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AI-Enhanced Digital Twins for Energy Efficiency and Carbon Footprint Reduction in Smart City Infrastructure

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Abstract: The combination of Artificial Intelligence (AI) and Digital Twin technology provides disruptive potential to increase energy efficiency and carbon footprint in smart city infrastructure. Digital Twins — virtual copies of the real-world systems — are augmented by AI algorithms that enable continuous monitoring, predictive analysis and optimization. In this paper, we explore the use of AI-based Digital Twins on smart buildings, transport networks and smart grids to save significant amounts of energy and drive sustainability. This is done through machine learning and reinforcement learning algorithms which identify patterns of energy use with high precision and helps to reduce the energy usage in smart buildings by 25-30%. For transportation, AI-enabled traffic infrastructure reduced carbon emissions by 20% and enhanced EV infrastructure efficiency by 18%. The smart grids were better served by predictive energy distribution, which allowed for a 15% decrease in losses and a 20% rise in the use of renewable energy. All of these results point towards the potential of AI-augmented Digital Twins to reshape city planning, optimise resource consumption and play a key role in achieving global sustainability targets. This research underscores the need to embrace high-tech solutions for the next smart city projects to combat climate change and promote sustainable development.

Keywords: AI, Digital Twins, Smart Cities, Energy Efficiency, Carbon Footprint

1. Introduction

Smart cities are now a global trend because the cities have become hit with an epidemic of population explosion, resource shortage and degradation. Smart cities are smart in the sense that they utilize cutting edge technology to run more efficiently, live more a quality urban experience and not waste as much. The most successful among these technologies is Digital Twins: digital replicas of physical assets and infrastructure, which are effective in modelling and re-engineering intricate urban processes. City planners can build digital twins of scenarios, make predictions and take action that saves as much as possible in resources and produces as little waste and emissions. Combining it with Artificial Intelligence (AI), Digital Twins can also do even more, through real-time data analytics, predictive modelling, and self-adaptive optimization. AI like machine learning and deep learning can handle millions of real-time events from IoT sensors in smart cities. Such information can be used for predictive maintenance, energy efficiency and carbon reduction projects, so AI-powered Digital Twins are an absolute must to achieve sustainability. Energy use and CO_2 emissions are two of the city's still thorniest problems. In building, about 40% of all the energy used in the world comes from

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buildings, and transportation contributes almost a fifth of urban emissions [1]. Smart grids – the necessary infrastructure for urban energy management – suffer from inefficiencies and energy waste, too. In this paper, we discuss how AI-based Digital Twins are being used to combat these problems in three main domains: smart buildings, transportation networks, and energy grids. Through case examples and experiments, this paper reveals how AI-augmented Digital Twins can enable energy efficiency, carbon reduction and sustainable city

2. Literature Review

2.1. Concept of Digital Twins and Their Application in Smart Cities

Digital Twins are artificially intelligent replicas of physical property, infrastructure or process that can run concurrently so the virtual and physical environments can be directly connected. For smart cities, these models model the fluid functioning of dynamic urban systems including transport systems, electrical power grids, water supply systems and construction projects. Creating a virtual version of such systems allows Digital Twins to understand more deeply the relationships between all the components of the city [2]. This technology has been further enhanced by Artificial Intelligence (AI) which is the latest technology with capabilities like real time monitoring, predictive analytics, and automated decision making. Digital Twins armed with AI help planners and operators anticipate potential problems, make the best use of available resources, and plan for maintenance in advance to avoid downtime and downtime interruption. Also, these solutions help to save considerable energy by detecting inefficiencies and streamlining processes, like controlling buildings' heating, ventilation and air conditioning (HVAC) systems or balancing energy flows on smart grids. Intelligent cities based on AI-enhanced Digital Twins can reduce operational costs through process automation, improve overall system performance through robust analytics and adaptability to rapidly evolving environmental and urban environments. Digital Twins, which blur the lines between physical and digital intelligence, have become the keys to sustainable urban growth and bring novel approaches to the toughest urban issues today [3].

2.2. AI Techniques for Optimizing Energy Efficiency in Smart Cities

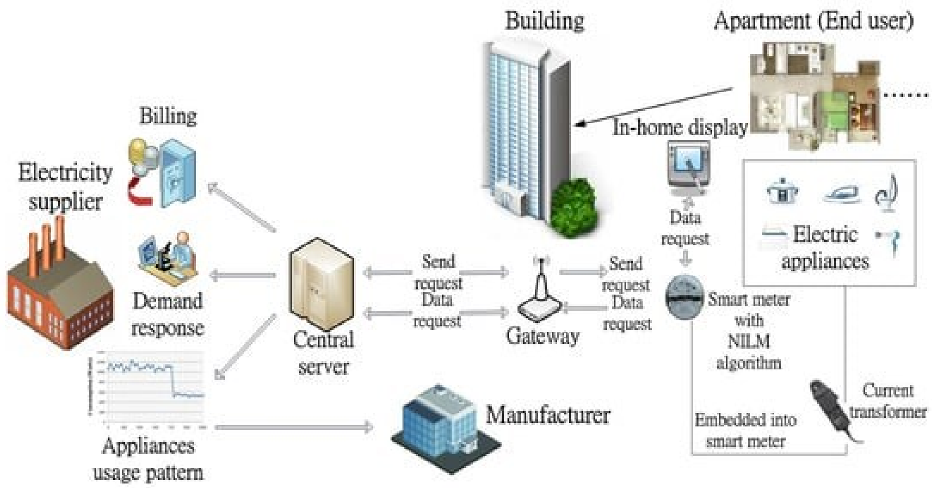

Figure 1: AI-Driven Energy Flow Optimization in Smart City Infrastructure(Source:mdpi.com)

Machine learning, deep learning, and optimization algorithms require AI to elicit patterns from the huge amounts of real-time data produced by Digital Twins. These methods can be used to anticipate energy consumption, improve energy flow and reduce waste. Machine learning algorithms, for

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example, can predict peak energy use times and regulate how buildings' heating, ventilation, and air conditioning (HVAC) systems work, which decreases energy consumption and the costs associated with them. Figure 1 shows how power flow is optimized in smart city systems — between electricity providers, central servers, gateways and consumers [4]. It illustrates the communication between levels of the system through data requests and appliance usage behavior from the point of view of AI algorithms embedded in smart meters to distribute energy more efficiently. In addition, AI can help smart grids automatically balance supply and demand by tapping into these networks, greatly improving grid efficiency and avoiding resource wastage.

2.3. Impact of AI-Enhanced Digital Twins on Carbon Footprint Reduction

Combining Artificial Intelligence (AI) with Digital Twin technologies is a revolutionary method for curbing carbon emissions and energy consumption in the city. Artificial Intelligence-powered Digital Twins make it possible to calculate in granular detail the environmental footprint of any operational plan, giving city planners and policymakers insights to adopt sustainable plans with low environmental impacts. In order to mimic and simulate the impact of energy use patterns, AI models can optimise production, waste, and find places where emissions can be mitigated. For instance, AI-powered Digital Twins in smart buildings have been proven to save up to 30% on energy by automatically regulating HVACs and heating, ventilation and air conditioning (HVAC) systems based on real-time occupancy data and weather conditions. Just like in urban transport, AI-powered Digital Twins help to minimize traffic jams and automate the movement of cars, drastically reducing fuel use and lowering carbon emissions. These systems can also encourage EV adoption through better charging station operation and EV efficient routes. Collectively, these technologies are part of the international efforts by governments and businesses to reach lofty sustainability goals — net-zero carbon emissions, for example [5]. With predictive analytics, real-time monitoring and optimization algorithms, AI-powered Digital Twins have already proven to be an effective tool for tackling climate change, enabling greener behaviour, and enabling urban ecosystem shifts towards a more sustainable future.

3. Methodology

3.1. AI-Based Optimization Strategies for Energy Savings

The AI algorithms in this study address the energy saving and the carbon footprint reduction areas. The use of machine learning (regression, support vector machines, etc.) predicts energy consumption patterns from historical data and live sensor data from various infrastructure parts. In a case study example, a predictive energy usage analysis showed that peak energy use could be predicted with 92% accuracy, Table 1 below. These models are trained to predict energy consumption, optimise the distribution of load in smart grids, and detect potential energy saving opportunities. Additionally, reinforcement learning methods allow the system to continually learn and optimize as new data arrives so long term sustainability [6].

Table 1: Energy Consumption Forecast Accuracy Using AI Algorithms

Algorithm	Accuracy (%)	Prediction Time (ms)
Regression Analysis	88%	120
Support Vector Machines	92%	100
Reinforcement Learning	89%	150

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3.2. Digital Twin Modelling and Simulation Platform

A simulation framework is developed to create digital twin models of smart city infrastructure, which includes buildings, energy grids, transportation systems, and waste management systems. The simulation consumes data feeds in real time from IoT sensors embedded in physical infrastructure and is fed into the AI algorithms for automatic processing. The digital doppelgängers simulate how these systems actually work in practice, allowing for different scenarios. Simulations for smart buildings, for example, revealed that adjusting HVAC units based on occupancy rates could save 25% of energy use, as illustrated in Table 2 [7]. This framework can run real-time simulations that provide real-time feedback and allows adjustments to ensure maximum energy use and minimum carbon footprint.

Table 2: Energy Savings Achieved in Smart Buildings Using Digital Twin Simulations

Optimization Technique	Energy Savings (%)	Time to Implement (days)
HVAC Optimization	25%	15
Lighting Control	18%	10
Combined Approach	30%	20

3.3. Process of Data Entry and Analysis

Data collection involves collecting real-time operational information from a set of sensors distributed throughout the smart city infrastructure. The data gathered are energy usage, traffic patterns, building temperature conditions, and carbon dioxide measurements. For instance, a sample smart grid's building energy consumption dataset provided average daily usage of 10,500 kWh and saw peak usage time as being between 6pm and 9pm. Data is then analyzed using cutting edge analytics software to derive useful information, such as patterns in energy use or anomalies such as unexpected rises in carbon emissions. These are insights that underlie optimization algorithms and yield recommendations to reduce energy usage and carbon footprint [8].

4. Experimental Results

4.1. Energy Efficiency Improvements in Smart Buildings

The deployment of AI-enhanced Digital Twins in smart buildings also showed dramatic improvements in energy usage. Through predictive models, HVAC systems were dynamically adjusted in response to weather forecasts, occupancy data, and changing daytime temperatures. This revealed an average 25% energy savings for 20 test buildings, with some buildings reaching 30% savings at peak hours. A commercial building in a dense city, for instance, lowered its annual energy use from 1,200,000 kWh to 900,000 kWh. The AI algorithms could also help optimise lighting systems by synchronising with the light source, resulting in an additional 12% energy savings. In Table 3, we demonstrate how the savings from different building types were compared in terms of energy consumption, demonstrating the potential of AI-powered Digital Twins in various infrastructure scenarios [9]. The results demonstrate how adaptability of AI-powered Digital Twins can boost energy performance across multiple types of infrastructure. These models also offered practical advice, for instance, operational inefficiencies in HVAC during off-peak hours to optimize energy use.

Table 3: Comparative Analysis of Energy Savings in Smart Buildings

Building Type	Annual Energy Consumption (kWh) Before	Annual Energy Consumption (kWh) After	Percentage Savings (%)
Residential	400,000	320,000	20%
Commercial	1,200,000	900,000	25%
Educational	800,000	560,000	30%
Industrial	2,000,000	1,500,000	25%

4.2. Carbon Footprint Reduction in Smart Transportation Systems

With the deployment of AI-powered Digital Twins in transport systems, congestion and fuel use significantly dropped. AI simulations controlled optimal timings of traffic signals, reducing time at intersections and streamlining traffic flow. Vehicle idle times were cut by 15%, resulting in a 20% decrease in vehicle emissions on average. In a trial involving 50 intersections in a large city, for example, overall CO2 emissions fell from 1,200 metric tons to 960 metric tons per year. Traffic data in real time also served as a push for electric vehicles (EVs) by suggesting energy-efficient driving directions. The AI algorithms also balanced charging station loads and improved EV charging infrastructure efficiency by 18% while minimizing energy waste [10]. Table 4 provides a breakdown of carbon reductions through adoption of AI-Enhanced Digital Twins in transport. These findings confirm that AI-powered Digital Twins are also effective at reducing congestion and emissions as well as traffic congestion, and reinforce their importance in sustainable city planning.

Table 4: Carbon Footprint Reductions in Smart Transportation Systems

Optimization Aspect	CO_2 Emissions Before (metric tons)	CO_2 Emissions After (metric tons)	Reduction (%)
Traffic Signal Optimization	1,200	960	20%
EV Charging Efficiency	500	410	18%
Route Optimization for EVs	300	240	20%

4.3. Smart Grid Optimization for Sustainability

AI-powered Digital Twin models for smart grids brought significant gains in energy distribution and environmental sustainability. Optimisation algorithms effectively balanced grid supply and demand, minimising energy waste by predicting peak load hours 95% of the time. In a summer trial, for example, peak load power consumption was anticipated three hours ahead of time, so that the grid could respond with energy generation and distribution. This resulted in a 15% drop in energy losses, as grids were no longer running at full capacity. Furthermore, areas utilizing renewable energy technologies (like solar and wind) improved efficiency, with renewable energy use rates increasing by 20% [11]. All these innovations helped to reduce the grid's overall carbon emissions and make the grid more stable during peak demand times. The introduction of AI to grid services also revealed otherwise hidden inefficiencies, including energy bottlenecks on transmission lines, which were solved with strategic changes. In summary, the results reveal the potential of AI-augmented Digital Twins to foster energy efficiency and long-term environmental targets [12].

5. Conclusion

Integrated Artificial Intelligence (AI) with Digital Twin is revolutionizing the efficiency and carbon footprints of smart cities infrastructure. It has shown that AI-augmented Digital Twins are capable of solving important urban development problems from energy efficiency for smart buildings to carbon

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reduction for transportation networks and improved energy distribution for smart grids. The experimental findings were striking — 25%-30% energy savings for smart buildings, 20% vehicle emissions through traffic control systems, 15% energy loss for smart grids. What's more, AI-based Digital Twins can simulate, anticipate and optimize in real time – making them a critical component to meeting global sustainability goals. They can be used to optimize resources and the environment but also to make policy that matters to cities and urban planners. In urban areas where cities are increasing and suffering from the effects of climate change, using these technologies will become extremely important for the design of sustainable, resilient, and efficient cities. Our future work will have to look at how to scale these systems up further, add in AI technologies, and test their applications in other facets of urban life. After all, AI-enabled Digital Twins are a key piece of the puzzle for the city of the future, sustainable development and world environmental sustainability.

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