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Creating Zero Carbon Communities: The Role of Digital Twins

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TABLE OF CONTENTS

Section 1
EXECUTIVE SUMMARY

1.1 Smart Communities Are the Building Blocks for Zero Carbon Cities

Cities around the world have announced commitments to meet the global climate change goals established at the Paris conference in 2015. Often more ambitious than national government targets, many cities have plans to be carbon neutral or zero carbon cities by 2050. The Global Covenant of Mayors estimates that, if fully implemented, commitments made by the 9,000-plus cities aligned to its goals would achieve annual reductions of 1.4 Gt CO2e in 2030 and 2.8 Gt CO2e in 2050.

The challenge is to make such commitments a reality. A comprehensive reduction in urban emissions requires an increased focus on transforming energy use in buildings and transport, as well as a shift from fossil fuels to renewable energy sources. It also requires a holistic approach to the decarbonisation of city operations, infrastructure, and services.

> *Digital twins have an important role to play in understanding and managing the complex integration of multiple assets and systems that characterize community-scale projects.*

Understanding the interplay of different sectors at city-scale is a daunting task. This challenge is leading to a growing interest in community-scale programmes that encompass most of the elements of a city system but at a more manageable scale. Smart energy communities, zero carbon districts, and positive energy blocks are among the labels used to identify district- and community-level schemes. Community-scale initiatives also include bounded complex environments such as islands, university campuses, airports, and large real estate developments. Such projects represent an important upward scaling of climate action within individual sectors to a more holistic view that encompasses integrated energy systems and broader behavioural and social changes. Community-scale projects are the place where broader policy objectives and practical programmes for transformation can come together.

To realise the potential of community-scale projects requires tools that can help planners, designers, managers, and users make the right decisions across a complex set of possible actions and investments. Digital twins can provide the complex modelling, analytical, and simulation capabilities needed. They can also support the needs of diverse user groups, including citizens and other service users.

1.2 The Role of Digital Twins

> *Digital twins enable new forms of modelling and analysis that were previously either impossible or uneconomic to perform.*

At its simplest, a digital twin can be defined as a digital representation of a real-world asset or group of assets. However, digital twins potentially offer a much richer capability to model and analyse real-world systems and how they change over time. Digital twins are not based on any one technology. They require a combination of capabilities for data management, analytics, simulation, visualisation, and information sharing. Machine learning and advanced analytics combined with an understanding of real-world conditions (such as energy flows, environmental conditions, and material attributes) means digital twins can provide new insights into the behaviour of assets and infrastructure under current and future conditions. The ability to visualise this data in 2D and 3D models and over time makes the information accessible to many levels of user.

1.3 Lessons from Pioneers

Digital twins have an important role to play in understanding and managing the complex integration of multiple assets and systems that characterize community-scale projects. Examples of digital twin projects covered in this paper include:

- An island community looking to optimise the use of local energy through a combination of grid improvements, distributed energy generation and storage, and energy efficiency
- A university looking at integrated approaches to buildings and energy services to create the greenest campus in the world
- A new residential development deploying a community energy system that includes one of the largest community batteries in Europe
- A city looking to create positive energy blocks across several districts based on a holistic approach to energy, transport, building, and social development

Key insights from these and other digital twin projects include:

- **The biggest challenge in developing a digital twin is accessing and managing data:** Common data management issues are amplified in community-scale projects, which require data from multiple systems, in many different formats, and with different governance models.
- **Working with digital twins requires new skills in modelling, analytics, and visualisation:** A successful digital twin project needs an integrated team, often from different organisations. Building a collaborative partnership is as important as accessing the right technical capabilities.
- **Community-scale projects need to support multiple stakeholders, including residents and other end users in the community:** The single point of truth that digital twins provide is the basis for simulation and exploration from multiple perspectives.

1.4 Report Scope

This paper provides a roadmap for the use of digital twins in the development of zero carbon communities. It includes:

- An overview of the key elements of digital twin solutions and their value in supporting community-scale projects
- Examples from a diverse range of organisations that are using the capabilities of digital twin technologies to improve their energy efficiency and reduce greenhouse gas (GHG) emissions
- Recommendations for organisations getting started with digital twin projects and advice on how to tackle the most common challenges

Section 2

MAKING ZERO CARBON VISIONS A REALITY

2.1 Cities and Communities Take the Lead in Decarbonisation

According to the Intergovernmental Panel on Climate Change (IPCC) *Global Warming of 1.5ºC* report, holding the global temperature rise below 1.5°C will require 'rapid, far-reaching and unprecedented changes in all aspects of society'. The importance of cities to meeting global climate targets is undisputed. By 2050, the world's urban population is expected to reach 6.3 billion, and two-thirds of the people on the planet will be living in urban centres. Cities are responsible for more than two-thirds of the world's energy use and greenhouse gas (GHG) emissions.

The International Energy Agency estimates that the potential emission reductions related to urban energy use by 2050 is equivalent to 70% of the total energy-related reductions required to meet climate targets. But time is of the essence. The C40 Cities Climate Leadership Group (C40) estimates that 97% of the actions needed to achieve global emissions goals for 2050 need to be implemented in the world's leading cities by 2030 if the goals set out in the Paris Agreement are to be met.

Table 2-1. Climate Action Plans of Selected Cities

City	Country	Climate Action Plan
Boston	US	Reduce GHG emissions 25% by 2020 (compared with 2005 levels); carbon neutral by 2050
Cape Town	South Africa	Carbon neutral by 2050 (commitment made with eight other African cities)
Copenhagen	Denmark	Carbon neutral by 2025
Glasgow	UK	Carbon neutral by 2037 (with proposal to move to 2030 target)
Houston	US	Carbon neutral by 2050
London	UK	Reduce CO_2 emissions 60% by 2025 (compared with 1990 levels); zero carbon by 2050
Melbourne	Australia	100% renewable energy, zero building emissions, and zero transportation emissions by 2050
Munich	Germany	100% renewable energy powered by 2025
San Diego	US	100% renewable electricity by 2035
Stockholm	Sweden	Fossil fuel free by 2040
Sydney	Australia	Reduce GHG emissions 70% by 2030 (compared with 2006 levels); net zero emissions by 2050
Vancouver	Canada	100% of city energy (including transport) from renewable sources and a carbon neutral city by 2050

(Source: Navigant Research)

City leaders are committing to deliver the reduction in urban emissions needed to meet global climate goals. Table 2-1 highlights a selection of the many cities that have announced ambitious climate mitigation programmes.

In addition, 19 cities have signed the Net Zero Carbon Buildings Declaration. City leaders from Copenhagen, Johannesburg, London, Los Angeles, Montreal, New York City, Newburyport, Paris, Portland, San Francisco, San Jose, Santa Monica, Stockholm, Sydney, Tokyo, Toronto, Tshwane, Vancouver, and Washington DC pledged that all buildings in these cities, old or new, will meet net zero carbon standards by 2050.

The Global Covenant of Mayors for Climate & Energy estimates that, if fully implemented, commitments made by the 9,000-plus cities aligned to its goals would achieve annual reductions of 1.4 Gt CO2e in 2030 and 2.8 Gt CO2e in 2050 from business-as-usual levels. A reduction in 2030 equivalent to taking all the cars in the US off the road for 1 year.[1]

Impressive as such commitments may be, making them a reality requires new approaches to urban infrastructure and services enabled by new energy systems, building technologies, and digital analytics. It also requires new platforms and tools that can support collaboration between city departments, businesses, and citizens in the transformation to a zero carbon economy. Digital twins can play an important role in meeting these needs.

2.2 Cross-Sector Programmes Are Key

A zero carbon city needs to comprehend and manage a complex set of interdependencies that are changing over time. Diverse aspects of city operations, infrastructure, and platforms must also be understood in relation to city priorities such as improving health, mobility, sustainability, and economic prosperity. Developing such a city vision requires new forms of collaboration between cities, utilities, and other energy sector players, as well as transportation providers, building owners, and technology companies.

[1] The Global Covenant of Mayors for Climate & Energy, *Implementing Climate Ambition,* 2018.

Much of the potential for carbon reduction comes from policy initiatives that link urban planning, buildings, transport, energy generation, and energy efficiency. Planning policies, for example, can influence the demand for transport, reduce or increase commuting times, and improve integration with low carbon mobility options. Transport policies are also increasingly linked with improvements in the energy infrastructure, for example, using electric vehicles as part of active grid management services to help integrate renewable energy. Similarly, the ability to reuse waste heat from industrial processes and the provision of district cooling systems can reduce energy requirements. However, implementing such cross-sector initiatives remains a daunting challenge given the complexity of the modern city and the difficulty in developing a holistic understanding of the transition needed across a city's infrastructure, operations, and services.

This challenge is leading to a growing interest in community-scale programmes that encompass most of the elements of a city system but at a more manageable scale. Smart energy communities, zero carbon districts, and positive energy blocks are among the labels used to identify district- and community-level schemes. Other environments with similar characteristics of a bounded complexity include islands, university campuses, ports, airports, and large real estate developments. Such projects represent an important upward scaling of climate action from individual sectors (for example, improving building energy efficiency or increasing the use of renewable energy) to a more holistic view that encompasses integrated energy systems and broader behavioural and social changes. Community-scale projects are where broader policy objectives and practical programmes for transformation can come together.

2.3 From Buildings to Smart Energy Communities

New approaches to building energy management provide a good example of the system-wide perspective needed for community-scale programs. Improving the energy efficiency of the building stock is a crucial first step in creating a zero carbon city or community. According to the IPCC, the global building stock needs to have 80% to 90% lower emissions in 2050 compared with 2010 levels to achieve a pathway consistent with a 1.5°C target for global warming. This goal also requires a minimum 5% annual rate of energy retrofits of existing buildings in developed countries as well as all new buildings being built fossil-free and near zero energy by 2020.[2]

[2] Intergovernmental Panel on Climate Change, *Global Warming of 1.5ºC,* 2018.

The extension of building systems from standalone applications focused on the operation of a single building to hubs within a wider network of energy and environmental monitoring systems will be one of the most dramatic changes in the technical infrastructure of the city.

Buildings are responsible for around 40% of global final energy use and around one-third of GHG emissions—and for much higher percentages in many urban areas. Important steps already being taken to reduce the carbon footprint of the buildings sector include stronger building energy efficiency standards for new development, retrofit programmes for existing buildings, the development of district heating and cooling systems, and a shift to renewable energy, often produced locally.

Any building is part of a complex network of services for energy, water and waste management, telecommunications, and transport. Traditional approaches leave the buildings as endpoints in those networks, using services but remaining oblivious to the wider network. In a zero carbon city, this perspective changes as buildings become active elements in these networks. As more buildings become energy generators and part of sophisticated demand management programs, they become integrated with the energy grid. Water recycling and waste management systems also link buildings more tightly into a city's ecosystem. In addition, buildings are integrated with transport systems through the provision of EV charging points or connection to traffic and public transport information systems.

Energy efficient buildings are also increasingly smart buildings. Building control and automation systems are evolving to incorporate advanced building energy management systems and new adaptable and highly granular Internet of Things–based systems. These developments are enabling the monitoring and optimisation of building performance, supporting centralized management across portfolios of buildings, and paving the way for new connections between individual buildings and the city's digital and physical networks.

The extension of building systems from standalone applications focused on the operation of a single building to hubs within a wider network of energy and environmental monitoring systems will be one of the most dramatic changes in the technical infrastructure of the city. It is estimated that less than 1% of the commercial building stock globally is actively participating in the energy system, but over the next decade, this will rise to more than 10%.

2.4 The Need for Community-Scale Tools: The Rise of the Digital Twin

The potential for carbon reduction offered by closer integration of actions across multiple sectors is clear. However, cross-sectoral approaches introduce significantly more complexity into already difficult decision-making processes. Understanding the interdependencies across building optimisation decisions, energy grid management, and mobility planning, for example, requires data integration across many sources and sophisticated analysis, visualisation, and decision support systems. Digital twin technologies can help cities understand these relationships, the options available to drive a transformation in energy consumption and carbon emissions, and the impact on different communities.

Digital twins need to be understood as a combination of capabilities brought together on a shared platform that provide a single point of truth for multiple use cases and diverse stakeholders.

Digital twins are evolving from several key trends in the development of new digital tools, notably:

- **The proliferation of sensor technologies that provide real-time, highly granular data on assets and processes that were previously invisible.** In addition, a wide range of rich contextual data is available, for weather patterns, demographics, infrastructure and building design, social sentiment analysis, and transport patterns, for example.
- **Machine learning and artificial intelligence (AI) capabilities can analyse these vast data sources and their complex interdependencies to provide insights to decision makers.** AI can also help improve data quality and fill gaps in operational data.
- **Dynamic simulation modelling tools that use the fundamental principles of physics, building information modelling, energy networks, infrastructure data, and developments in CAD tools to create models that accurately replicate real-world behaviour.** These models can then be used to analyse multiple scenarios for improved system design and optimisation.
- **Visualisation tools improve the ability of decision makers to work with sophisticated datasets and advanced analytics tools to understand the real-world implications of changes across a complicated network of assets and relationships.** They also make new forms of stakeholder engagement possible—providing the means for users at all levels to understand the impacts and the potential of new approaches.

The digital twin has emerged as an umbrella term for these and other technologies, which when combined, provide new insights into the complexities of integrated systems. By enabling more sophisticated and accessible models of those systems to be built and manipulated, digital twins allow for the simulation of changes on real-world assets. Impacts across the life cycle of buildings and other infrastructure can be assessed, as can cascading effects on dependent systems. This allows informed decisions to be made regarding complex problems spanning multiple operational sectors and classes of assets.

Digital twins are not a solution looking for a challenge—as so often with new technologies—but rather a confluence of technology evolution and pressing real world challenges.

2.5 Digital Twins Enable Zero Carbon Communities

Digital twins enable new perspectives on the creation of zero carbon communities spanning the entire life cycle of from planning, design, and construction to ongoing operational management and optimization. Employing a digital twin approach supports the move towards zero carbon communities in various ways. Drawing on data from buildings, energy networks, planning, environmental systems, transport infrastructure and services, and sociodemographic indicators, a cross-sector digital representation of the community can be built. This model can then be used to simulate the impact of changes, anticipate ripple effects through different community assets and services, and understand potential impacts on key community goals. Particularly important is the ability to simulate different scenarios for the community based on different approaches to energy management and emissions reduction. It becomes possible to look at costs and benefits across the whole system for initiatives such as district heating, local energy production, community energy storage, and increased EV charging capacity. Moreover, digital twins allow for what-if analysis of the future impact of changes to the system, as well as to external factors, such as climate and demographic changes

Examples of how digital twins can support community-scale energy and climate programmes include:

- A community can look at alternative scenarios for investing in building energy efficiency programs, distributed energy resources (solar PV, energy storage), and behavioural change programs to prioritise activities and investments.
- Cross-sector benefits can be understood through analysis of the interdependence of building, energy, and transport systems. For example, providing community EV charging may change demand profiles for energy, raise issues around grid reliability, open opportunities for vehicle-to-grid services, and have implications for community transit planning and operation. Similarly, increased use of transit or better bicycle or walking options could change the likely demand profile for EV charging.
- The evolution of community-scale systems can be monitored, systems modified, and alternative paths chosen. Significant system changes that can have an impact on zero carbon goals, such as changes in user behaviour or socioeconomic trends, can be anticipated.
- Stakeholder engagement can be enhanced. The need to support multiple stakeholders across the community and to increase their engagement with new systems requires accurate but accessible means of visualising not only the current state but also the impact of potential changes.

2.6 Positive Energy Districts as a Foundation for a Smart City

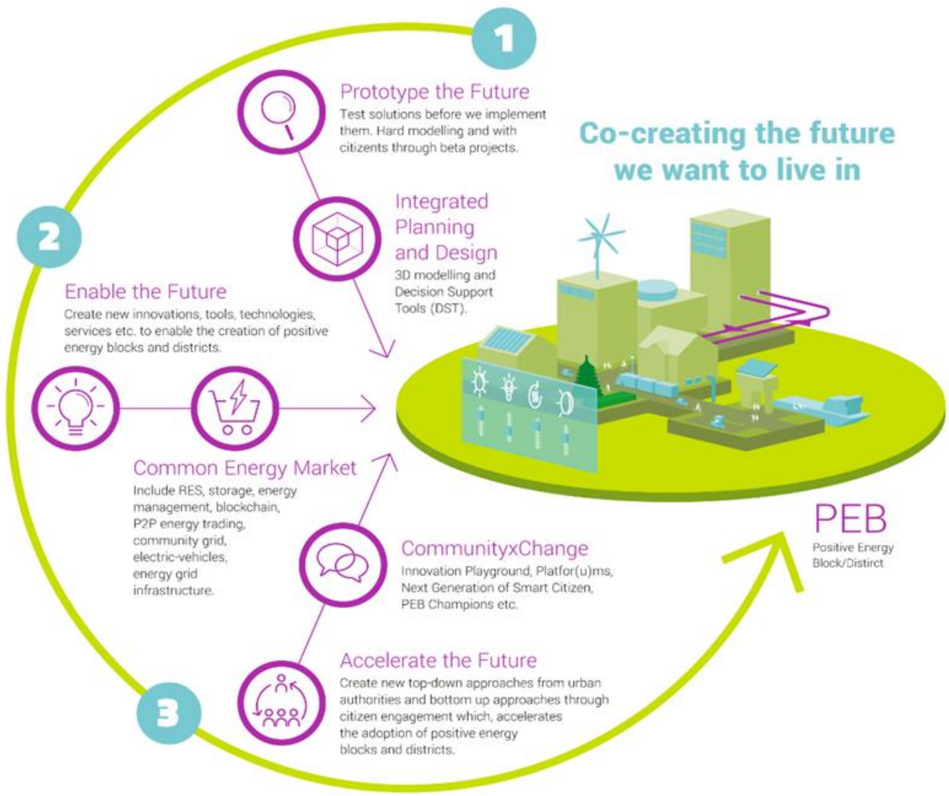
The +CityxChange (Positive City ExChange) project provides a good example of how digital twin technology can support the shift to zero carbon communities.

The European Commission's Programme on Positive Energy Districts and Neighbourhoods (PED Programme) is one the most ambitious visions for community action on climate change. The goal of the PED Programme, established in 2018, is to support the planning, deployment, and replication of 100 PEDs across Europe by 2025 for urban transition and sustainable urbanisation. +CityxChange is one of the latest projects under the PED Programme. It is funded under the Smart Cities and Communities call of the EU Horizon 2020 research and innovation programme.

Led by the lighthouse cities of Trondheim and Limerick, +CityxChange is exploring how to create smart positive energy cities that use digital services to improve quality of life and generate more energy than they consume. The outcomes of the work in these two lighthouse cities will guide the follower cities (Alba Iulia, Pisek, Sestao, Smolyan, and Voru) in replicating successful solutions adapted to local conditions.

In Limerick, Limerick City and County Council is leading the implementation and testing of 11 demonstration projects grouped under the headings of Integrated Planning and Design, Common Energy Market, and Community Exchange. These projects are taking place in close alignment with the demonstration projects in Trondheim.

Figure 2-1. +CityxChange Project Overview



(Source: +CityxChange)

The Limerick projects combine a series of specific actions across the district alongside programs for community and stakeholder engagement. Several initiatives are being explored as ways of creating a PED, including:

- Reducing the energy demand of existing buildings, for example, through improvements to the building envelop or to ventilation systems to reduce energy losses
- Replacing fossil fuels, for example, through installation of heat pumps and solar PV on buildings and the use of other local renewable energy sources such as tidal generation
- Integrating technologies at a building or district level, such as district heating and community batteries

- Installing building or home energy management systems to ensure optimal operation at both the community and building levels and to enable interaction with the smart grid and potential future energy trading platforms
- Exploring the possibility of an energy trading platform that allows the community to trade energy on a peer-to-peer basis, potentially exploiting blockchain technology

An important element of the Limerick project is the exploration of cross-sectoral improvements and the importance of taking an integrated view on community space across energy, buildings, transport, and other infrastructure and services. The impact of changes on different groups within the community is also being assessed.

Digital twin technologies have an important role to play in collecting data from multiple sources, analysing the impact of proposed projects, and understanding the complex interdependencies among these elements of the city. Examples of how the Limerick project plans to use digital twins include:

- Building a community information model to help identify priority requirements and establish a picture of current energy demand
- Developing detailed virtual models for the initial building analysis
- Aggregating data from multiple sources and using advanced analytics to build enriched, calibrated models[3]
- Using virtual network models to look at the interdependency among systems, changing demand profiles, alternative energy sources, energy storage, EVs, and potential impacts on electricity networks
- Providing socioeconomic context in the form of population structures and growth, and social indicators for health and well-being, education, employment, and housing, for example

Limerick's ambitions and challenges reflect the priorities of many cities. The project is in its early stages but, among other insights, the way it uses digital twin technology to inform project decisions and to engage with the wider community is of great interest to many cities as they look to meet climate goals.

[3] Calibration is the process of improving and verifying the accuracy of a simulation model by systematically comparing model outputs to real measured data from a building. Operational data rather than design data is used directly in calibrated energy/simulation models to enable more accurate predictions, optimised control, and informed decisions on improvement/refurbishment measures under consideration.

Section 3
UNDERSTANDING DIGITAL TWINS

3.1 What Is a Digital Twin?

Stripped down to its essentials, a digital twin is a digital representation of a real-world asset or group of assets. This broad definition encompasses basic tools that have been available for many years through emerging technologies at the leading edge of innovation.

But digital twins are more than old wine in new bottles. The availability of highly granular data, from a wide range of sensors and intelligent devices, new analytic tools based on machine learning and AI, accurate modelling of the real-world behaviour of systems and objects, simulation of complex changes, and an ability to render information in accessible visualisations is transforming the way digital models are used for planning, design, operation, and optimization of assets and systems. Digital twins enable new forms of modelling and analysis that were previously either impossible or uneconomic to perform.

> *Digital twins are not a based on any one technology. They require a combination of capabilities for data management, analytics, simulation, visualisation, and information sharing.*

Above all, the growing interest in digital twins reflects a new approach to the use of digital information to analyse and manage complex real-world objects and systems. Digital twin tools provide the basis for this new approach, which can be called digital twin thinking. At its core, digital twin thinking builds on a single source of truth for all assets that is accessible by a variety of users and stakeholders. Digital twin thinking also focuses on the combinatorial benefits of linking previously distinct models to enable enterprise- and community-wide visibility into assets and the relationships between them.

3.2 The Evolution of Digital Twin Technologies

The emergence of highly sophisticated digital twins establishes the basis for much more complex analysis, where sensing data is augmented with a rich history of additional asset-related data, physical behaviour of a system is accurately rendered, and complex interdependencies between assets and other processes is understood. Each individual twin is contextually linked to all other twins in a system, providing the ability to compare the twin of one asset against the twin of a similar asset elsewhere in the system. A complicated asset such as a building can thus be modelled to very fine levels of granularity and that model tested in ways that provide insight into the behaviour of the real-world entity. The value of the model is precisely its ability to simulate the behaviour of that entity under different current and future conditions. Data can be visualised in advanced 3D models and made accessible to many levels of user.

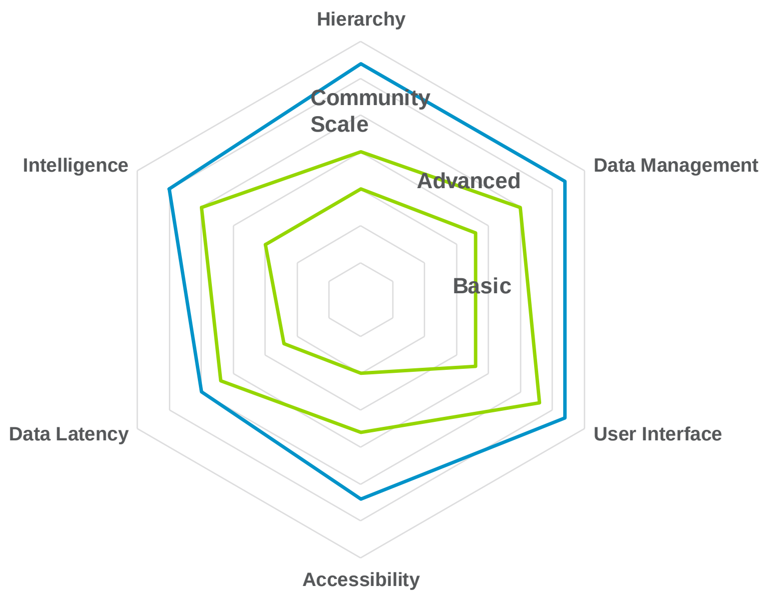
One of the most exciting developments is the ability to combine multiple assets and model the relationships between them to build accurate digital representations of complex environments such as a city district, university campus, or airport. The ability of digital twins to capture the relationships that define such communities allows new levels of analysis of complex environments. The ability to run different scenarios and explore their impacts across the system enables new insights that enhance the ability to take more holistic approaches to building design, energy strategies, and transportation planning, for example. Simulating how a complete system will respond to change improves decision-making for a range of questions, such as the costs and benefits of different storage technologies, the impact of increased EV charging on local power networks, and how changes in resident behaviour may alter demands on the system

It is also important these digital representations are available to different stakeholders. Sharing a common model and providing appropriate tools for different uses makes it possible for digital twin technologies to engage stakeholders in different ways. So while an engineer can have access to complex analysis tools to explore optimization strategies, community residents can be provided with visualisations of the impact of different design choices or other changes. The most sophisticated twins will use machine learning and AI to provide another level of analysis in terms of the relationships made manifest in the digital model that would be near impossible to recognize in the real-world environment.

3.3 Digital Twin Maturity Dimensions

Digital twins need to be understood as a combination of capabilities brought together on a shared platform that provide a single point of truth for multiple use cases and diverse stakeholders. Digital twins vary in the range of capabilities they provide and the sophistication of the tools available. These capabilities can be envisaged along six dimensions that encompass the most simplistic of digital deployments (such as a digital twin of a single asset) to the most complex (simulation of a complete community energy system). Figure 2-1 provides an overview of the development, from simple solutions to the capabilities required for community-scale projects. An explanation of the dimensions of the maturity model follows.

Figure 2-1. Digital Twin Maturity Dimensions



(Source: Navigant Research)

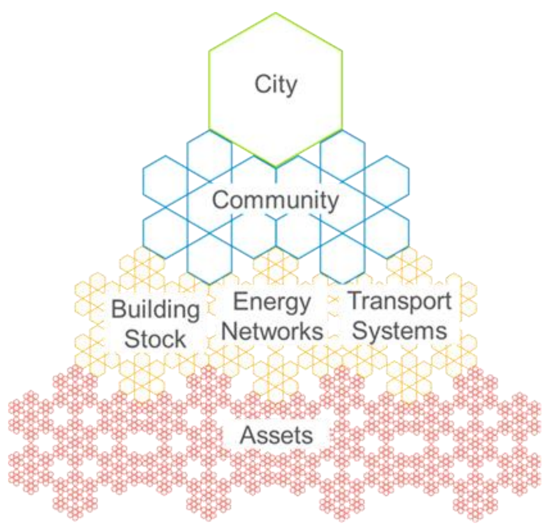
3.3.1 Hierarchy

In the context of digital twins, hierarchy represents the level at which digital representations of specific assets are integrated. At the lowest level of the hierarchy are twins of single assets. Multiple asset twins combine to create more complex hierarchies:

- **Single-asset twin:** At the most granular level is a digital twin of a single asset. This can be an HVAC unit, boiler, or elevator. The asset must be sufficiently complex to warrant it being fitted with sensors, but small enough to be considered an independent unit.
- **Building twin:** The next step up is to integrate single-asset digital twins within the same building. The building digital twin is built by merging all the single-asset twins within the building, and the location of each of these assets within the building.
- **Community-wide twin:** Community-wide twins bring together the individual twins of a portfolio of buildings and other relevant models, such as the energy grid, water systems, or transport networks. This portfolio could be buildings in a district, a university campus, an airport, or the distributed buildings of a property firm, for example.
- **City-wide twin:** A city-wide twin brings together twins for multiple communities, as well as those for city-wide infrastructure and networks.

For example, Figure 3-3 depicts how asset twins combine to form building twins, which can ultimately combine to provide an overview of the entire built environment. This hierarchy could also start from modelling of an energy network, transportation system, or manufacturing complex, rather than from building assets.

Figure 3-3. Integrating Digital Twins to Create Hierarchies



(Source: Navigant Research)

3.3.2 Data Management

Most definitions of a digital twin mention real-time or near-real-time data on an asset's performance. However, this data is only part of the equation. The more data that is made available, the better the potential insights:

- **Breadth:** Digital twins collect as much data as possible about an asset, including manufacturing and construction information, maintenance history, current health, ownership, financial data, and time-series data from a range of smart meters, sensors, and other digital devices. It may also include contextual data such as weather data, data from behavioural sciences, sentiment analysis from social media, or inputs from wearable technologies.
- **Depth:** Digital twins also benefit from a rich history of data over time. Historical data, for example, gives context for machine learning algorithms to better predict future outages. Historical data includes not only performance data for equipment but also maintenance records, weather data, and usage patterns. Examining asset performance under different historical conditions provides a strong basis for the simulation of future behaviour. Such projections can then be used to identify anomalies and for more informed scenario planning.

Advanced digital twin tools are also able to fill the gaps in the available data. For example, if there is little or no historic data, which is the case during design and initial operation, then simulation and physics-based models can provide the necessary understanding of how assets are expected to behave in real-life. So, for example, the expected temperature changes in a room over a day or a week can be modelled based on an understanding of its expected performance, even if no data is available on that specific space.

The breadth and depth of the data used for digital twins means that advanced data management tools have an important role to play. Machine learning tools, for example, can help identify gaps or inconsistencies in data. Automated tools for data collection can help reduce the resources needed for ongoing data update and maintenance.

3.3.3 Accessibility

One of the most attractive qualities of digital twins is that they provide a shared dynamic model that can be analysed, manipulated, and visualized from multiple user perspectives. Thus, accessibility for multiple users with different requirements, skills, and authorisations is an important facet of any solution. Simple digital twins may support a limited range of user roles, while at the other end of the scale, community projects may span a broad spectrum of users from engineers and data scientists to community residents.

Digital twins provide a shared dynamic model that can be analysed, manipulated, and visualised from multiple user perspectives.

Accessibility requires a selection of tools suitable for the needs of different users. It also requires adequate data and user management tools and the requisite authorisation and security features.

3.3.4 User Interface

Digital twins are often seen as synonymous with a 3D or 4D representation of an asset or system. Although advanced visualisation has some compelling uses, it is not a prerequisite for a digital twin project. A digital representation of a physical asset does not in fact require any investment in an advanced user interface.

The pinnacle of digital twin visualisation is currently CAD-based 3D and 4D imagery. Other cutting-edge technologies incorporate the use of augmented reality to better visualize assets in real-time. Although most use cases do not require this level of detail, such tools can improve interactions with citizens, building occupiers, community representatives, city managers, and other stakeholders. The important consideration is that there are tools suitable to the needs of different users. For example, an energy manager may be comfortable handling and manipulating raw performance data but other users—such as city officials, building managers, and community residents—benefit from clear visualisation of complex systems and their interactions.

3.3.5 Data Latency

The latency requirements of different use cases vary greatly. Providing real-time data is critical for various applications such as monitoring energy systems. Other applications, such as modelling system options during a design phase, are less demanding. For community-scale digital twins, latency must be viewed as a system-level feature as well as for specific assets or functions. A complex simulation run in real time is constrained by the ability of the slowest feeder systems.

3.3.6 Intelligence

Analytics is arguably the most important aspect of digital twins. Digital twins are nothing if they do not improve insights into the assets they represent. A variety of analytics technologies can be applied to a digital twin. Basic analytics can be supported by spreadsheets or other business intelligence or modelling tools. However, community-scale projects with complex cross-sector interdependencies require more sophisticated tools.

Machine learning and AI tools can identify patterns and inconsistencies that may not otherwise be identified. This functionality is particularly important for advanced models that need to consider very large, multidimensional datasets and track the impact of changes at many levels and over time.

Advanced digital twins also require an understanding of underlying physical models for energy flows, materials behaviour, and water systems, for example. This capability differentiates them from static building information models or simple 3D representations. The combination of asset data and an understanding of the physical reality in which assets function enables dynamic simulations, one of the most powerful capabilities used with digital twins. Simulations support what-if planning and can help identify unexpected behaviours resulting from equipment failures or changes of use. Simulations converge with sensor data, advanced analytics, and visualisation tools in digital twins to enable a new understanding of how a city, community, or building works.

Integrated Environmental Solutions Intelligent Communities Lifecycle: An Example of a Digital Twin Platform

The Integrated Environmental Solutions (IES) Intelligent Communities Lifecycle (ICL) platform is an example of how digital twin solutions combine multiple capabilities to enable analysis and optimization of complex energy systems. The platform brings together existing modelling and analytics capabilities for buildings and energy networks with features specifically designed to address multi-sector, multi-stakeholder projects at community scale. The key components of the platform include:

Intelligent Community Design (iCD): A collaborative 3D urban design and master planning tool for cities, districts, campuses, and other complex environments, this component makes it possible to understand from simple asset information the baseline of a community's energy/resource use and identify potential what-if scenarios for improvements at scale; including transport and utilities integration.

IES Virtual Environment (IESVE): A dynamic simulation modelling environment that enables deep analysis of building performance, IESVE can replicate reality by simulating the physics of energy and heat flows throughout a building or even across an entire community. These virtual models can be based on data imported from iCD and enhanced with operational data through iSCAN.

Intelligent Control and Analysis (iSCAN): This component enables time-series real world data to be collated from many sources to deliver insights using a single pane view. Machine learning and other analytics tools help users identify issues and anomalies, test scenarios, and provide automated insights into potential improvements. The data can be combined with IESVE physics-based simulation to develop detailed calibrated models that can be shared with other ICL tools.

Intelligent Virtual Network (iVN): A modelling and scenario analysis environment for complex networks and built environments, which simulates the interaction between networks (electricity, heating or cooling) and other elements such as buildings, renewables, batteries, EVs, and people.

ICL Collaboration Cloud: A cloud-based ecosystem of tools encompassing: Intelligent Community Information Model (iCIM), an interactive 3D environment that uses live data feeds from any ICL tool for community engagement with the digital twin; Intelligent Portfolio Information Model (iPIM), which is designed to provide an integrated view across communities at a national or even global level; and Command Centre dashboards that can be tailored to specific requirements.

The ICL platform demonstrates the key elements of the digital twin maturity model. Established tools for building simulation and analysis have been extended to model further levels of interaction with other assets and the broader environment. Machine learning and AI tools analyse the complexities of these multi-level models. Simulation tools allow users (from experts to end users) to engage with the models to understand the way different design choices affect energy flows, user experiences, financial metrics, and socioeconomic outcomes.

Section 4
CASE STUDIES: DIGITAL TWINS AND COMMUNITY ENERGY PROGRAMMES

4.1 Understanding the Value of Digital Twin Thinking

This section looks at three practical examples of how digital twin technologies can support new forms of modelling, simulation, and design for complex community-scale systems. These case studies span different community types and project objectives:

- An island community that needs to understand how a combination of energy efficiency measures and local energy resources could improve the lives of residents and create the conditions for a zero carbon community
- A community energy scheme that is integrating energy technologies and a programme of community engagement to develop new perspectives on the way energy is generated, managed, and consumed at the community level
- A university looking to create the greenest campus in the world by meeting ambitious targets for energy efficiency, waste management, and reductions in water consumption

They all show a need for tools that can represent a complex environment of buildings, energy systems, and other infrastructure; the relationships among those entities; and the impact of changes on system performance and community. Each of these projects is using a combination of digital twin technologies.

4.2 Eday, Orkney: A Community Approach to Energy Reduction

Island communities provide a good example of the importance of understanding the interdependency of systems when exploring options for new energy solutions. Often dependent on fossil fuel imports and with limited connections to national grid systems, island communities present excellent opportunities to reduce high energy costs, reduce GHG emissions, and improve resiliency. Doing so requires an understanding of the complex interplay among elements of an island's energy systems and an ability to model different investment scenarios.

A project on Eday, an island in the Orkney archipelago in north-eastern Scotland, provides a good example of how digital twin technology can help island communities. The community was looking to reduce its energy consumption, improve the comfort of local homes, and reduce emissions. The island is home to a large wind power facility, but it is isolated from the island's electricity system. Many homes had their own 5 kW turbines installed, and there was a desire to optimise their local energy resources. IES worked to create a digital twin for the island's energy system that could be used to analyse the different options available.

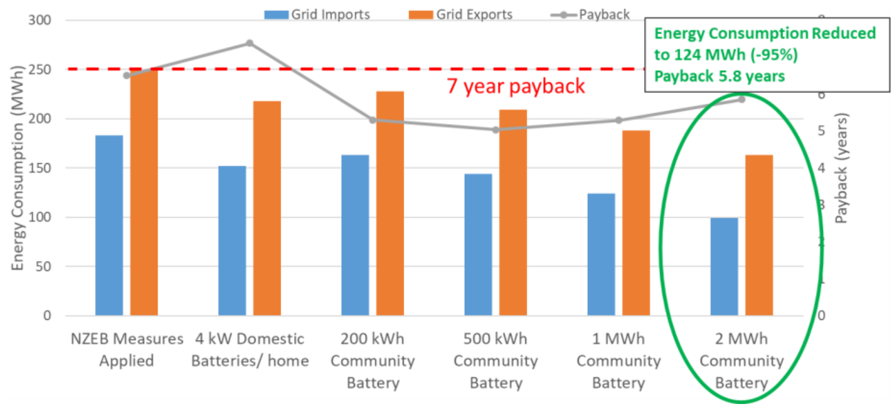
Initial engagement with the community highlighted their key concerns as the need to make their homes more comfortable and to benefit from local energy resources, reducing their dependency on the mainland grid. After the impact of energy efficiency measures on the island's building stock had been modelled, the focus shifted to analysing how to reduce grid imports and optimisation of the island's systems to maximise the use of local generation. The overall aim of this analysis was to understand if it was economically viable to achieve a 'zero energy' community, which would produce more energy on an annual basis than it consumes.

The IES iVN tool was used to create a virtual network model of the island based on information on the grid infrastructure from the local distribution network operator and energy profiles for the island's buildings. The demand profiles for each building were generated using survey responses and data on building construction, heating systems, fuel type, and occupancy behaviour. The model was calibrated using utility bill data from a selection of buildings to provide validation and increased accuracy.

A zero carbon scenario was explored by adding interventions in sequence to each building across the island to determine the achievable savings. It was found that improving the building fabric, insulating hot water tanks, replacing existing lighting with LEDs, and a switch over to heat pumps across all buildings could eliminate the requirement for fossil fuels on the island. In total, energy savings of 76% were identified. The already existing high wind resource on the island makes a move towards electrification of heating systems and the addition of storage systems a much more financially viable solution than for other communities. However, to gain full benefit of the existing wind energy, it was clear that energy efficiency measures would be required.

Another proposed measure was to provide local energy storage that would maximise the use of local wind generation. The cost and benefits for both a community storage battery and individual residential batteries were modelled. Although a 2 MWh battery was shown to be most effective at minimising grid exports, a 500 kWh battery offered the best payback period for the community and a lower upfront cost.

Figure 4-1. Assessing Storage Options for Eday



(Source: Integrated Environmental Solutions)

The Eday project demonstrates how community energy projects need to consider multiple factors, including:

- Current and potential energy sources and flow
- Existing energy infrastructure
- Demand profiles of the current building stock
- Existing and potential energy efficiency measures
- Alternative investment scenarios and their cost-benefit implications

With digital twin technology, these aspects of a community's energy system can be combined in an integrated model that allows the impact of different options to be understood by all stakeholders.

4.3 Trent Basin, Nottingham: Engaging the Community

Community energy systems are not only about technical innovation. They also open new opportunities for communities to be active players in their local energy systems, with much closer engagement with the design and operation of such systems. Residents' behaviour and response to the systems evolution are as much part of the system as the technical components that enable new approaches to the production and consumption of energy. For this reason, it is important that residents understand the impact of new systems and how they can interact with them.

Understanding the relationship between technical innovation and community engagement in community energy schemes is a key element in an ambitious project located in the city of Nottingham in the UK. Part of the new Trent Basin development, Project SCENe (Sustainable Community Energy Networks) is a sustainable community energy project supported by Innovate UK funding and the Energy Research Accelerator. The £10 million ($13 million) project is part of a £100 million ($130 million) new development and brings together companies involved in the energy supply chain and academics to work with around 120 homes to deliver new models for community energy schemes. Project SCENe looks to accelerate the adoption of community energy systems as a new approach to generating and supplying locally generated heat and electricity to homes and commercial buildings. The benefits are reduced cost and more efficient use of distributed renewables to reduce the overall carbon emissions from the energy system. In addition, energy storage technologies provide greater efficiency and services to help stabilise the power network. The project is deploying solar PV panels, local thermal energy production, and storage technologies, including a 2 MW Tesla battery, Europe's largest community battery installation.

The Trent Basin-Community Information Model (TB-CIM) is an interactive online platform that displays historical and real-time energy data of the Trent Basin community. The primary aim of this visualisation tool is to engage the community residents, informing them of communal energy generation, storage, and consumption. It also aims to promote public engagement of the community energy scheme and disseminate the results of the project. The TB-CIM platform was designed by IES in collaboration with the University of Nottingham.

The platform provides details of the energy performance of individual buildings and utilities. It is linked to real-time and aggregated energy data and provides analysis tools that enable people to interact with their energy systems in new ways. Residents can access community energy data to help them make more informed decisions and to contribute to the optimization of the overall community energy scheme. Using the online platform or a communal touch screen, residents can compare household-level data with the community average, see how much energy the project is producing and selling to the grid, and look at additional real-time data such as the weather.

A key feature of TB-CIM is the ability of multiple users to interact with the model at the same time using a multiple-touch wall screen system located in the Trent Basin community hub. The wall screen is designed to be inclusive, self-explanatory, and easily accessible (including for children and people with reduced mobility).

Figure 4-2. The TB-CIM Interface

(Source: Project SCENe)

4.4 Nanyang Technological University, Singapore: Creating the Greenest Campus in the World

University campuses provide a different example of the potential for community-scale energy actions. Large universities with their complex mix of buildings, large and distributed populations of staff and students, and specific transport requirements, can serve as a microcosm of many city challenges.

Nanyang Technological University (NTU), Singapore, has a vision to be the greenest campus in the world. The university has around 40,000 students and staff and the campus consists of 200 buildings spread over 250 hectares. It undertook a collaborative project with IES to examine how digital twin technology could help achieve its goals of reducing energy, water, and waste footprints by 35% for 2020. IES's ICL technology was used to plan, operate, and manage the campus facilities to reduce energy consumption.

In Phase 1, an overall masterplan was created using the iCD tool to provide an overview of energy consumption across the campus building stock, based on existing energy and build stock data. The resulting campus information model, accessed through iCIM, enabled the quick identification of immediate energy savings. This identification led to a 10% reduction in campus energy, an 8.2 kton reduction in carbon emissions, and a financial saving of S$4 million ($2.8 million).

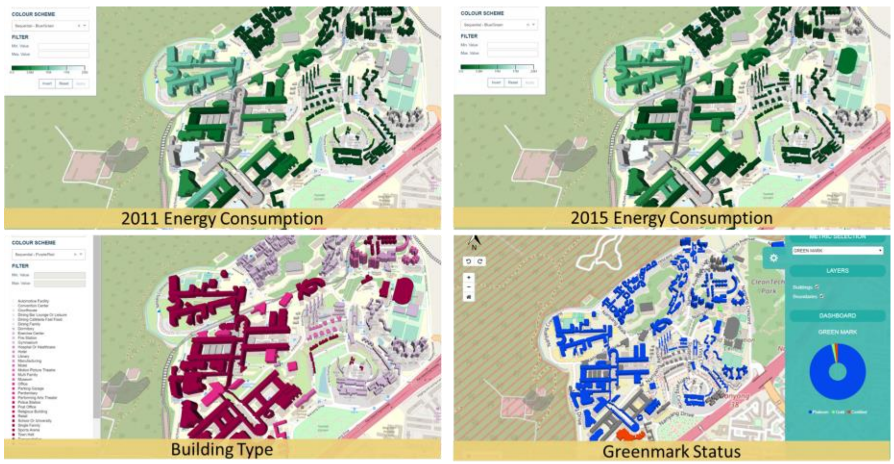
Phase 2 then focused on 21 buildings on the campus for a more detailed investigation using the IES Ci^2 process (Collect, Investigate, Compare, Invest) to identify further savings:

- **Collect:** The initial data collection spanned a range of sources including utility bills, automated meter readings, building management systems data, and operational information.
- **Investigate:** Using the ICL iSCAN tool, the collected data—including time-series data—was integrated and analysed to discover additional energy savings. This process identified a number of issues with heating and ventilation systems, energy meters, and room management.
- **Compare:** Virtual models were then created for each building in IESVE and calibrated using detailed operational data. These models established a baseline for existing building operations that could be used to determine savings for a range of potential technologies during the next stage.
- **Invest:** Five new technologies were simulated using the calibrated models to determine what the savings would be if they were installed in the building: high resistance envelope for walls and roofs, high resistance envelope for windows, lighting with occupancy sensors, plug load management, and high performance optimised chillers.

The calibration identified total energy savings of almost 23,000 MWh, monetary savings of almost S$5 million ($3.5M), and 9.6 kton in carbon reduction. On average, 31% energy saving were simulated for technology implementation on buildings. The results of this process were then loaded into the campus masterplan to enrich the management data and to provide a visualisation of the options available in the campus information model.

A good example of how a digital twin can help improve decision-making is provided by a project to improve the efficiency of the campus cooling systems. Campus management wanted to understand if decentralized cooling systems in each building would be more efficient and cost effective than a centralized, multi-building system. The campus information model enabled them to analyse alternative scenarios based on expected building performance across the campus portfolio. Using time-series data to show the performance of the different systems throughout the day demonstrated that a centralized system provided a significant reduction in carbon emissions throughout the operational life cycle.

Figure 4-3. Masterplanning for NTU, Singapore



(Source: Integrated Environmental Solutions)

Section 5
CHALLENGES, BEST PRACTICES, AND RECOMMENDATIONS

5.1 Working with Digital Twin Technologies

Digital twin technologies have an important role to play in helping cities, communities, and their partners understand the best pathways to a low carbon future. Above all, digital twins provide the analytical, simulation, and visualisation tools that allow multiple stakeholders to understand the complexity of integrated systems. Digital twins create new perspectives on the relationships among different assets and their shared context. They also provide a new understanding of how those relationships may change over time depending on different factors and decisions.

Most of the technologies used in digital twins are well-established. The emergent capabilities for more sophisticated modelling and simulation reflect the growth of real-time data from sensors, increasing computing power available over cloud platforms, access to powerful analytical tools, and innovative approaches to visualisation.

Digital twins offer specific benefits for community-scale projects:

- **Managing complexity:** Making decisions on technologies and platforms in a world where change is rapid and outcomes uncertain requires new management approaches. A greater emphasis needs to be placed on adapting strategy in the light of experience and retaining flexibility, which runs counter to many traditional operating models. Digital twins allow decision makers to understand the ramifications of different scenarios and interventions in the context of real-world impacts.
- **Quantifying benefits:** Many of the investments needed to address the issues of climate change and the reduction in GHG emissions have a long-term payback that is not easy to fit into short-term budget or electoral cycles or to measure against pressing city issues. Digital twins allow city leaders to examine the balance between short-term costs or benefits and long-term implications, using models that are sensitive to the constraints of both physical and socioeconomic realities.
- **Engaging stakeholders:** The shaping of future cities is dependent on changes in infrastructure, assets, and services over which cities have limited or no control. Energy policy and infrastructure, regional and national transportation, and commercial building stock are just some of the key elements that may be outside city influence. Driving change therefore requires strong stakeholder management, identification of interdependencies, and the layout of clear transition paths. Digital twins enable multiple parties to explore the implications of different decisions and to explore alternative approaches using a consistent shared model of the world.

5.2 Addressing the Challenges

Digital twins offer many benefits but also require organisations to adapt their approaches to systems design and management, develop new ways of working, and invest in building new skills, internally and through partners. The main issues when considering digital twin technologies can be grouped under three main categories: data, skills, and the need to develop a digital twin perspective that is shared by all users and potential contributors.

5.2.1 Data Challenges

The growing availability of sensor data is a key driver for the development of digital twins. The availability of accurate, highly granular, real-time data enables the simulation of real-world entities and events in ways that have not been possible before. An awareness of the potential issues associated with the collection, management, and use of that data in digital twins is therefore essential for any project.

Data collection is the single biggest challenge for any digital twin project. Common data management issues are amplified by the complexity and diversity of the data sources involved.

The creation of a useful digital twin requires data accessed from many systems and integrated successfully into a single model. Data collection is the single biggest challenge for any digital twin project. Common data management issues are amplified by the complexity and diversity of the data sources involved. Issues that need to be considered include:

- **Availability:** Unrealistic expectations of the data available (particularly when multiple systems and asset owners are involved) can cause significant issues downstream. An initial audit of existing and new data sources that are required for a digital twin and how any gaps may be addressed will save time, effort, and money further down the line.
- **Quality:** It is important to assess the quality of any data used in terms of completeness, accuracy, timeliness, or duplication and to develop a plan for how any problems will be addressed.
- **Accessibility:** How will the data be collected? Is it available as a real-time feed or will it be updated at regular intervals? Can the systems holding the data be accessed directly and what authorisation or security clearances are needed?
- **Data management:** How will data be kept securely? How will sensitive data about people or systems be managed in line with organisational standards and legal requirements, such as General Data Protection Regulation in the EU.

It is also important that a digital twin project does not become over-focused on data collection. An initial model using the most readily available data can often provide insights that can then help focus further investment in data collection on the most valuable areas.

Data quality is an ongoing issue, not just an initial challenge. The complex interactions that characterize a digital twin and the ability to simulate and test real-world changes means that there must be a continual process of data validation. There is also an important role for advanced analytic tools in managing and ensuring data quality.

5.2.2 The Skills Gap

Digital twins involve tools that will be familiar to some users and capabilities that will be new to many. The combination of technologies used for digital twin platforms for community-scale projects means that any project will require a combination of skills and expertise. As well as developing internal capabilities, it will be essential to find the right public and private sector partners to provide supplementary expertise and support.

As well as core IT, data management, and project management skills, digital twin projects require:

- Sector-specific skills in, for example, building optimization, energy systems, and transport services
- Advanced analytical capabilities, which are particularly important with the increasing role for machine learning and AI tools in community-scale projects
- Stakeholder management and community engagement skills, including socioeconomic and behavioural analysis capabilities will be important for many community projects, as will communication and other soft skills for engagement

Another aspect of the skills gap is the lack of time available to take advantage of the potential insights provided via a digital twin. Machine learning can have a role here. A projection of the expected behaviour of a system over the coming week, allowing for weather and other changing factors, for example, can allow variations from normal parameters to be highlighted to managers.

5.2.3 Developing a Digital Twin Perspective

The most successful digital twin projects start off with a suitable mindset. Digital twin thinking is more important than any one technology. The benefits of a single source of truth that is accessible for multiple use cases and diverse uses are most likely to be realised if a common philosophy is established across stakeholders and project leaders. This mindset is vital in breaking down organisational—and cross-organisational—silos, creating a collaborative approach that draws on diverse technical and sector-specific skills and allows common ownership of the results.

Changing attitudes to data management and overcoming territorial barriers to data sharing will be core to developing a digital twin perspective. As part of that change, the benefits of a digital twin need to be explained to stakeholders in terms of the relevance to their priorities and to broader organisational or community goals. Early engagement with potential data providers can reduce access issues later in the project. It is also important to ensure decision makers, who will be key to implementing any suggested improvements or investments, understand how the digital twin has been used to derive the recommendations being made.

5.3 Conclusion and Recommendations

The emergence of rich digital twin platforms presents a significant step change in the ability of cities and other organisations to understand and optimise complex community-scale systems. As well as being aware of the challenges previously discussed, any organisation looking to explore the benefits of digital twins should bear in mind three basic principles.

5.3.1 Think Beyond the Hype

Many organisations will have made initial steps towards digital twins. They will be familiar with some if not all the tools involved and may have built simple digital twins of existing assets. A digital twin changes the focus of the conversation to a single source of truth for all asset-related data and provides the ability to merge these twins into a single view of the entire built environment. The most successful digital twin project starts with a mindset. Where digital twin thinking brings value is in the idea that a holistic approach to managing digital representations of physical assets as a whole is far more valuable than the sum of its constituent parts.

5.3.2 Identify Quick Returns

The broad applicability of digital twin technology and the potential to encompass a wide range of assets may shift the focus from immediate benefits. To show the value of any investment in digital twins, there should be a focus on high value projects that can deliver benefits in a relatively short period of time.

For community-scale projects, this focus could be on identifying quick energy savings (as with Phase 1 of the NTU campus project), optimizing a specific investment decision (as with the energy storage analysis for the island of Eday), or building community engagement (as in the Trent Basin project). Initial data collection and modelling should focus on such projects while not ignoring the longer-term potential. This focus is also an opportunity to build understanding of the data issues involved, identify skills gaps, and create a collaborative team to drive future projects.

5.3.3 Understand the Long-Term Opportunities

Although digital twins should be able to show value relatively quickly—for example, through simple energy savings or early community engagement—their real benefits become apparent over time. This consideration is particularly important in the context of delivering on zero carbon city and community projects. The ability of digital twins to support long-term planning through dynamic and flexible simulations can be a vital support to organisations looking at multiple paths to achieving their emissions and energy goals in a changing world. They can also support new forms of engagement with citizens, community residents, and service users that will be vital in building the sustainable cities of the future.

Section 6
ACRONYM AND ABBREVIATION LIST

AI .... Artificial Intelligence

C40 .... C40 Cities Climate Leadership Group

CO2e .... Carbon Dioxide Equivalent

EU .... European Union

EV .... Electric Vehicle

GHG .... Greenhouse Gas

Gt .... Gigaton

HVAC .... Heating, Ventilation, and Air Conditioning

ICL .... Intelligent Communities Lifecycle

IES .... Integrated Environmental Solutions

IESVE .... IES Virtual Environment

IPCC .... Intergovernmental Panel on Climate Change

IT .... Information Technology

kton .... Kiloton

kW .... Kilowatt

kWh .... Kilowatt-Hour

MW .... Megawatt

MWh .... Megawatt-Hour

NTU .... Nanyang Technological University

PED .... Positive Energy District

PV .... Photovoltaics

TB-CIM .... Trent Basin-Community Information Model

UK .... United Kingdom

US .... United States

Section 7
TABLE OF CHARTS AND FIGURES

Section 8
SCOPE OF STUDY

Navigant Research has prepared this report, commissioned by IES, to provide a roadmap for the use of digital twins in the development of zero carbon communities. It provides an overview of the key elements of digital twin solutions and their value in supporting community-scale projects; examples from a diverse range of organisations that are using the capabilities of digital twin technologies to improve their energy efficiency and reduce greenhouse gas emissions; recommendations for organisations getting started with digital twin projects and advice on how to tackle the most common challenges.

SOURCES AND METHODOLOGY

Navigant Research's industry analysts use a variety of research sources in preparing Research Reports. The key component of Navigant Research's analysis is primary research gained from phone and in-person interviews with industry leaders including executives, engineers, and marketing professionals. Analysts are diligent in ensuring that they speak with representatives from every part of the value chain, including but not limited to technology companies, utilities and other service providers, industry associations, government agencies, and the investment community.

Additional analysis includes secondary research conducted by Navigant Research's analysts and its staff of research assistants. Where applicable, all secondary research sources are appropriately cited within this report.

These primary and secondary research sources, combined with the analyst's industry expertise, are synthesized into the qualitative and quantitative analysis presented in Navigant Research's reports. Great care is taken in making sure that all analysis is well-supported by facts, but where the facts are unknown and assumptions must be made, analysts document their assumptions and are prepared to explain their methodology, both within the body of a report and in direct conversations with clients.

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[4] On October 11, 2019, Guidehouse LLP completed its previously announced acquisition of Navigant Consulting Inc. In the months ahead, we will be working to integrate the Guidehouse and Navigant businesses. In furtherance of that effort, we recently renamed Navigant Consulting Inc. as Guidehouse Inc. We will continue to perform as proposed during and after this consolidation, using the same personnel and methods described in this report.