your community.

Authors Bio

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Andrea Kerstens is a scientist at TNO Vector in The Hague, The Netherlands, specializing in collaborative business models and innovation orchestration at the intersection of digital technologies and sustainability. In addition to this position, she is a Ph.D. candidate in innovation management at Delft University of Technology, where her research centers on innovation intermediaries in cross-

sector partnerships, particularly in implementing and scaling innovations to tackle wicked problems in the built environment.

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