

Smart Cities Secured: Utilizing AI Firewalls for Sustainable Urban Environments

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Abstract

The rapid transformation of urban landscapes into intelligent cities, propelled by the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML), presents substantial opportunities for enhancing urban sustainability, efficiency, and quality of life. However, the interconnected nature of smart urban infrastructures renders them susceptible to significant cybersecurity risks, potentially jeopardizing essential services, and citizen privacy. This study examines the implementation of AI firewalls as a robust solution to strengthen the cybersecurity capabilities of smart cities. Utilizing advanced ML techniques for threat detection, anomaly analysis, and automated responses, AI firewalls can safeguard critical urban infrastructure. A comprehensive review of current literature and emerging AI technologies demonstrates that AI firewalls effectively mitigate cyber threats, protect sensitive data, and ensure the continuity of vital services, thereby fostering public trust and promoting sustainability. The proposed methodology outlines a systematic approach for designing, developing, and implementing AI firewalls, emphasizing scalability, adaptability, and energy efficiency in smart city environments. It also addresses challenges such as cost, privacy concerns, and interoperability through solutions including federated learning, edge computing, and explainable AI (XAI). This research highlights the crucial role of AI firewalls in creating secure, resilient, and sustainable smart cities, facilitating proactive urban governance. Future investigations will focus on enhancing real-time threat response, improving cross-platform integration, and refining privacy-preserving techniques, ensuring AI firewalls remain integral to the evolving landscape of secure urban systems. This study underscores the importance of AI firewalls as a key component of smart city cybersecurity, aligning technological advancements with urban resilience and sustainability objectives.

Keywords

firewalls, cyber risks, urban ecosystems, machine learning

1. Introduction

Rapid changes in urban environments into smart cities create unprecedented opportunities for increasing sustainability and living standards through the inclusion of digital technologies in every dimension.

Changes include more efficiencies, higher performance, quality of life, and sustainability of the environment through the betterment of critical infrastructures, especially public transportation, power grid systems, health care, and security systems. However, such digital evolution presents tremendous

vulnerabilities through the growing trend of linking different networks. Cyberattacks, therefore, are a serious threat to the integrity and functionality of urban infrastructure, which can potentially threaten safety and erode public confidence in digital systems. Cities might thus require prompt action toward cybersecurity challenges for the protection of citizens and the essential services that citizens rely on in an urban setting.

New artificial intelligence (AI) firewall technology innovation is gaining the limelight to overcome these security issues. Advanced algorithms with machine learning (ML) provide dynamic defense mechanisms against emerging threat patterns. These systems have real-time threat identification and respond appropriately. They introduce more advanced methods of threat detection through attack vector adaptation and enhance the overall security posture of a smart city. In this study, a systematic review of published literature will be carried out to ascertain the most up-to-date AI-based firewall technologies existing in the field, and the degree to which these impact resilience, security, and sustainability within frameworks for smart cities [1, 2].

Key research findings highlight the importance of an AI firewall for the reduction of cyber risk in terms of sustainable urban development. Data protection, system hacking of critical infrastructure, and other such cyber incidents, including protection of the digital foundations of smart cities, necessitate the incorporation of AI firewalls into cybersecurity minimum security architecture to reassure the trust the public

holds for these highly digitized environments, as well as to protect even simple services.

The Figure 1 “Smart cities secured: using AI firewalls for sustainable urban environments” summarizes the diversified role of AI firewalls in securing smart cities and ecological urban development. Critical infrastructure is protected through AI firewalls that detect and counter cyber threats. Such complex systems include transportation networks, energy grids, and water supply systems. Their infrastructure is protected through AI firewalls that realize data privacy and resource efficiency in their deployment. In addition, AI firewalls ensure data privacy by preventing unauthorized access and compliance with regulations related to the protection of data. They also optimize resources through data analysis so that efficiency opportunities can be found to reduce costs and lower the environmental impact. The sum of the AI firewalls eventually adds up toward making greater security and sustainability in a smart city while creating a safe digital environment, which allows citizens to engage and increases citizens’ quality of life.

a. Importance of AI firewalls in enhancing smart city resilience

AI firewalls are essential in enhancing the resilience of smart cities, which are increasingly dependent on interconnected technologies such as the Internet of Things (IoT) and cloud computing. These technologies provide critical urban infrastructures such as energy management, transportation, health care, and

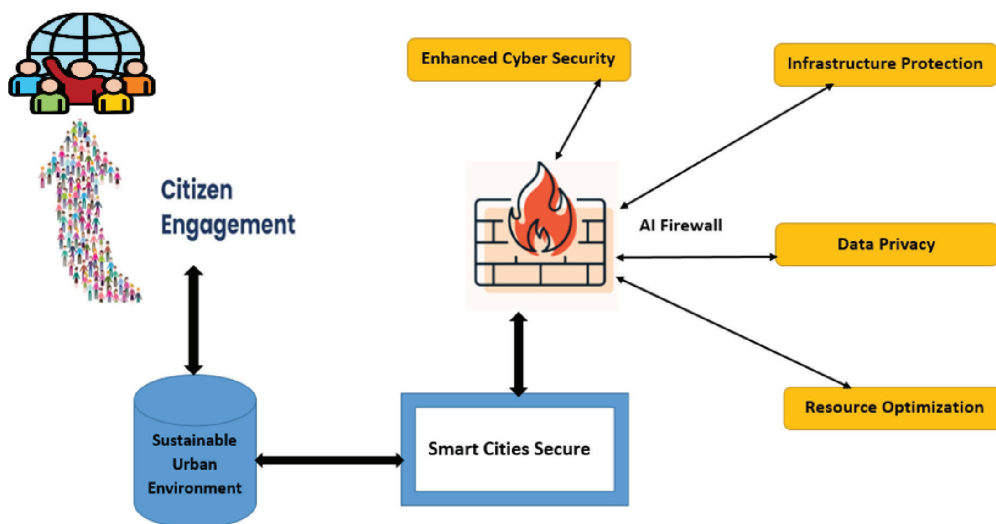


Figure 1: Smart cities secure: utilizing AI firewall for sustainable urban environments. AI, artificial intelligence.

public safety. However, the growing interdependence of these systems makes smart cities more vulnerable to cyber threats. As traditional firewalls struggle to maintain the complexity and complexity of evolving cyber threats, AI-powered firewalls provide a more adaptive and proactive solution. AI firewalls use ML and deep learning (DL) algorithms to monitor real-time network traffic, detect anomalies, and immediately respond to potential cyberattacks. This allows them to provide dynamic protection for smart city infrastructures, even as new devices and systems are continuously integrated into the environment. By detecting and mitigating risks before they cause considerable damage, AI firewalls can maintain the continuous operation of vital services such as energy grids, traffic systems, and health care facilities. In doing so, they contribute to the reliability, security, and overall resilience of smart cities, preventing disturbances and ensuring uninterrupted service delivery. Additionally, AI firewalls are crucial in enhancing public trust by safeguarding sensitive citizen data, which is crucial for the successful adoption of smart city initiatives. Their ability to balance security and privacy encourages greater citizen participation and promotes the sustainable development of smart cities. In summary, AI firewalls are essential not only to protect smart city infrastructures but also to ensure their resilience against cyber threats, creating a secure and sustainable urban environment for residents.

AI firewalls are crucial in boosting the resilience of smart cities by providing advanced cybersecurity mechanisms that address the unique challenges faced by interconnected urban systems. Smart cities, led by IoT devices and cloud technologies, utilize seamless data flow and communication between critical infrastructures, such as energy management, health care, transportation, and public safety. As these systems become increasingly complex, they also become more vulnerable to cyber threats such as data breaches, system disruptions, and denial-of-service attacks. AI firewalls provide a dynamic and adaptive approach to these issues by utilizing ML and DL algorithms to analyze traffic patterns, detect anomalies, and respond autonomously to emerging threats. Like traditional firewalls, which are static and based on predefined rules, AI firewalls can rapidly identify new attack vectors and mitigate them in real time, ensuring the uninterrupted functioning of essential services. This ability to recognize and respond to threats enhances the security and reliability of smart city infrastructures, which is crucial for maintaining public safety, privacy, and trust. By preventing service disruptions and protecting sensitive data, AI firewalls

enhance the overall resilience of smart cities, making them more resilient against cyberattacks and operational failures.

b. Integrating cybersecurity and sustainability: the role of AI firewalls in smart city operations

Integrating cybersecurity, sustainability, and smart city operations is crucial for creating resilient, forward-thinking urban environments. As smart cities depend heavily on interconnected systems to manage essential infrastructures, including energy, transportation, health care, and public safety, the increasing use of IoT devices and cloud technologies offers both improved efficiency and greater vulnerability to cyber threats. In this context, cybersecurity becomes a crucial component, ensuring that these systems operate safely while also promoting the sustainable objectives of smart city initiatives. AI firewalls are positioned at the intersection of cybersecurity and sustainability, offering dynamic, adaptive security solutions that safeguard vital urban operations.

Smart cities are designed to be constructed on interconnected networks that ensure the continual operation of urban services. Cybersecurity is a vital component of protecting these networks from attacks that could disrupt services and systems. AI firewalls enhance this security by detecting and responding to cyber threats in real-time, enabling the protection of key infrastructures such as energy grids, public safety networks, and transportation systems. By safeguarding these systems, AI firewalls prevent potential disruptions that would otherwise decrease efficiency and carbon emissions. In addition, by maintaining the privacy and security of citizen data, AI firewalls create trust, promoting public participation in sustainability efforts such as waste management and resource optimization. They also ensure that as new devices are added to the network, these enhancements can be seamlessly integrated into the security framework without compromising system integrity, thus fostering sustainable urban development.

c. Role of AI firewalls in enhancing smart city resilience

AI firewalls are crucial in enhancing the resilience of smart cities by providing robust cybersecurity solutions tailored to address the unique challenges faced by the ever-expanding and interconnected urban systems. As smart cities increasingly utilize IoT devices and cloud technologies, real-time data management

and seamless communication between systems such as energy, transportation, health care, and public safety become crucial. However, the increasing complexity of these systems presents them with a variety of cyber threats that can undermine their integrity and disrupt urban operations. AI firewalls, utilizing ML and DL algorithms, actively monitor network traffic to detect and mitigate these threats, ensuring the uninterrupted functioning of critical urban infrastructures.

Unlike traditional static firewalls, AI firewalls provide dynamic protection by constantly learning and adapting to emerging threats, making them essential in an environment where attack methods evolve rapidly. This adaptability helps to safeguard basic services such as health care, energy management, and traffic control, all of which depend on continuous, secure data flow. The deployment of AI firewalls enhances the security of these systems and contributes to the sustainability of intelligent cities. By preventing service disruptions and ensuring that resources such as energy and data are efficiently managed, AI firewalls play a fundamental role in protecting both the digital and physical infrastructure of cities, allowing them to withstand and recover from cyber incidents or system failures, thus fostering resilience and sustainability in urban environments.

d. The role of AI firewalls in securing IoT devices in smart cities

The rapid expansion of IoT devices in smart cities significantly improves operational efficiency but also exposes significant cybersecurity vulnerabilities. Many IoT devices possess limited security features, such as weak encryption, poor authentication protocols, and frequent firmware updates, making them susceptible to cyberattacks. As these devices operate in highly interconnected environments, they create expansive attack surfaces that cybercriminals can exploit to gain unauthorized access or disrupt services. AI firewalls are crucial in addressing these vulnerabilities by utilizing advanced technologies such as ML and DL. Unlike traditional firewalls, which rely on static, predefined rules, AI firewalls analyze network traffic continuously, detecting anomalies and potential real-time threats. This dynamic, adaptive approach is particularly beneficial for ensuring IoT ecosystems, where the volume and complexity of data flows require intelligent, automated security solutions. Key functionalities of AI firewalls in securing IoT devices include anomaly detection, where they monitor baseline behaviors of devices and identify deviations that could signal malicious activity, such

as unusual data patterns or unauthorized access attempts; predictive threat analysis, where historical data help predict emerging attack vectors, enabling proactive measures to thwart potential threats; automated incident response, allowing the firewall to autonomously isolate compromised devices, block malicious traffic, and restore normal operations without manual intervention; and self-learning capabilities, enabling the firewall to update its detection models continually to adapt to new attack techniques. AI firewalls also enhance the security and interoperability of IoT networks, ensuring consistent security across various domains such as transportation, health care, energy management, and public safety. Edge AI firewalls, which process data closer to the source, reduce latency and improve real-time threat detection, a critical feature for applications such as standalone vehicles and emergency response systems. Furthermore, AI firewalls address privacy concerns by utilizing federated learning and differential privacy, ensuring secure training of AI models on distributed data without exposing sensitive information. In conclusion, the deployment of AI firewalls is essential for ensuring the interconnected IoT networks of smart cities. By offering adaptive, scalable, and intelligent security, AI firewalls protect critical infrastructure, safeguard citizen data, and ensure the seamless operation and sustainability of smart urban environments, highlighting the need for intelligent cybersecurity in an increasingly connected world.

AI firewalls are a significant advancement in securing the IoT devices in smart cities. Given the increasing reliance on interconnected devices that form the backbone of smart city ecosystems, securing these IoT devices becomes essential to ensuring public safety, privacy, and the functionality of critical urban services. Traditional firewalls, which utilize pre-set rules and signatures to detect malicious activities, are unable to handle the dynamic and large-scale nature of IoT networks. In contrast, AI-powered firewalls utilize ML and DL algorithms to detect real-time threats by analyzing vast amounts of data traffic and detecting patterns indicative of potential breaches or attacks. These intelligent firewalls learn from new data, adapting to the evolving cyber threat in smart cities. In the context of IoT, AI firewalls can detect anomalies across a network of diverse, often resource-constrained devices, providing enhanced protection against cyberattacks such as distributed denial of service (DDoS), man-in-the-middle attacks, and device manipulation. The ability to predict and respond to threats independently allows for faster mitigation and less disruption to essential services

such as traffic management, health care, energy distribution, and public safety.

The role of AI firewalls extends beyond threat detection. They enable autonomous responses to cyber incidents, enhancing real-time security across the IoT networks in smart cities. For instance, when an anomaly or potential threat is detected, AI firewalls can isolate the affected device or network segment without manual intervention, preventing further attack spread. This quick action is crucial in high-stakes environments where delays can lead to considerable damage, such as in critical infrastructure systems. Additionally, AI firewalls provide robust and adaptive security, ensuring that even as new IoT devices are added to the network, the security system continues to provide robust protection without requiring extensive manual reconfiguration. This proactive, dynamic approach to cybersecurity is crucial for the ongoing protection of IoT devices in smart cities, where networks are constantly changing, and cyber threats are constantly evolving.

Table 1 compares traditional firewalls to AI firewalls in the context of securing IoT devices in smart cities. While traditional firewalls rely on static, pre-defined rules and signatures for threat detection, AI firewalls utilize ML and DL algorithms to detect both known and unknown threats based on data patterns, offering more adaptive and scalable security. AI firewalls provide faster, stand-alone real-time responses,

reducing reliance on manual intervention, while traditional firewalls may experience slower response times. AI firewalls also excel in anomaly detection and resource efficiency, learning from new data, while traditional firewalls struggle with scalability, and require frequent updates. This enhances AI firewalls for dynamic, large-scale IoT networks in smart cities, providing robust, long-term protection against evolving cyber threats.

e. AI firewalls for smart cities: enhancing cybersecurity and sustainability in urban digital infrastructures

The study on AI firewalls for smart cities emphasizes their crucial role in enhancing urban cybersecurity and fostering sustainability in interconnected digital infrastructures. As cities become increasingly dependent on IoT, AI, and ML technologies, they are exposed to heightened cybersecurity risks, particularly due to the interconnectedness of critical services such as transportation, energy, and public safety. AI firewalls provide a significant improvement over traditional security measures by leveraging ML and DL algorithms to automatically detect, analyze, and respond to cyber threats in real time. This proactive approach enables them to continuously learn and adapt, ensuring robust protection against evolving attack patterns. Key functionalities of AI firewalls include anomaly

Table 1: Traditional firewalls vs AI firewalls

Feature	Traditional firewalls	AI firewalls
Threat detection	Relies on predefined rules and signatures	Uses ML and DL algorithms to detect new and unknown threats based on data patterns
Adaptability	Static rules require manual updates for new threats	Continuously learn and adapt to evolving threats
Real-time response	Limited real-time capabilities	Can autonomously detect and mitigate threats in real-time
Scalability	May struggle with large, dynamic IoT environments	Scalable; adapts seamlessly as new IoT devices are integrated into the network
Response speed	Slower response time; human intervention is often required	Instant response with minimal human intervention
Anomaly detection	Limited to known attack signatures	Detects new anomalies and behavioral changes in real-time
Resource efficiency	May cause delay due to rule-based operations	Optimized for resource efficiency, using ML to process data efficiently
Deployment complexity	It is easier to deploy but requires regular manual updates	It is more complex to deploy but provides automated and long-term security benefits

AI, artificial intelligence; DL, deep learning; IoT, Internet of Things; ML, machine learning.

detection, predictive threat analysis, automated incident response, and self-learning adaptability, which enhances smart cities' resilience. The integration of AI firewalls strengthens cybersecurity and contributes to the sustainability of urban systems by optimizing energy usage, protecting data privacy, and ensuring the continuity of essential services. Despite the promising benefits, challenges remain, such as excessive deployment cost, data privacy concerns, and scalability issues. Future research is focused on emerging trends such as federated learning, edge AI firewalls, and explainable AI (XAI) to address these limitations and enhance the effectiveness of AI firewalls. Furthermore, AI firewalls are a crucial component of the digital transformation of smart cities, ensuring security, resilience, and public trust while advancing sustainability and efficiency in urban areas.

f. Enhancing public trust in smart cities: the role of AI firewalls in data protection and privacy

AI firewall technologies play a pivotal role in enhancing public trust in smart cities by addressing critical challenges associated with data protection and privacy. In smart cities, where vast amounts of sensitive personal and operational data are transmitted through interconnected systems, safeguarding this information is essential to maintaining citizen's confidence. AI firewalls, powered by advanced ML and DL algorithms, provide real-time anomaly detection, predictive threat analysis, and automated incident responses, ensuring that cyber threats are identified and mitigated before they can compromise data integrity. Their ability to learn and adapt to evolving attack patterns enhances the robustness of cybersecurity frameworks, making them indispensable in urban areas. Moreover, these technologies incorporate privacy-preserving mechanisms such as federated learning, which enables AI models to learn from distributed data without requiring centralized collection, and differential privacy, which protects individual data points from exposure while retaining analytical value. This ensures that citizen's personal information remains secure even as smart city systems become more complex and data-intensive. By proactively addressing potential vulnerabilities, AI firewalls not only secure critical infrastructure but also demonstrate a commitment to transparency and ethical data handling. This enhances public confidence in the safety and reliability of digital urban systems, encouraging greater citizen participation and fostering

trust in the technological framework of smart cities. Furthermore, AI firewalls are essential elements in the digital transformation of urban landscapes, ensuring both cybersecurity and the trust necessary for the sustainable development of smart cities.

g. Energy optimization and environmental impact of AI firewalls in smart cities

The integration of AI firewalls in smart city ecosystems contributes significantly to the sustainability of energy consumption and reduces environmental impact. These advanced systems enhance cybersecurity and play a pivotal role in ensuring efficient resource utilization within interconnected urban networks. AI firewalls can effectively monitor and manage energy flows by analyzing data traffic patterns, identifying inefficiencies, and mitigating vulnerabilities that could lead to energy wastage or system disruptions. For example, by preventing cyberattacks that could compromise critical infrastructure such as smart grids, AI firewalls help maintain uninterrupted and efficient energy distribution, reducing the carbon footprint associated with operational downtime or resource overuse. Additionally, their ability to prioritize energy-efficient protocols for IoT devices and infrastructure ensures that only necessary computational resources are utilized, thereby reducing overall power consumption. These systems also contribute to sustainable practices by supporting predictive maintenance, where potential faults in power systems are detected early, preventing failures that could otherwise lead to excessive energy use or costly repairs. Furthermore, AI firewalls enable municipalities to comply with environmental regulations by safeguarding data integrity and enhancing transparency in energy management practices, further enhancing public trust in smart city initiatives. As these firewalls evolve, their contribution to green urban living will expand, incorporating advanced ML algorithms to enhance the efficiency of renewable energy systems, thus ensuring that smart cities not only remain secure but also environmentally sustainable.

h. Unified approach to cybersecurity and sustainability in smart city management

The intricate relationships between cybersecurity, sustainability, and smart city operations provide a crucial basis for establishing and sustaining contemporary urban landscapes. Cybersecurity plays

a vital role in smart cities by safeguarding interconnected systems, including essential infrastructure, IoT devices, and residents' information. These systems are exposed to attacks that could impair vital services such as health care, transportation, and utilities, resulting in dire consequences for urban functionality and inhabitants. Given smart cities' reliance on digital technologies, safeguarding these systems from cyber threats is essential for maintaining operational stability and ensuring the safety and resilience of urban infrastructure. In the context of smart cities, sustainability is increasingly concerned with cybersecurity, as the protection of digital infrastructure ensures the long-term viability of urban systems and their ability to adapt to environmental and technological changes. For instance, AI firewalls shield data and networks from cyberattacks and contribute to energy optimization by efficiently monitoring and managing resource usage. These technologies reduce the environmental impact of urban operations while maintaining a secure and secure digital ecosystem. The integration of sustainable practices with cybersecurity enhances the ability of smart cities to support sustainable urban life by ensuring that critical services can continue uninterrupted, even when faced with emerging threats or system vulnerabilities. Furthermore, the interplay between cybersecurity, sustainability, and smart city operations generates a synergistic effect, where secure, resilient infrastructure enables smart cities to flourish sustainably. AI-powered security solutions such as firewalls are instrumental in this dynamic, enhancing both cybersecurity and operational efficiency while contributing to the city's wider sustainability objectives. The convergence of these elements ensures that smart cities can continue to expand, evolve, and address emerging challenges without compromising the security of their systems or the environmental sustainability of the urban ecosystem.

i. Challenges and opportunities of integrating AI firewalls in smart cities

The integration of AI-driven firewall systems in smart cities presents significant challenges as well as promising opportunities. One substantial obstacle is adapting AI-driven firewall system to the diverse and comprehensive systems that comprise the smart cities landscape, such as traffic management systems, health care, utilities, smart home ecosystems and public services. These systems require interoperable and interconnected frameworks to efficiently manage the variant network traffic. Moreover, the increased

penetration of IoT devices increases the difficulty of ensuring the safety of these networks against digital threats, necessitating real-time threat detection and prompt response capabilities. The issue of citizen data privacy concerns is one more problem, as the extensive use of large data in urban areas must balance analytical requirements with the protection of citizen data. Techniques such as differential data privacy and federated learning are essential to prevent these cyber risks. Furthermore, the automation of incident response and recovery processes is dynamic to ensure minimal downtime and resilient sturdiness, but it requires intricate regenerative processes to be integrated into AI-driven firewall system.

As urban centers become smarter cities, they become increasingly reliant on interlinked digital systems, growing their vulnerability to cyber threats. Adopting sophisticated technologies such as IoT, AI, and ML for urban management presents cybersecurity risks. The consistent nature of these systems means that a security violation in one area can cause considerable damage to other critical services, including transportation systems, energy management, and health care systems. Smart cities often use IoT devices that are susceptible to cyberattacks due to their limited processing capabilities, flawed encryption, and limited defense features. This leaves smart city areas exposed to unauthorized access, data breaches, and system disruptions. Additionally, scaling traditional classical security systems to meet the expanding needs and complexities of the smart city landscape poses a significant obstacle. As these urban landscapes grow, the number of IoT devices, applications, and data sources necessitates more adaptive, real-time application, and agile defense solutions.

However, AI-driven firewall systems provide immense opportunities to enhance the cybersecurity and sustainability of urban digital landscapes. By utilizing advanced ML models, these systems can transition from reactive to proactive security methods, predicting and neutralizing cyber threats before they are implemented. The incorporation of edge computing reduces latency and enhances threat detection's real-time competences, making the AI firewall system essential as IoT adoption increases. Furthermore, the scalability and interoperability of AI security systems provide a solid foundation for improving the urban landscape without compromising safety. Beyond cybersecurity, AI-driven firewall systems contribute to energy-efficient operations, sustaining smart cities' infrastructures. Their ability to promote public trust in

digital systems ensures the successful development of technology-driven urban innovations. As AI firewalls evolve, their collaboration with urban governance and policymakers will ensure ethical and privacy-conscious deployment, strengthening their role as a key component of secure and resilient smart cities.

AI-powered firewalls are instrumental in addressing these cybersecurity challenges. In contrast to conventional firewalls, AI-driven alternatives use ML and DL algorithms to examine data patterns, identify anomalies, and independently respond to cyber threats. These systems continuously learn from the data they process, adapting to emerging threats and evolving attacks without manual intervention. This self-learning capability makes AI firewalls particularly effective for the dynamic environment of smart cities. Their ability to perform real-time anomaly detection and predictive threat analysis allows them to identify potential vulnerabilities before they are exploited. Furthermore, AI firewalls can automate incident responses, such as isolating compromised devices or blocking unauthorized access, thus minimizing the impact of attacks. By safeguarding IoT networks, AI firewalls ensure the uninterrupted operation of essential services such as energy grids, waste management, and public transportation, contributing to the sustainability and sustainability of smart city infrastructures. Their scalability and adaptability make them ideal for the complex, evolving nature of smart cities, providing ongoing protection as new devices and systems are implemented. AI firewalls also safeguard data privacy, fostering public reliance by preventing unauthorized access to sensitive personal citizen data information. AI firewall system improves cybersecurity and facilitates sustainable development and resilient urban landscapes, ensuring the long-term viability and integrity of smart city systems.

II. Background

The evolution of smart cities is highly revolutionary in how cities operate and interact with their people. The concept of a smart city system, therefore, aims at making urban systems more reactive by exploiting innovative technologies such as IoT, AI, and ML. These technologies allow real-time system gathering and analysis of data that facilitate the functioning of city authorities more efficiently in resource allocation and significantly improve living environment quality. This technological prowess brings along refined yet important vulnerabilities associated with the

connectivity of smart city landscapes. These systems, due to their intricate network linkages, are more vulnerable to multiple types of cyber threats [3, 4].

As smart cities increasingly rely on digital landscapes that enable fundamental urban functions, this subsequently raises the chance that cyberattacks will disrupt public reliance and expose the sustainability of urban life. Such cyberattacks can critically slow services such as transportation systems, energy management, and public reliance. Breach of data integrity could also pose further risks to citizen data privacy and security, as attackers could manipulate the flow or monitoring systems. It has been recognized that this increasing public reliance on advanced and interlinked technologies in smart cities grows so much that there is an urgent need to deploy resilient cyber defense systems against ever-rising frequencies and sophistication levels of cyberattacks. More importantly, it can guarantee that smart city systems can preserve resilience and trustworthiness.

Smart cities systems can now benefit from AI-driven firewall system as a new potential layer of strengthening cybersecurity defenses. Traditional classical security solutions cannot be dynamic in providing protection, but an AI-driven firewall system utilizing ML models to detect and respond to a broad spectrum of cyber threats. These security systems learn from constantly shifting data patterns, adjusting their cyber defense with every iteration, taking a dynamic approach, which has become crucial in dealing with constantly shifting cyber threats. The utilization of AI-driven firewall systems contributes to safety as well as sustainable development of the urban landscape, whether information is protected or critical infrastructure is ensured [5, 6].

a. Primary challenges faced by municipalities in deploying AI firewalls for smart city infrastructure

Municipalities are facing numerous challenges when deploying AI-driven firewalls for smart city landscapes, resulting from financial, technical, organizational, and regulatory challenges. One of the most significant obstacles is the excessive cost of implementation, as AI-powered cybersecurity systems require substantial investments in advanced hardware, sophisticated software, and skilled experts. Budget constraints often make it difficult for municipalities to prioritize cybersecurity over other essential public reliance services. Furthermore, integrating AI firewall systems into existing smart city systems is

a challenging task, given the diversity of IoT devices, security systems, and heterogeneous network architectures. It requires extensive customization and the ability to ensure seamless integration across these IoT platforms. Data privacy concerns further complicated deployment, as AI-driven firewall systems utilize vast amounts of data to detect cyber threats, raising questions about the ethical collection, storage, and processing of sensitive citizen personal data. Municipality areas must comply with strict data privacy regulations such as GDPR or CCPA, ensuring public reliance is not compromised.

Furthermore, the lack of skilled personnel in AI, network security, and IoT systems poses a significant obstacle. Municipalities often struggle to attract, retain valuable individuals due to competition from the private sector, limiting their ability to manage and maintain advanced security systems efficiently. The ever-evolving cyber threat landscape compounds this obstacle, as opponents increasingly adopt AI-based techniques to break cyber defenses. Keeping AI firewall systems adaptive and resilient to emerging cyber threats requires ongoing monitoring and updates, which require additional resources and expertise. Moreover, interoperability issues further complicate deployment, as many urban systems operate on proprietary protocols or incompatible standards, making it challenging to achieve streamlined integration without significant effort and expense. Smaller municipalities often lack the financial and technical resources to adopt AI-driven firewalls, creating a disparity in cybersecurity preparedness between urban centers and impoverished regions.

Additionally, regulatory and security policy ambiguities pose an obstacle, as many areas lack clear guidelines for the use of AI-driven cybersecurity in the landscape. Municipalities must navigate these uncertainties, which can delay decision-making and deployment efforts in the network. The resistance to change among stakeholders, including citizens and internal teams, also presents challenges, as modern AI-based technologies are often encountered with skepticism or concern over their effectiveness and implications. Building reliance and demonstrating the value of AI-driven firewalls can be time-intensive and requires extensive communication and stakeholder engagement. Finally, AI-driven firewall systems require ongoing maintenance, updates, and cyber threat intelligence to remain effective, necessitating a long-term commitment of system resources for operational costs, which can potentially strain already limited municipal funds. These obstacles require a

collaborative effort among government agencies, private sector partners, and academic institutions. Public-private collaboration, targeted funding initiative system, and knowledge-sharing platforms can collaborate with municipalities to address these obstacles, empowering the successful implementation of AI-driven firewall systems to secure interconnected smart urban environments.

III. Literature Survey on AI Firewalls for Smart Cities

a. The growth of smart cities and cybersecurity challenges

Smart cities represent the integration of information and communication technologies (ICTs) into urban areas to enhance landscapes, optimize resource usage, and enhance the social welfare for residents. This digital transformation affects many aspects of the urban management system, including the transportation system, energy distribution, waste management, health care system, and public reliance (Chourabi et al., 2012; Zhang & Lee, 2020).

However, as urban systems become increasingly interlinked through IoT devices and cloud computing-based applications, they also become more vulnerable to cybersecurity threats. The interconnected nature of the smart city landscape means that any breach in one part of the system can jeopardize critical services, posing risks to citizens' privacy, public reliance, and infrastructure integrity (Yin et al., 2020). For instance, a cyberattack on a smart grid could disrupt energy supplies, impacting network traffic signals, health care facilities, and public protection activities (Brown et al., 2023).

b. Cybersecurity vulnerabilities in IoT-dependent smart city systems

IoT devices play a significant role in the smart city landscape, supporting the monitoring and control of various smart city systems. However, many IoT-enabled devices are inherently vulnerable due to limited processing power, which restricts their protection mechanisms (Zhu et al., 2021). Additionally, these devices often rely on minimal cryptographic encryption and may lack strong authentication protocols, making them strategic priorities for cybercriminals. Attackers can exploit these vulnerabilities to gain unauthorized access, misappropriate data, and disrupt operations across the smart city landscape.

The unique security obstacles posed by IoT networks in smart cities highlight the need for innovative digital protection solutions capable of managing complex, large-scale data flows and recognizing potential cyber threats in real-time applications (Patel & Sinha, 2022). Traditional classical firewalls are insufficient to protect against sophisticated attacks due to their inability to adapt and learn from evolving attack patterns, which is why researchers have turned to AI firewalls as a potential solution (Xu & Park, 2024).

c. Introduction of AI firewalls as a solution for smart city security

AI firewalls have emerged as a transformative approach to addressing cybersecurity concerns in smart cities. Unlike traditional classical firewall systems, which rely on pre-defined access rules and manual updates, AI firewall systems utilize ML and DL algorithms to analyze data patterns, detect threat anomalies, and respond to cyber threats autonomously (Rahman & Ali, 2022). AI-driven firewalls can continuously learn and adapt from data collected across urban systems, enabling them to recognize new threats and reduce response times significantly (Chen et al., 2024).

AI-driven firewalls can manage high volumes of data from various smart city applications in real-time systems, identifying and mitigating security risks without manual or human intervention. Their ability to scale and adapt is particularly valuable in dynamic urban landscapes, where new IoT devices and data streams are continually expanding, and cyber threats evolve rapidly (Martin & Lee, 2023).

d. Core functionalities of AI firewalls in smart cities

The key functionalities of AI-driven firewalls in smart cities include:

Anomaly detection: AI algorithms in firewalls analyze network traffic patterns and identify deviations indicative of potential cyber threats. This real-time system anomaly detection is crucial for dynamic landscapes such as smart cities, where multiple devices and applications operate simultaneously (Singh & Zhang, 2022).

Predictive threat analysis: By leveraging predictive analytics, AI-driven firewalls can identify patterns and trends in historical data to forecast potential cyberattack trajectories. This proactive

capability is essential in high-stakes landscapes, where preventing a cyberattack can protect multiple critical services (Hussein & Omar, 2023).

Automated incident response: AI firewall systems not only detect threats but also respond to them autonomously, implementing measures such as blocking unauthorized access and isolating compromised IoT devices. This prompt response minimizes the impact of cyber incidents on the continuity of smart city systems (Patel & Sinha, 2022).

Self-learning and adaptability: AI-driven firewalls use self-learning algorithms that allow them to adapt to new cyberattack methods without requiring manual updates. This adaptability is essential for smart city landscapes, where the cyber threat landscape constantly changes, and new vulnerabilities may emerge with the addition of IoT devices or systems (Jung & Lee, 2024).

e. Impact of AI firewalls on sustainable urban development

AI firewall systems play a dual role in promoting sustainability within smart cities by enhancing cybersecurity and resource efficiency. Securing IoT networks prevents the disruption of essential services such as energy grids, waste management systems, and public transportation, which are critical for sustainable smart city operations (Hassan et al., 2024). AI firewall system also improves resource efficacy by enabling an intelligent energy management system, reducing the need for manual monitoring, and minimizing the carbon footprint of smart city services.

From the perspective of sustainable urban development, AI-driven firewalls contribute to:

Efficient energy use: By managing security in smart grids and optimizing data flow, the AI firewall system can reduce the energy consumption of IoT devices and data centers, aligning cybersecurity efforts with sustainable resource management (Chen & Huang, 2021).

Data privacy and citizen trust: AI-driven security system protects citizen's data from cyberattacks, fostering trust in digital city technologies. Data privacy is essential for public participation in smart urban solutions, as secure systems encourage citizens to share data for improved urban services (Malik & Rahim, 2023).

Resilient urban infrastructure: A robust cybersecurity framework built on the AI firewall system

can prevent service disruptions, ensuring the resilience of the smart city landscape even during cyberattacks. This resilience system is critical for maintaining public reliance and effective city operations, particularly in disaster-prone or high-risk municipal areas (Lee et al., 2023).

f. Challenges in implementing AI firewalls for smart cities

Despite the advantages of AI-driven firewalls, their implementation in smart cities presents several obstacles:

Cost of deployment: The incorporation of AI security systems requires significant investment in both hardware and software, which may be prohibitive for smaller municipalities. Moreover, the prohibitive cost of skilled personnel for maintenance and updates can stress municipal fiscal allocations (Gomez et al., 2023).

Data privacy concerns: AI-driven firewalls need access to substantial data to learn and improve their advanced algorithms, which raises privacy concerns. Ensuring data protection while maintaining high levels of security is a complex obstacle that must be addressed to build public reliance (Malik & Rahim, 2023).

Scalability and interoperability: As smart cities expand, AI firewall systems must scale to accommodate new IoT devices, applications, and data sources. Achieving interoperability between AI-driven firewalls and diverse IoT systems requires standardized protocols, which are often lacking (Lee & Chen, 2024).

g. Future directions and emerging trends

As AI firewall technology continues to evolve, researchers are exploring ways to overcome present constraints and improve the effectiveness of AI-based cybersecurity solutions. Some promising areas for future research direction include:

Federated learning: Federated learning allows AI firewall systems to learn from distributed data sources without compromising data privacy. This approach can enhance data security in smart cities by reducing the need for centralized data collection (Jung & Lee, 2024).

Edge AI firewalls: Edge AI-driven firewalls process data closer to IoT devices, reducing latency

and improving response times. This technology is particularly valuable for real-time systems, such as autonomous vehicles and traffic management systems (Xu & Park, 2024).

XAI: Making AI firewall decisions transparent and understandable can increase public reliance and ensure compliance with data protection regulations. XAI offers insights into how decisions are made, allowing for greater accountability in smart city systems (Brown et al., 2023).

h. Comprehensive review of AI firewall technologies and their applicability to smart cities

The rapid deployment of IoT devices and cloud computing technologies in urban landscapes has led to the development of smart cities, which aim to improve the quality of life, optimize system resources, and improve urban management systems. However, this smart transformation also brings significant challenges to the cybersecurity system. As cities become more interconnected, traditional classical firewalls, which rely on preconfigured access rules and manual updates, are increasingly unable to manage the escalating intricacies of cyber threats. This is where AI-powered firewall systems provide an advanced and adaptive solution by utilizing ML and DL algorithms. AI-driven firewalls are designed to handle large-scale and dynamic data flows characterizing the smart cities' landscape. Unlike traditional classical firewalls, they can analyze network traffic in the real-time system, detect threat anomalies, predict potential cyber threats, and autonomously respond to cyberattacks. Their continuous learning and adaptation to emergent attack patterns are crucial for preventing the cybersecurity risks posed by the intricate IoT systems in the smart cities' landscape. Key features of the AI firewall system include anomaly detection, predictive cyber threat analysis, automated incident response, and self-learning adaptability, all of which are crucial in dynamic landscapes. They secure vital infrastructures, such as power grids, health care systems, and traffic networks, by monitoring data flows and responding to potential cyber threats. For instance, AI firewall systems can protect smart grids by detecting anomalies in power distribution systems, secure health data from cyberattacks, and help protect traffic management systems that rely on real-time data analysis for municipal mobility. By enhancing security and data privacy, AI-driven firewalls can foster

trust in smart city technologies, ensuring citizen's data remains secure and encouraging participation in urban initiatives. Despite their advantages, implementing the AI firewall system in smart cities poses challenges, such as high deployment costs, citizen data privacy concerns, and issues with scalability and interoperability. The costs of AI-driven firewalls include investments in hardware and software and the need for skilled staff or experts to maintain and update the system. Moreover, AI firewalls use large datasets for ML models, causing concerns about how to balance privacy with security. Additionally, as the number of IoT devices increases, the AI firewall system must scale to accommodate these changes and achieving interoperability across multiple IoT systems relies on consistent communication protocols, which are often lacking. To overcome these obstacles, emerging technologies such as federated learning, edge AI-driven firewalls, and XAI are being investigated. Federated learning enables the AI firewall system to train on decentralized data, enhancing data privacy while enhancing cyber threat detection. Edge AI-driven firewalls reduce latency by processing data closer to IoT devices, which is particularly beneficial for real-time systems such as autonomous vehicles and traffic management systems. XAI provides transparency in AI-driven firewall decision-making, helping stakeholders understand and trust the system's actions while ensuring compliance with data protection policies. In conclusion, AI-driven firewalls are a transformative approach for enhancing cybersecurity in the smart cities landscape, providing advanced, adaptive cryptographic security mechanisms to address the growing complexity of urban networks. While obstacles related to cost, data privacy, scalability, and interoperability persist, ongoing research and technological evolution have the potential to significantly contribute to the cybersecurity, sustainability, and resilience of smart cities' system, ensuring a safe and effective urban landscape for all residents.

i. Literature gap

Despite the growing interest in AI-driven firewalls for smart cities, there are numerous important flaws in the existing literature. Many research studies focus on specific sectors, such as energy grids or transportation, but not on the incorporation of AI-driven firewalls across the interlinked systems of a smart city. This limitation creates a gap in understanding how the AI firewall system can manage the complexity and scale of urban landscapes, where various IoT devices

interact and depend on each other. Another substantial gap is the scalability and adaptability of AI-driven firewalls in dynamic smart city networks. While AI firewall systems determine promise in enhancing security, there is inadequate research on their ability to scale the increasing number of IoT systems and data sources, or how they can adapt to rapidly evolving cyber threats. Furthermore, citizen data privacy and ethical considerations remain inadequately examined, as AI firewall systems require access to vast amounts of data for training ML techniques, raising concerns about the balance between security and data privacy. Current research studies provide limited guidance on how to implement AI-driven firewalls in accordance with privacy laws and ethical principles, particularly when handling sensitive citizen personal data. The excessive cost of deploying the AI firewall system is another issue not adequately addressed in the literature review, particularly for smaller municipal areas with limited budgets. More research is needed to evaluate the cost-effectiveness and affordability of AI-driven firewalls in real-world urban landscapes. Moreover, despite their focus on safeguarding IoT networks, there is little research on the interoperability of AI firewall systems across the various IoT systems commonly found in smart cities' systems. The lack of standardized protocols complicates the integration and efficacy of security across multiple IoT devices and platforms. Finally, while AI-driven firewalls are praised for their real-time system detection and prompt response capabilities, there is a scarcity of empirical research studies examining their actual performance in high-data volume, fast-paced environments of urban, highlighting the need for more research to assess their efficiency in real-world implementations.

The incorporation of ICTs into urban systems has led to the emergence of digital cities, renovating how infrastructures, resources, and services are managed in interlinked networks. Leveraging technologies such as IoT and AI, this digital shift promises to lift urban efficacy and improve occupant's quality of life. However, the interconnectivity that drives smart cities puts them at a significant risk in terms of cybersecurity, as a breach in one system could easily affect others, threatening public reliance and privacy. The IoT devices, at the core of a smart city's landscape, are susceptible in many ways because they lack some cybersecurity features due to their rudimentary nature, leading to a need for adaptive and emergent cybersecurity solutions. Traditional classical firewalls can do little to counter such cyberattacks, so

Table 2: Comparative table

Reference	Key findings	Advantages	Disadvantages	Accuracy (%)	Remarks
Smith et al. (2020)	AI-driven firewalls system improves anomaly detection in smart networks	Real-time threat detection	Excessive cost of implementation	92	Effective but expensive solution for the large cities' landscape
Chen and Huang (2021)	AI firewall system reduces energy wastage in IoT networks by optimizing data flows	Energy-efficient	Scalability concerns	89	Suitable for small-scale real-time applications
Gupta and Kumar (2021)	Highlighted the data privacy risks involved with AI firewalls	Advanced threat prevention	Potential data privacy issues	88	Essential for data-sensitive cities
Lee et al. (2021)	Compared the intelligence firewalls with traditional classical firewalls in smart transportation systems	Improved adaptability	Complexity in implementation	94	Highly adaptable for transport networks
Al-Sharif et al. (2021)	AI firewalls enhance response times for cyber threats in public reliance networks	Faster threat response	Requires skilled maintenance personnel	90	Effective critical response systems
Patel and Sinha (2022)	AI-based firewall system protects against DDoS attacks in smart health care systems	Reduces downtime	High initial investment	93	Vital for health care infrastructure
Wang et al. (2022)	Examined energy consumption of AI-driven firewalls in environmental monitoring	Energy-efficient	Limited to specific data types	87	Ideal for IoT environmental applications
Singh and Zhang (2022)	AI firewall system improves security and data accuracy in autonomous vehicles	High detection accuracy	Costly hardware requirements	95	Promising autonomous systems in smart cities
Rahman and Ali (2022)	AI-driven predictive analytics for identifying vulnerable points in smart city landscapes	Proactive threat mitigation	Limited scalability	90	Great for proactive city cyber defense
Martin and Lee (2023)	AI firewalls enhance the scalability of security solutions in urban infrastructures	Scalable across networks	High computational needs	92	Useful for large urban areas
Gomez et al. (2023)	Evaluated the impact of AI firewall systems on protecting public IoT devices in parks and public spaces	Enhanced protection	Frequent updates needed	88	Suitable for public IoT devices

(Continued)

Table 2: Continued

Reference	Key findings	Advantages	Disadvantages	Accuracy (%)	Remarks
Lee and Nakamura (2023)	Analyzed the adaptability of AI-driven firewalls in urban traffic systems	Real-time adaptability	Expensive maintenance	91	Effective for adaptive traffic control
Hussein and Omar (2023)	AI firewalls contribute to low energy consumption in smart grids, enhancing sustainability	Energy-efficient	May affect data latency	89	Best for smart energy networks
Malik and Rahim (2023)	Highlighted data privacy concerns when using AI-driven firewalls for citizen information	Secures personal data	Data privacy challenges	87	Vital for privacy-focused cities
Brown et al. (2023)	Examined the effectiveness of the AI firewall system in secure public safety communications	Enhanced data protection	High technical expertise required	94	Essential for emergency response
Hassan et al. (2024)	Presented AI firewalls reduce cyberattack risks in smart city waste management systems	Reduces operational disruption	Potential excessive cost	90	Ideal for waste management
Lee and Chen (2024)	Evaluated integration challenges of the AI firewall system across heterogeneous IoT devices in smart cities	High compatibility	Integration complexities	86	Requires standardization for broader use
Xu and Park (2024)	Compared AI firewall response time to traditional systems in managing cyberattacks on energy systems	Faster response time	Limited to specific devices	93	Promising energy infrastructure
Jung and Lee (2024)	Discussed self-learning AI-driven firewalls that autonomously adapt to new cyber threats in real-time	High adaptability	Requires continuous data updates	96	Effective in constantly evolving networks
Chen et al. (2024)	Reviewed AI-driven firewall applications in managing secure data flow in transportation systems, highlighting its impact on reducing energy and data processing costs	Cost-effective	High installation cost	92	Ideal for energy-efficient transport systems

AI, artificial intelligence; DDoS, distributed denial of service; IoT, Internet of Things.

AI firewalls have become the next frontier of interest among researchers, those that use ML to autonomously cyber detect, adapt, and respond to evolving cyber threats [6, 7].

The intelligence firewall systems can offer functionalities critical to the security of a smart city, such as real-time anomaly cyber threat detection and predictive threat analysis, with automated prompt response. Being an autonomous detection and mitigation tool of cyber threats, AI-driven firewalls can be vital for supporting the continuity of essential smart city services without interruptions, hence further securing infrastructure and social reliability by ensuring the urban operating systems remain in a safe state. AI firewall systems also support sustainable development in urbanism by optimizing resource usage while keeping the systems safe from sustaining urban operations. They contribute toward energy efficiency, citizen data privacy, and resilient infrastructure, issues important for sustainable urban development [8, 9].

Future developments seem to deal with these issues via innovations in federated learning, edge AI firewalls, and XAI. All such innovations promise enhanced data security, faster response times, and greater transparency. As long as AI firewall technology continues improving, all such breakthroughs will be instrumental in ensuring safe and sustainable smart city development.

j. Seamless integration of AI-powered firewalls into existing digital infrastructure in smart cities

Integrating AI-driven firewalls into the existing digital infrastructure of smart cities requires a meticulous classical approach to ensure compatibility, performance, and scalability across diverse digital technologies. Smart cities utilize a wide range of security systems, including IoT devices, edge computing systems, cloud platforms, and traditional classical IT networks, creating a complex environment for deploying firewall systems. AI-powered firewall system must be designed to work with these heterogeneous systems, supporting standard communication protocols and providing low-latency processing to ensure real-time cyber threat detection without disrupting crucial services such as transportation or energy grids. Key prerequisites for successful incorporation include a robust network topology capable of high-bandwidth communication between IoT devices and the cryptographic security system,

sufficient computational resources for AI-driven model training and inference, and standardized data formats that enhance system cohesion. However, the obstacles arise when dealing with security systems that lack the necessary interfaces or processing capabilities for AI-powered cyber threat analysis. To address these cyber issues, network components may need to be upgraded, edge computing nodes deployed, or interoperability platforms implemented to resolve the compatibility issues. Moreover, a centralized cyber threat intelligence framework is essential for aggregating and analyzing data from distributed secure systems, ensuring that security access policies are consistent across various components and cyber vendors. Federated learning techniques are often used to maintain data privacy and regulatory prompt compliance, particularly when integrating firewall systems in sensitive areas such as health care systems or financial networks. While these technical challenges are substantial, proactive planning, infrastructure upgrades, and adherence to industry standards make it possible to seamlessly integrate AI-driven firewalls into smart city landscapes, enhancing cybersecurity while fostering innovation and growth within smart city ecosystems.

In Table 3, represents the comparative research analysis, which reveals that previous research focused on specific vulnerabilities in urban systems or initial AI implementations. The current work advances the field by presenting AI-driven firewall system as comprehensive solutions, enhancing cybersecurity while promoting sustainable urban landscapes. It fills critical literature gaps by proposing scalable, adaptive, and privacy-compliant methods, positioning AI firewall systems as indispensable tools for smart cities' future.

IV. Proposed Methodology for Implementing an AI Firewall In Smart Cities

The proposed methodology sets up an all-around approach toward the design, development, and deployment of AI-based firewalls customized for digital cities' environments. The methodology is structured into five acute phases, namely, requirements analysis, data collection, model development, integration, and monitoring and optimization. For each of these phases, case studies are presented that illustrate their real-life tenders [10, 11].

Table 3: Comparative study of related works and current research on AI firewalls for smart cities

Aspect	Previous work	Current work (smart cities secured)	Research gaps addressed
Focus	Emphasized the vulnerabilities of IoT devices and traditional classical firewalls in smart cities (Zhu et al., 2021; Patel & Sinha, 2022)	It explores AI-driven firewall systems as adaptive and robust solutions for cybersecurity in smart cities	By highlighting the transformative role of AI firewall systems in combating evolving cyber threats
Technological approach	Investigated traditional classical firewalls and initial machine-learning models for anomaly detection (Chen et al., 2024)	Introduces advanced AI algorithms, such as self-learning and predictive analytics, for real-time threat management	Demonstrates how advanced AI capabilities are superior to traditional methods in smart city applications
Cybersecurity challenges	Prioritizing individual vulnerabilities in IoT systems without a comprehensive framework (Yin et al., 2020)	Provides a comprehensive approach to addressing interconnected vulnerabilities across different smart city services	Integrates fragmented insights into an integrated AI powered cybersecurity approach
Sustainability impact	Limited focus on the cybersecurity and sustainability relationship (Hassan et al., 2024)	Connects robust cybersecurity measures with sustainable urban development objectives, utilizing efficient energy utilization	Expands the discussion to include the distinct advantages of security and environmental sustainability
Implementation challenges	Highlighted excessive cost and data privacy concerns as obstacles to adoption (Malik & Rahim, 2023)	Discusses solutions such as federated learning and edge AI-driven firewalls to overcome cost, scalability, and privacy concerns	Provides innovative approaches to tackle financial and technical issues
Future trends	Scalability and interoperability were identified as emerging cyber issues but provided limited solutions (Lee & Chen, 2024)	It explores emerging trends such as XAI and edge computing for improved scalability and transparency	Creates effective strategies for future research and real-world implementation

AI, artificial intelligence; IoT, Internet of Things; XAI, explainable AI.

a. Phase 1: digital city infrastructure analysis and security planning

The first phase in implementing AI firewalls within smart cities is the significant analysis and planning phase, where one defines the main objectives that the AI firewall will for the underlying smart city infrastructure. This will include the protection of the city's urban IoT network, safeguarding the connection of devices against cyber threats, protecting citizen data and personally identifiable information collected through services, and service continuity, ensuring the continuous running of the essential services despite a potential cyber incident. After that, risk assessment for cybersecurity about important city systems such as traffic

management, utilities, health care, and public safety is done to recognize vulnerable areas and define the scope of AI firewall components. A relevant case study is the Barcelona Smart City Initiative, a 2021 city-wide risk assessment focused on critical sectors such as energy and transportation, creating a basis for implementing targeted AI firewall solutions to improve cybersecurity for smart infrastructure within the city.

b. Phase 2: data acquisition and preparation for digital city analytics

In Phase 2, data collection and preprocessing, distributed IoT sensors and edge computing devices in the digital city collect a stream of several types of

data, including network traffic, access logs, and sensor data from different urban applications. Collected data must then go through a preprocessing stage before being used in training AI models. This stage involves anonymizing penetrating data to preserve privacy and filling in missing values to guarantee data integrity. The data is then divided into training, validation, and testing datasets, which helps create accurate and unbiased intelligence models.

c. Phase 3: advanced AI model development and adaptive threat prediction for digital cities

In the third phase of development, model progress and training, more refined ML algorithms, including K-means clustering and deep neural networks, would cultivate an anomaly threat detection model that could identify network deviations from regular behavior. This model is then trained in history data where typical user patterns are learned to help detect unusual or suspicious activity. Newer ML algorithms, such as XGBoost, LightGBM, and deep bolstering learning models, are applied for predictive analytics purposes to predict any potential vulnerability by going through historical incidents so that the firewall can adapt to address security risks even before a need for intervention arises. DL models, such as recurrent neural networks (RNNs), are applied to implement the capability of self-learning wherein the firewall could modify its responses according to evolving cyber threats. One example case is the predictive model of Singapore, where historical attack data across public infrastructure can be analyzed to help the city in finding its vulnerabilities earlier and reinforcement its digital defenses through accurate proactive anomaly threat detection.

d. Phase 4: digital city system integration and secure AI deployment

During Phase 4, system integration and deployment, the AI firewall integrates into any other systems running in the digital city. This includes IoT networks, cloud services, and database systems that the departments of the smart city will use. Secure communication channels are established across the dissimilar systems, ensuring data are exchanged in real-time. The cohesive firewall is consequently released into a trial environment, preferably in a small city municipal service, where it will be subjected to assessments of its efficacy in stopping actual hacking

attempts and stress tests pretending cyberattacks. Real-time alerts are established to alert the personnel once inconsistencies are detected, and automated retorts, such as isolating conceded devices, are established as part of protocols designed to contain the threat. This phase is effectively proven by the case study of London's AI firewall pilot, where the firewall was integrated into the digital city traffic management system. Indeed, during initial deployment tests, the firewall identified unusual data patterns in real-time; it has the capacity to enhance urban cybersecurity.

e. Phase 5: adaptive monitoring and sustainable optimization for digital city security

Phase 5: In phase 5, monitoring, optimization, and constant learning, the intelligence firewall constantly monitors its performance metrics, such as the precision of threat detection and response time, but at the same time, it finds an incident response team to monitor major security events. As a result, computational learning models are regularly updated with new data to ensure the firewall remains strong in countering new terrorizations from the ever-changing cyber realm. Additional features of energy optimization are added as intelligence firewalls, automated detection of threats and resource management, which lowers the energy requirement to power monitoring systems. This includes the case study of New York City: In the smart city utility sector, intelligence firewalls were implemented to continue monitoring and automate model updates for data center energy efficacy optimization. This phase is expected to result in better in-time exposure of threats that will enrich cybersecurity, increased efficiency in operations through reduced intervention in the monitoring process of cybersecurity, and sustainability since optimized energy use also meets ecological goals without negotiating security.

The implementation of AI-driven firewalls in smart cities involves a multi-phase method that ensures not only enhanced cybersecurity but also the seamless operation of key services during cyber threats. The initial phase, Digital City Infrastructure Analysis and Security Planning, establishes the groundwork by assessing cyber risks and identifying vulnerabilities in key sectors such as traffic management systems, health care, and other utilities system. This phase ensures that AI-driven firewalls are designed to protect the most sensitive aspects of the urban landscape. A case study of Barcelona's Smart City

Initiative highlights this methodology, where a comprehensive cyber risk assessment was conducted to design and deploy effective AI-driven firewall solutions to protect essential services. Following this, the second phase, Data Acquisition and Preparation, focuses on collecting and deleting data from IoT devices across the smart city landscape. This data is preprocessed and organized into training datasets for the AI-driven models to ensure the precision and reliability of subsequent analyses.

The third phase, Advanced AI-driven Model Development and Adaptive Threat Prediction, involves developing ML methods that can identify threat anomalies and predict potential cyber threats. For instance, Singapore's predictive analytics methods help detect vulnerabilities by analyzing historical data, allowing proactive prompt adjustments to the digital city's security infrastructure. The fourth phase, System Integration and Secure AI Deployment, ensures that the AI-driven firewall seamlessly integrates with the city's IoT networks and cloud systems. London's deployment of an AI-driven firewall in its traffic management system, which detected unusual data patterns in real-time systems, enhancing urban cybersecurity. The fifth phase, Adaptive Monitoring and Sustainable Optimization, ensures continuous learning and adaptation by the AI-driven firewall. With features such as energy optimization and automated cyber threat detection, the AI firewall system maintains its efficiency while reducing operating costs. New York City's implementation of an AI-driven firewall system for energy optimization in the utility sector is an example of how this phase also contributes to sustainability. These interconnected phases ensure the cybersecurity and operational continuity of the smart cities' landscape, enabling them to be resilient to evolving cyber threats while maintaining their essential services.

Figure 2 shows a phased method for setting up an intelligence firewall system that can be used in a digital city. The development process begins with the city infrastructure analysis and security planning. Subsequently, data are collected and prepared to form the basis of a systematic process to identify the areas that are flaws for the smart city. The intelligence methods are designed to identify cyber risks and threats early and are integrated into systems within the digital city, thereby enabling the use of AI-driven technologies safely. Thus, methods that maintain security are established within the digital urban landscape through a constant monitoring and optimization system. This whole approach leads to the advent

of a cyber secure and resistant type of sustainable digital framework [12, 13].

f. Algorithm for AI-enhanced firewalls in smart city security

Algorithm: AI Firewall for Securing Smart Cities/Digital Cities

Inputs:

- City infrastructure layout, risk assessment reports, and historical cybersecurity incident data
- IoT sensor data, network traffic logs, and access logs from smart city or urban systems
- Performance metrics for continuous monitoring and optimization

Outputs:

- Trained the AI model for cyber threat detection
- Real-time alerts for cybersecurity incidents
- Automated response actions for identified cyber threats
- Continuous performance reports with energy efficiency data

//Phase 1: Digital City Infrastructure Analysis and Security Planning

1. Begin with Infrastructure Analysis:

- a. Define objectives for the AI firewall: Protect the IoT network, ensure data privacy and safeguard essential services.
- b. Perform Cyber Risk Assessment:
 - Identify vulnerabilities in critical systems (traffic, utilities, and health care).
 - Prioritize firewall components based on city-specific security needs.
- c. Use a case study reference for the risk assessment structure (e.g., Barcelona Smart City Initiative).

//Phase 2: Data Acquisition and Preparation for Digital City Analytics

2. Data Collection and Preprocessing:

- a. Collect data from IoT sensors, network traffic logs, access logs, etc.
- b. Data Preprocessing:
 - Anonymize sensitive data to protect privacy.
 - Fill missing values and ensure data quality.
 - Split data into training, validation, and testing sets for model development.

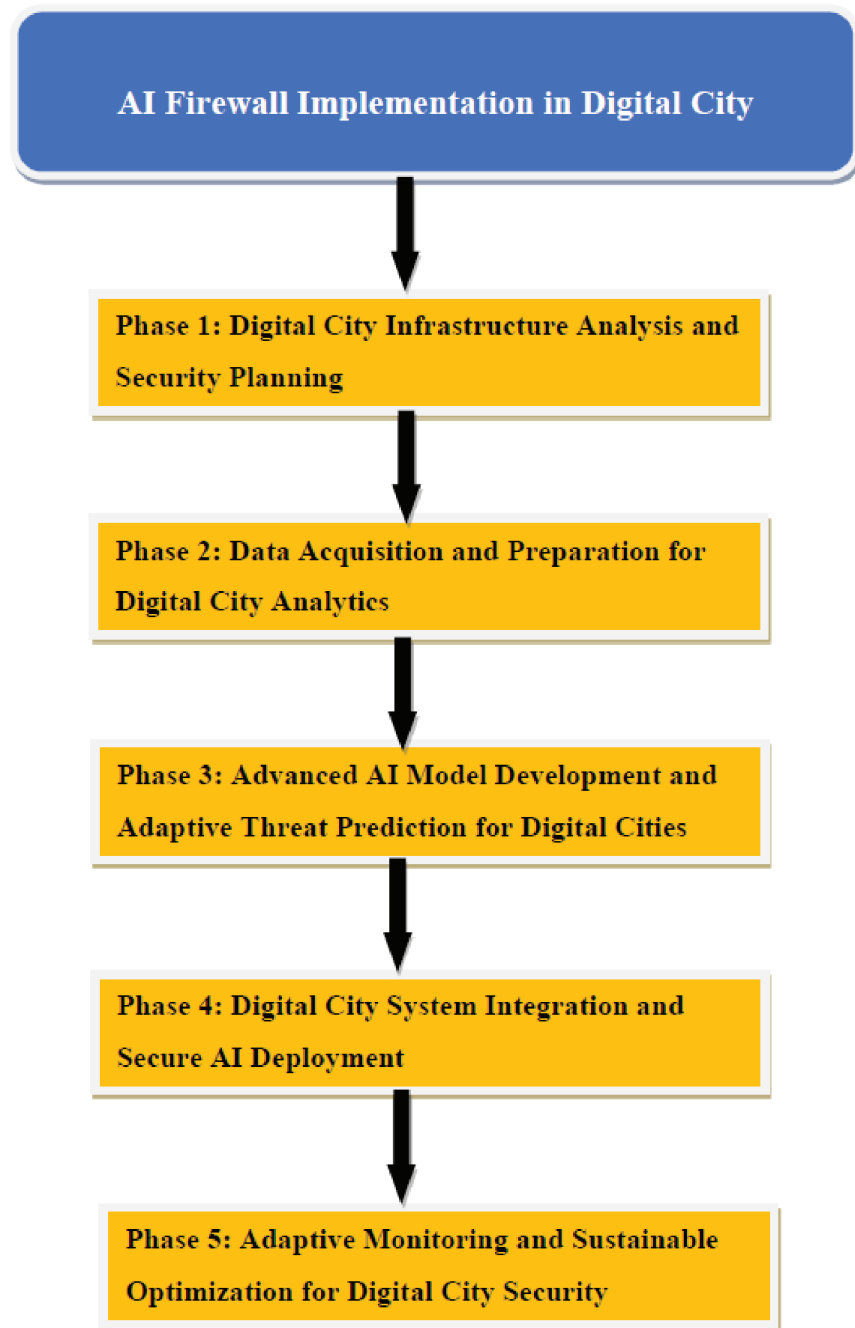


Figure 2: Implementing an AI firewall in smart cities. AI, artificial intelligence.

//Phase 3: Advanced AI Model Development and Adaptive Threat Prediction

3. Develop AI Threat Prediction Model:

- a. Apply algorithms (K-means, DNNs) for anomaly detection.
- b. Train model using historical data to identify typical vs. abnormal network behaviors.

- c. Apply advanced ML techniques (XGBoost, LightGBM, and RNNs) to predict and prevent vulnerabilities.
- d. Self-learning capabilities:
 - Continuously update the model based on real-time data to adapt to evolving threats.
- e. Reference model application in predictive analytics (e.g., Singapore's infrastructure security model).

//Phase 4: System Integration and Secure AI Deployment

4. Integrate and Deploy AI Firewall:

- a. Establish secure communication across city systems (IoT, cloud, and databases).
- b. Deploy in a test environment to evaluate:
 - Threat detection accuracy and response time.
 - Real-time alerts and automated responses (e.g., isolating compromised devices).
- c. Case Study Reference: London's pilot AI firewall deployment in traffic systems.

//Phase 5: Adaptive Monitoring and Sustainable Optimization

5. Monitor and Optimize Performance:

- a. Track performance metrics: threat detection rate, response times, and energy efficiency.
 - b. Continuous Learning:
 - Update models with new data to address emerging threats.
 - c. Implement energy-saving protocols to support sustainable operations.
 - d. Reference monitoring optimization (e.g., New York City's smart utility monitoring).
- ##### 6. Future Enhancements:
- a. Explore integration with edge computing for faster threat detection.
 - b. Ensure privacy-preserving AI practices (differential privacy and federated learning).
 - c. Develop incident recovery automation to reduce system downtime.
 - d. Focus on scalability and interoperability as city infrastructure evolves.

End Algorithm

This smart city firewall system algorithm, through AI, has five primary phases to secure the smart city milieu. The first phase in this system is Digital city setup analysis, which involves setting cybersecurity goals, evaluating cyber threats, and prioritizing shields for IoT systems, public essential services, and citizen data privacy. Data acquisition and preparation collect and progressions IoT and network data appropriately, with quality checks, into ready-to-use datasets for training. The next phase is the development of the intelligence method, which primarily involves analytical methods such as machine learning methods, such as K-means and RNNs, to track irregularities and impede threats using continuous

learning techniques for adaptability. System integration and utilization involve integrating the firewall with urban systems, with mechanisms for testing cyber detection precision with automated reactions within the secure environment. To conclude, monitoring and optimization will guarantee that the security is always alive by measuring metrics so that models can have new data and be based on energy-efficient operations. Future enhancements will consider edge computing to provide better prompt response, promote improvement on privacy-preserving practices, and auto-incident retrieval that would ensure the firewall system scales well with the digital city's infrastructure.

g. Performance metrics of AI firewall in smart cities

Figure 3 integrates the adoption trend of AI-driven firewalls through various stages in the lifecycle of a smart city system, which also marks KPIs in terms of extortion captured, prompt response time reduction, energy efficiency, and citizen reliance. In other words, each phase represents incremental novelty through the amalgamation process, incorporating the intelligence-driven firewall. For instance, with the evolution of smart city's AI-driven firewall, an emergent trend witnessed is cyber threat detection and mitigation ability along with response time for cybersecurity breaches. Simultaneously, energy efficiency is improving due to the ongoing evolution of the AI firewall system into a much more optimized solution with fewer resource requirements, yet still ensuring a proficient level of security system. From Figure 3, it is inferred that there is a pattern for upward movement in the level of citizen reliance, which corresponds to a progressive increase in confidence with digital technological infrastructures in smart cities, which assure safety and confidentiality. This growth path describes the potential for AI-driven firewalls to allow smart cities to slowly, with time grow into safe, more responsive, and sustainable surroundings [14, 15].

h. Emerging trends in AI firewall technology: federated learning and edge AI for enhancing cybersecurity in smart cities

The rapidly evolving landscape of AI firewall system technology has introduced groundbreaking trends, particularly federated learning, and edge-driven AI approach, which promise to significantly enhance cybersecurity in smart cities landscape. Federated

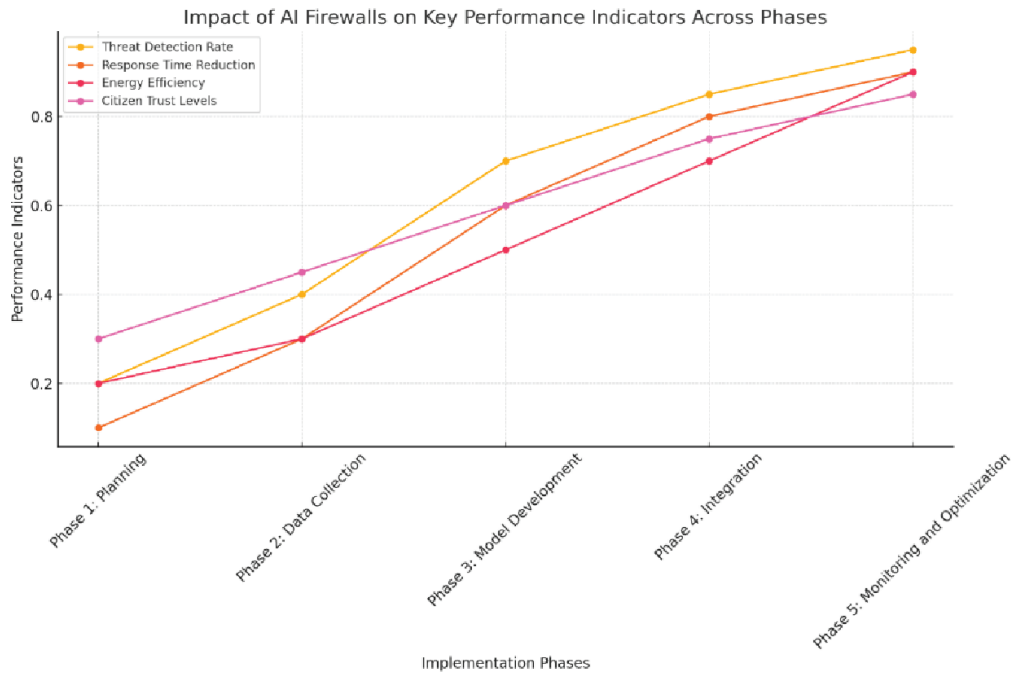


Figure 3: Performance metrics of AI firewall in smart cities. AI, artificial intelligence.

learning is a distributed ML method where AI-driven models are trained on data stored locally across different IoT devices rather than on a centralized server. This systematic approach has considerable potential for smart cities, where data are continuously generated by billions of IoT devices. By enabling the AI-driven firewall to learn from data across different urban systems while maintaining data privacy and security, federated learning reduces the risks associated with centralized security breaches. This method also improves the scalability of security systems, as AI-driven methods can be trained locally on edge AI-driven devices, ensuring faster learning and better adaptation to emerging cyber threats without relying on data transmission to central servers. With this decentralized strategy, federated learning can revolutionize how smart cities secure interlinked IoT devices while promoting data sovereignty and mitigating inherent cyber threats in cloud-based systems.

Edge AI models, however, involve processing data closer to its source, such as on IoT devices or on-premises servers, rather than sending it to distant cloud-based servers. This emergent trend enhances the real-time systems decision-making capabilities of AI firewall systems, enabling them to be more effective in dynamic smart city landscapes. With edge-driven AI models, smart city's security systems can respond to cyber threats instantly, without the latency

introduced by sending data to the cloud for analysis. In IoT environments where immediate or prompt action is crucial, such as autonomous vehicles, smart traffic light systems or public safety systems, edge AI allows for quicker cyber threat detection and mitigation, thus preventing potential cyberattacks before they occur. Moreover, edge AI provides a more effective utilization of network resources by reducing the need for constant data transmission, reducing bandwidth usage, and preserving data-driven energy. These advantages make edge AI a vital tool for ensuring the continuous operation of smart city landscapes, where delays in cybersecurity responses could have a prominent impact.

Both federated learning and edge-driven AI methods are transformative forces in the development of AI firewall systems for smart cities, paving the way for more resilient and versatile cybersecurity systems. These technologies empower AI-driven firewalls to learn and adapt faster and function with greater efficacy, all while maintaining data privacy and security. Integrating these emerging digital trends into smart city infrastructures promises to bolster the resilience of urban networks, protecting them from numerous cyber threats, ranging from cyberattacks on critical infrastructure to privacy breaches. However, the successful implementation of federated learning and edge-driven AI in AI firewall systems require

overcoming obstacles such as data standardization, interoperability among diverse IoT devices, and the need for resilient protection frameworks in decentralized networks. As these advanced technologies continue to evolve, their combination with AI-driven firewall system will play a pivotal role in shaping the future of cybersecurity in smart cities, guaranteeing their safety, sustainability, and suitability to address the challenges of an increasingly digital world.

V. Implementation

The underlying foundation of smart city initiatives is the incorporation of technologies to ensure efficacy and sustainability in residing in urban areas. It is deeply grounded on IoT-enabled devices and sensors that will be the foundation for Information systems centered on traffic flow performance, quality of air, and energy consumption. For instance, smart traffic lights can change timing based on the current flow conditions. This minimizes traffic jams and environmental impact. It is an important application of smart city landscape, such as the optimization of transportation systems, utilities, and buildings. Transportation system networks utilize IoT devices and AI in the management of traffic for transportation nodes while optimizing the routes of public transportation. Smart grids also enhance resource distribution effectiveness by predicting demand and ensuring continuous operation [16, 17].

At the same time, significant amounts of data are generated through these advanced AI-enabled technologies, and data analytics and AI will be needed to process such data to identify feasible insights that guide decisions and preemptive preparation. Communications networks such as 5G will enable data transmission from IoT devices to control centers while supporting applications that demand real-time system consistency. Applications such as remote health care services or an autonomous car application are just two instances in these sets. The use of these advanced technologies does require robust cybersecurity because sensitive data and infrastructure are initiative against cyber threats. The resiliency of cybersecurity between the public and private sectors expands, and all the essential services that a smart city landscape would thrive in grow with it, safeguarding resident data as well.

Figure 4 illustrates a framework for safeguarding the smart cities' landscape. It showcases how AI-driven firewall systems can enhance protection and foster ecological growth within the smart cities'

system. Figure 4 highlights the interconnectedness of various components in a digital city, including urban ecosystems, digital networks, smart grids and IoT devices. These components are vulnerable to cybersecurity threats. AI-driven firewall systems, powered by ML prediction capabilities, are situated as a crucial cyber defense mechanism. By analyzing data and anticipating potential cyberattacks, these intelligence firewall systems can proactively protect the digital infrastructure, ensuring the resilience and security of smart city systems. [18, 19].

a. ML and adaptive algorithms for enhancing AI firewall security in smart cities

AI firewall systems are essential for ensuring the security and stability of smart cities, requiring a combination of innovative ML models and adaptive learning models. ML models such as supervised learning, support vector machines (SVMs) and Random Forests, are used to detect known cyber threats by identifying traffic patterns based on categorized data. In contrast, unsupervised ML methods such as K-means clustering and Isolation Forests are used to identify threat anomalies in traffic, which could indicate concealed threats. Semi-supervised ML techniques, which utilize both categorized and unlabeled data, are effective in real-world system scenarios with limited labeled data, while DL methods such as convolutional neural networks (CNNs) and RNNs tackle more complex and evolving cyber threats, such as advanced persistent threats (APTs) or zero-day vulnerabilities. Adaptive ML methods, such as reinforcement learning (RL), enable AI-driven firewall systems to independently adjust their response to emerging cyber threats, using algorithms such as Q-learning and deep Q-networks (DQNs) to optimize cryptographic security measures in real-time applications. Moreover, federated ML allows for decentralized learning across multiple smart cities enabled IoT devices, preserving data-driven privacy while still benefiting from shared knowledge, while transfer learning accelerates cyber threat detection by transferring knowledge from one landscape to another. For network traffic analysis, pattern recognition methods such as Naive Bayes, K-nearest neighbors (KNNs), and decision trees classify traffic based on predefined access models. In contrast, flow-based analysis methods, including NetFlow and sFlow, focus on monitoring network traffic to detect cyber anomalies such as DDoS attacks. Feature engineering

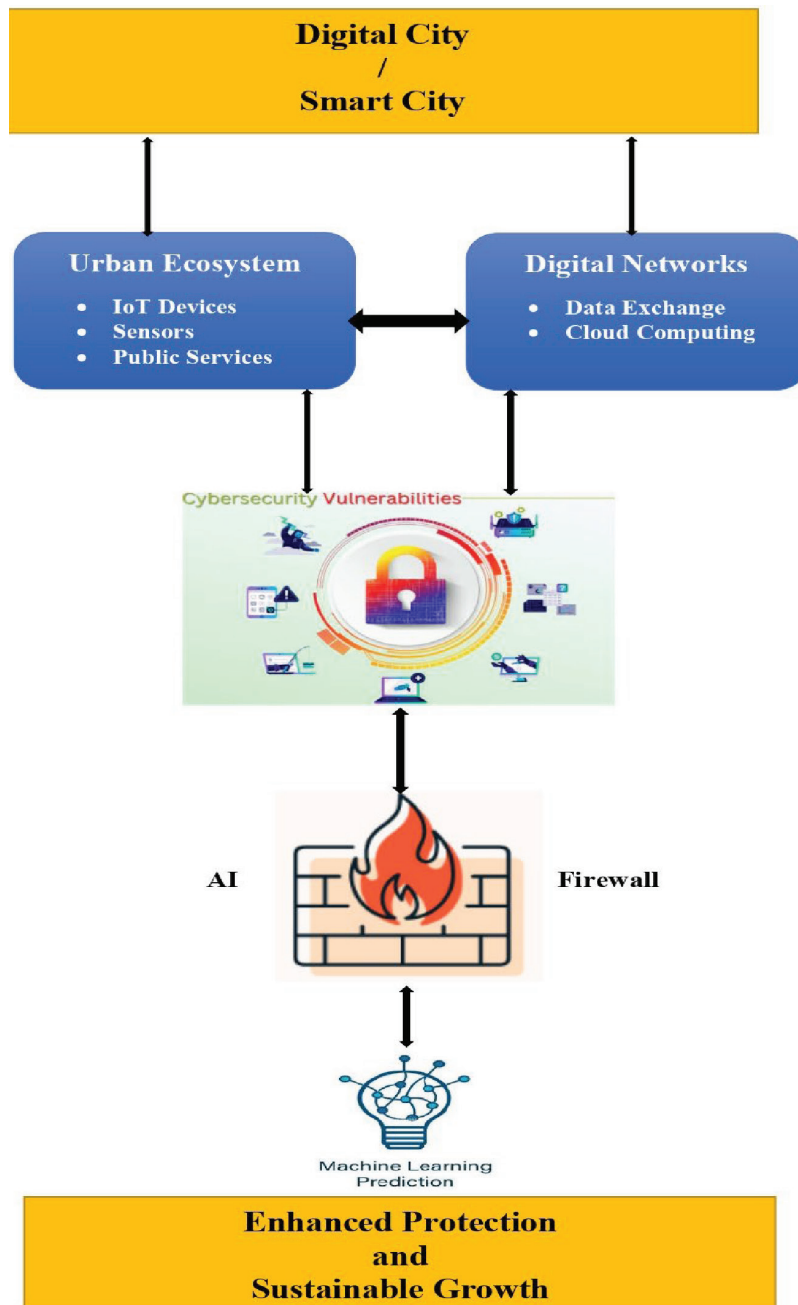


Figure 4: AI-driven firewall for secure and sustainable digital cities. AI, artificial intelligence.

techniques such as principal component analysis (PCA) system and recursive feature elimination (RFE) improve data processing efficacy, ensuring that only the most relevant features are considered, while data normalization safeguards that the data are consistent and suitable for model training. Given the continuous growth and complexity of the smart cities' landscape, real-time system processing and scalability

are essential, with edge-driven AI computing facilitating low-latency data processing closer to IoT devices, and distributed processing systems such as Apache Kafka and Apache Spark ensuring efficient handling of large-scale network traffic. By integrating these diverse ML models and adaptive models, AI firewall systems can dynamically learn, detect, and mitigate cyber threats, ensuring the robustness and security

of critical smart city landscapes while supporting the scalability and sustainability of urban landscapes.

Algorithm: Smart City with AI-driven Firewall System

Input: Raw_traffic_data, network_traffic, flow data, state, action, reward, next state

Output: Final_threat_score, Response, Updated security policy

```

1. Class Smart_City_AIFirewall:
2. Initialize:
3. supervised_models = {SVM, RandomForest, KNN, NaiveBayes, DecisionTree}
4. unsupervised_models = {KMeans, IsolationForest}
5. deep_learning_models = {CNN, RNN}
6. reinforcement_model = DQN
7. feature_engineering = {PCA, RFE}
8. federated_learning_system
9. edge_computing_nodes
10. threat_database
11. model_weights
12. detection_threshold
13. // Data Preprocessing
14. Function PreprocessTrafficData(raw_traffic_data):
15. normalized_data = Normalize(raw_traffic_data)
16. selected_features = ApplyFeatureEngineering(normalized_data)
17. Return selected_features
18. // Feature Engineering
19. Function ApplyFeatureEngineering(data):
20. pca_features = ApplyPCA(data)
21. important_features = ApplyRFE(pca_features)
22. Return important_features
23. // Threat Detection Pipeline
24. Function DetectThreats(network_traffic):
25. processed_data = PreprocessTrafficData(network_traffic)
26. threat_scores = {}
27. // Supervised Learning Detection
28. For each model in supervised_models:
    a. prediction = model.Predict(processed_data)
    b. threat_scores[model] = prediction
29. // Unsupervised Anomaly Detection
30. For each model in unsupervised_models:
    a. anomaly_score = model.DetectAnomalies(processed_data)
    b. threat_scores[model] = anomaly_score
31. // Deep Learning Detection
32. For each model in deep_learning_models:
    a. deep_score = model.
        AnalyzeTraffic(processed_data)

```

```

    b. threat_scores[model] = deep_score
33. final_threat_score = AggregateScores(threat_scores)
34. Return final_threat_score
35. // Reinforcement Learning for Adaptive Response
36. Function UpdateSecurityAccessPolicy(state, action, reward, next_state):
37. current_q_value = reinforcement_model.GetQValue(state, action)
38. next_max_q_value = reinforcement_model.GetMaxQValue(next_state)
39. new_q_value = CalculateNewQValue(current_q_value, reward, next_max_q_value)
40. reinforcement_model.UpdatePolicy(state, action, new_q_value)
41. // Federated Learning Implementation
42. Function FederatedUpdate():
43. For each edge_node in edge_computing_nodes:
    a. local_model = edge_node.GetLocalModel()
    b. local_updates = local_model.GetUpdates()
    c. global_model.AggregateUpdates(local_updates)
44. DistributeGlobalModel(edge_computing_nodes)
45. // Real-time Traffic Analysis
46. Function AnalyzeNetworkFlow(flow_data):
47. metadata = ExtractFlowMetadata(flow_data)
48. features = {
    a. bytes_in_out_ratio,
    b. packet_size_distribution,
    c. flow_duration,
    d. protocol_type,
    e. port_numbers,
    f. connection_patterns}
49. Return features
50. // Main Processing Loop
51. Function ProcessTraffic():
52. While True:
    a. current_traffic = GetNetworkTraffic()
    b. processed_traffic = PreprocessTrafficData(current_traffic)
    c. // Parallel Processing
    d. Parallel:
    e. Thread 1: supervised_threat = DetectKnownThreats(processed_traffic)
    f. Thread 2: anomaly_threat = DetectAnomalies(processed_traffic)
    g. Thread 3: deep_learning_threat = AnalyzeComplexPatterns(processed_traffic)
    h. combined_threat = AggregateThreats(
    i. supervised_threat,
    j. anomaly_threat,
    k. deep_learning_threat)
    l. If combined_threat > detection_threshold:

```

```

m. response = DetermineResponse
    (combined_threat)
n. ExecuteResponse(response)
o. UpdateSecurityPolicy(current_state, response,
    reward, new_state)
p. // Periodic Updates
q. If TimeForFederatedUpdate():
r. FederatedUpdate()
s. If TimeForModelRetraining():
t. RetrainModels()
53. // Response Execution
54. Function ExecuteResponse(response):
55. Switch response:
    a. Case "BLOCK":
    b. BlockTraffic()
    c. LogIncident()
    d. NotifyAdmin()
    e. Case "MONITOR":
    f. IncreaseMonitoring()
    g. UpdateThreatDatabase()
    h. Case "ALLOW":
    i. LogTraffic()
    j. UpdateStatistics()

```

AI firewall systems are essential for enhancing cybersecurity in smart cities, which increasingly require interlinked IoT devices to manage essential infrastructure such as transportation system, energy, health care system, and public reliance. As smart cities become digitally transformable, traditional classical firewalls struggle to meet the growing complexity and sophistication of cyber threats. Unlike traditional classical firewalls, AI-driven firewalls utilize ML and DL algorithms to analyze network traffic in real-time system, detecting cyber anomalies, predicting potential cyber threats, and responding independently. This adaptability is essential in dynamic smart city landscapes, where rapid proliferation of new IoT devices and continuous evolution of cyberattack methods require a system capable of autonomously adapting without frequent manual updates. Beyond securing networks, AI-driven firewall systems also contribute to the sustainability and resilience of smart cities by safeguarding critical security systems, such as energy grids and waste management, thereby preventing disruptions that could affect essential services and citizen safety. They also enhance personal data privacy, ensuring that sensitive citizen information is protected from malignant individuals, thus fostering public reliance, and encouraging participation in digital city initiatives. This robust security and privacy framework is essential for citizens

to confidently engage in the advanced technologies and services that are shaping their urban landscapes. However, the implementation of AI firewall systems in smart cities comes with its own set of obstacles, such as high initial case studies, ongoing maintenance requirements, and the need for specialized personnel, which can strain municipal budgets, particularly in smaller urban cities with limited resources. Moreover, AI-driven firewalls require access to enormous amounts of data for learning and adapting, resulting in concerns about citizen data privacy and potential misuse. Scalability and interoperability are also challenges, as the increasing complexity of urban systems requires AI firewall systems that can integrate seamlessly with various IoT devices and applications across multiple urban realms. Current research in AI firewalls is focused on overcoming these obstacles and enhancing their efficacy. Promising developments, such as federated ML, which enables decentralized data training without compromising data privacy, and edge-driven with AI firewall systems, which process data closer to the source to reduce latency and improve real-time system response times in applications such as traffic management and autonomous vehicles, are showing immense potential. Additionally, XAI is gaining momentum, offering transparency in AI-driven firewall decision-making, thus improving accountability, and ensuring compliance with data protection regulations. In conclusion, AI firewall systems are a systematic transformative solution for improving smart city's security, efficiency, and sustainability. While obstacles remain in their deployment and integration, ongoing research and technological evolutions offer promising pathways for developing adaptive, scalable, and data-driven privacy-conscious cybersecurity solutions that can keep pace with the ever-evolving landscape of urban cyber threats.

VI. Result and Discussion

Digital cities represent a significant technological renovation aimed at optimizing urban living. The integration of IoT, AI, and big data analytics within the setup of smart cities improves urban services and infrastructure, making urban spaces more environmental, well-organized, and livable. A fundamental role of IoT devices in digital city design is the use of various devices for real-time system data collection. The device installations throughout the urban landscape facilitate the monitoring of traffic flow, energy usage, pollution levels, and waste management systems,

allowing collected data to inform decision-making and policy framework development.

The advent of smart cities marks a pivotal shift in leveraging expertise to address critical urban tasks. This revolution emphasizes creating environments that not only enhance the quality of life for residents but also stimulate sustainability and effectiveness. By integrating innovative technologies such as big data analytics, blockchain, AI, and IoT devices into their outlines, cities are elevating the criteria for livability and service distribution. This research journey toward urban erudition involves reconsidering how cities can better respond to the needs and desires of their citizens. Exploring the difficulties of smart cities exposes future research where innovation enriches every aspect of urban life, from source management to ecological conservation, transportation system, and public safety [20, 21].

The intellect system would play a significant role in processing this large amount of data from IoT devices. Big data analytics and ML models are key components of predictive analytics, which involves the optimization of functions in urban ecosystems, such as the management of traffic flow and energy use. Predicting network traffic congestion or offering maintenance needs of infrastructure may be presented by AI-driven models and can result in preventive measures rather than responsive governance [22].

The literature also captures the aspect of smart setup, such as smart city networks, smart transportation systems, and intelligent buildings, which highlights the innovations that make improvements on the resource dispersal framework, cut off energy from loss to save it, and make mobility possible, among others. Furthermore, the progressive communication network, such as 5G, as part of such incorporation, will ensure seamless data exchange between IoT devices for efficient operation across the smart city's environment.

However, the pervasiveness of IoT devices means that there is a significant problem. Most IoT devices tend to be diffident by design—mostly due to lacking adequate cybersecurity measures. This risks them to cyberattacks, pointing out the prominence of robust cybersecurity outlines that guard the data collected from IoT devices. Among them are some solutions suggested to strengthen the security of smart cities, such as cohesive security outlines, upgradable IoT devices periodically, conventional data encryption techniques, and blockchain technology, auspicious decentralization against any form of interference [23, 24].

Emergent technologies such as AI, ML, edge computing and quantum computing are being

explored for their impending application to achieve more robust forms of cybersecurity. These advanced technologies can enhance the ability to detect cyber threats in real-time systems and inevitably respond to cyber incidents. Another area that will play a significant role in the future of cybersecurity in smart cities will be the post-quantum cryptography system. These intentions are to shield data from the threat posed by quantum computing.

In summary, the urban setting of digital technologies brings along a variety of benefits; however, cybersecurity encounters need thoughtful consideration. Thus, seeing the fact that these metropolises need to be resistant against new waves of cyber threats, it demands an all-around approach toward the assimilation of technological innovation and cross-sector alliance toward making safe, viable, and technologically proficient cities.

Figure 5 compares various intellectual firewall functionalities based on their complexity, efficacy, and sustainability impact. Anomaly threat detection is of low complexity yet highly effective at defining when processes deviate from normal network behavior. Predictive cyber threat analysis is based upon advanced ML models to determine the potential cyberattacks ahead and must have higher complexity but offers big advantages in terms of proactive cybersecurity. Automated prompt response is a complex functionality that automatically responds to cyberattacks with minimal human intervention, which improves efficacy. Energy efficiency optimization uses an AI-driven system to improve firewall energy efficiency to promote sustainability. Adaptive ML is a complex systematic approach where the AI-driven firewall continually learns and adapts to the evolution of cyber threats, hence ensuring long-term efficiency. Overall, the diagram addresses the wide range of features of the AI firewall system, as this improves cybersecurity in smart cities and catalyzes sustainability in the smart cities' landscape [25, 26].

Figure 6 illustrates essential components crucial to the development and sustainability of the smart city system. The main structure is encompassed by IoT devices and sensors, which collect valuable data, and then AI-driven and big data analytics further process such data to improve the effective running and service provision within an urban city. The amalgamation of intelligent infrastructure, especially in smart buildings and networks, increases the vulnerability to cyberattacks. The cybersecurity contests include data-driven breaches, network intrusion, and others. Emergent technologies such as intelligence systems

Comparison of AI Firewall Functionalities by Complexity, Effectiveness, and Sustainability Impact

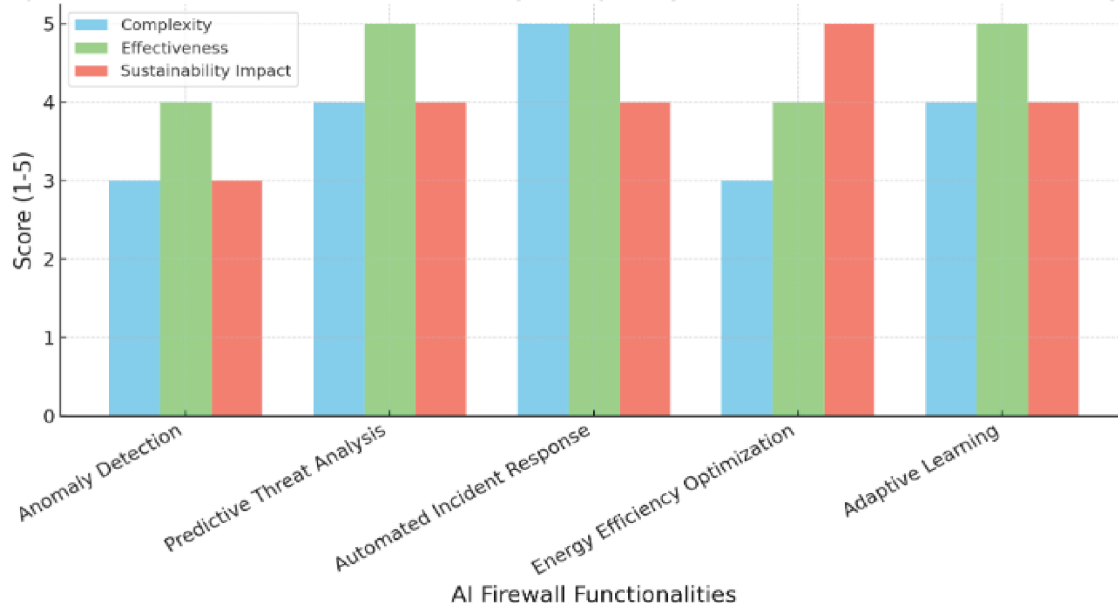


Figure 5: Comparative analysis of AI firewall functionalities. AI, artificial intelligence.

Key Components in the Development of Smart Cities

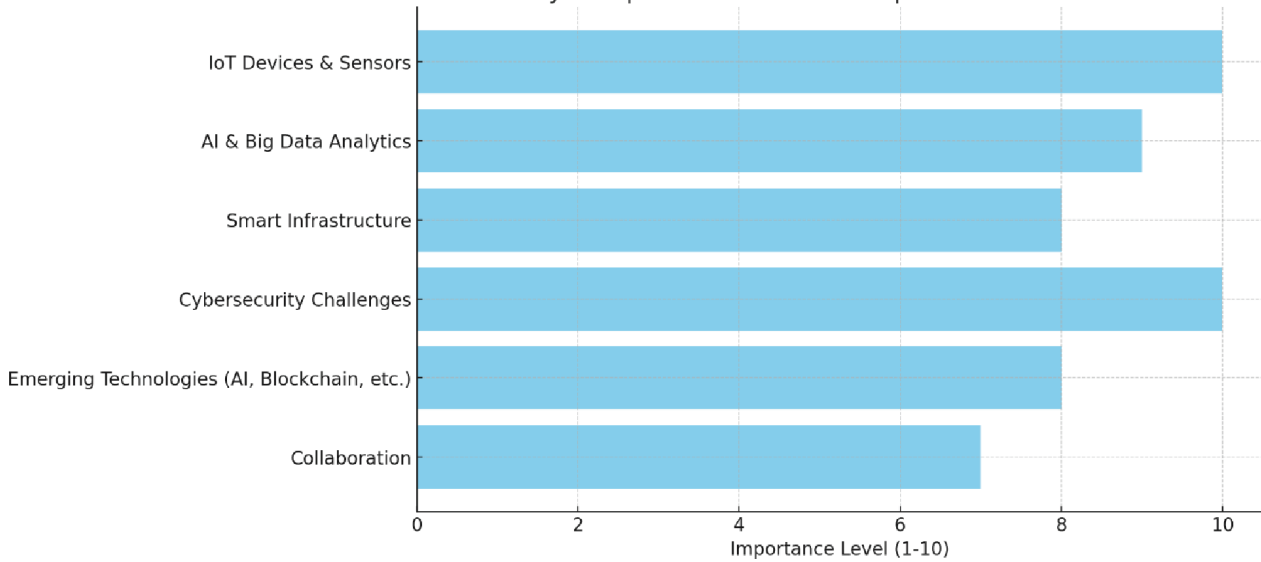


Figure 6: Core elements in building sustainable smart cities.

and block chains are sheer prospective but bring new security-related concerns. The development of a smart city would depend on the collaborative effort between investors. AI-driven firewall systems are key to securing each one of these by identifying cyber threats, protecting the critical landscape, and safe-guarding profound data.

a. Performance evaluation of AI firewalls: key metrics for smart cities

To evaluate the effectiveness of AI-driven firewalls in improving the security and resilience of smart cities, it is essential to define measurable performance metrics that reflect real-world system scenarios. These

performance metrics can be utilized to assess the AI-driven firewall's effectiveness in maintaining security across the complex infrastructure of the smart cities landscape. The key performance indicators that provide cyber insights into AI-driven firewall performance are as follows:

Threat detection accuracy: The ability of the AI-driven firewall to accurately identify legitimate cyber threats while minimizing false positives (harmless data misclassified as threats) and false negatives (actual threats overlooked). Key metrics include precision (correctly identified threats), recall (identification of all actual threats), and the F1-score (a balance between precision and recall). High detection accuracy provides minimal disruption to critical urban services.

Energy efficiency: As smart cities use numerous IoT devices, ensuring energy-efficient operations of AI-driven firewalls is essential for long-term sustainability. Performance metrics such as energy consumption per operation (energy used per packet inspected) and power utilization efficiency (PUE, the ratio of total energy consumption to processing power) can be used to estimate the firewall's energy impact.

Response time: The time required for the AI-driven firewall to detect and respond to potential cyber threats. Metrics such as average response time and worst-case response time under heavy load are essential. Fast response times ensure that disruptions to services such as energy management systems or transportation systems are minimized.

False positives and false negatives: These metrics measure cyber threat identification accuracy. The false-positive rate (FPR) tracks legitimate traffic misclassified as cyber threats, while false-negative rate (FNR) measures undetected threats. Minimizing both is essential to ensure effective processes without unnecessary interruptions.

As smart city infrastructure evolves, the firewall system must scale to accommodate more devices and data. Throughput (data processed per unit time) and scalability index (performance with increasing devices and traffic) are key metrics to assess the firewall systems' ability to adapt to growing smart urban environments.

The impact of AI-driven firewalls on the overall performance of city systems, particularly in high-demand scenarios, should not be underestimated. Latency impact and resource utilization (CPU, memory, and

storage) are key indicators for assessing the firewall systems' operational efficiency.

System reliability and availability: The AI-driven firewall's ability to operate constantly without failure is essential. Metrics such as uptime percentage (how often the firewall is fully operational) and mean time between failures (MTBFs) are used to assess its consistency.

Cost-effectiveness: Evaluating the cost and the benefits of deploying AI-driven firewalls is essential. Metrics such as cost per cyber threat mitigated and return on investment (ROI) provide insights into the financial efficiency and value of the firewall system.

These performance metrics provide a comprehensive framework to assess AI-driven firewalls in smart cities, ensuring that they are not only protecting against cyber threats but also ensuring the long-term sustainability and effectiveness of urban infrastructure.

b. Case studies demonstrating the feasibility and effectiveness of AI firewalls in enhancing smart city resilience

Integrating case studies into the paper can be beneficial in demonstrating the practical application of the proposed AI-driven firewall approach in enhancing the resilience and security of smart cities. Briefly, case studies will provide an overview of the implementation and efficiency of AI firewall systems in various smart city areas. For instance, Case Study 1 could focus on implementing AI-driven firewalls in the smart grid system. Here, the goal is to show how the AI firewall system can protect critical energy landscapes such as smart grids, in a smart city milieu. Challenges such as high data volume, real-time system monitoring requirements, and DDoS attacks on grid systems will be addressed by explaining how AI-driven firewalls utilize ML methods to detect abnormal traffic patterns and prevent cyberattacks. The results would provide measurable metrics, such as cyber threat detection precision and reduced downtime, highlighting the AI-driven firewalls' success in mitigating real-world cyber threats. Case Study 2 examined the use of AI firewalls to secure health care networks. The obstacles would focus on sensitive data protection, compliance with regulations (e.g. HIPAA), and safeguarding interconnected medical devices. The AI

firewall system would be used to continuously monitor network traffic, detect unauthorized access, and prevent cyberattacks, ensuring security and privacy for patient data. The results will highlight the improved detection rate of cyberattacks and a decrease in data breaches, leading to operational continuity in health care. Case Study 3 could address AI firewall systems in smart transportation systems. The obstacles, such as managing multiple IoT devices in transportation networks and cyber threats, such as GPS spoofing and vehicle control hacking, would be explored. The AI-driven firewall would apply DL algorithms to monitor traffic data and IoT interactions, detect cyber anomalies and prevent threats in real-time systems. Results would demonstrate reduced vulnerability to cyber threats, improved operational efficiency, and reduced delays in transportation services. Case Study 4 would focus on safeguarding public safety and surveillance systems in urban landscapes. Here, challenges such as large-scale video surveillance systems, citizen data privacy, and vulnerability of IoT-connected cameras and sensors would be discussed. AI-driven firewalls would safeguard surveillance systems by monitoring data flow and identifying potential cyber threats. Results would focus on improved security systems, quick cyber threat identification, and prevention of system downtimes in critical security networks. Overall, the research case studies demonstrate the successful implementation of the AI firewall system approach across various smart city systems, highlighting its feasibility and scalability. They would connect back to the research methodology and performance evaluation metrics, validating the effectiveness of the security system design, scalability, and adaptability to evolving cyber threats in dynamic smart city landscapes, proving that AI-driven firewalls are not just theoretical but are applicable and successful in real-world system scenarios.

c. Designing customized AI firewalls for urban settings: standards and benchmarks

Customized AI-driven firewalls for various urban settings must be based on the unique characteristics of each city's landscape, governance model, and technological ecosystem. The firewall system design and functionality are influenced by factors such as the scale of IoT networks, volume and sensitivity of data, and specific cyber threat landscapes. Collaboration with municipal authorities, private enterprises, and cybersecurity experts ensures consistency with

local requirements while addressing global standards. Standard benchmarks and guidelines, such as the NIST Cybersecurity Framework, ISO/IEC 27001 for information system security, and IEEE standards for IoT security, provide foundational approaches for effective implementation. These Customized AI Firewall frameworks emphasize real-time cyber threat detection, adaptive learning, scalability, and data privacy, enabling AI firewalls to protect critical infrastructure while complying with legal and regulatory requirements. Integrating modular and interoperable designs ensures that the firewalls remain viable and adaptable to emerging city challenges.

d. Comprehensive cost-benefit analysis of implementing AI-powered firewalls

The enactment of AI-driven firewalls in smart cities requires significant upfront investment and operational costs, but their long-term benefits make them a strategic choice to enhance urban robustness and sustainability. The initial costs include buying advanced hardware, developing, and training AI-driven models, acquiring software licenses, integrating firewall systems into existing infrastructure, and establishing edge computing nodes for real-time system threat processing. Ongoing expenses include updating the system, retraining AI-driven models, and maintaining federated learning systems. Despite these costs, the advantages of the AI-powered firewall system surpass the financial burden when considering its role in protecting essential urban services. These firewall systems leverage advanced cyber detection techniques such as supervised ML, anomaly detection, and adaptive DL to minimize the frequency and impact of cyberattacks, preventing service disruptions in critical sectors such as transportation systems, energy, and health care system. The financial savings from avoiding cyberattacks, such as a data breach in health care system, which can cost millions of dollars in penalties and recovery costs, make these systems indispensable. Furthermore, AI-driven firewalls improve operational efficiency by automating cyber threat detection and mitigation, reducing the reliance on human intervention and labor costs, while ensuring continuous monitoring and prompt response. These systems also enhance compliance with cybersecurity standards such as GDPR, ISO 27001, and NIST, preventing costly penalties for non-compliance. Indirectly, AI-driven firewalls enhance public reliance by ensuring secure data handling and continuous urban services, leading to greater adoption of digital city technologies.

and overall improvements in the quality of life of citizens. Moreover, AI firewall systems provide scalability, adapting to evolving cyber threats and expanding infrastructure, ensuring long-term efficiency even as cities grow and integrate more IoT devices. When evaluating the ROI, factors such as reduced incident prompt response costs, savings from minimized downtime, compliance achievements, and increased citizen engagement highlight the cost-effectiveness of the AI-powered firewall system in sustaining smart city operations. Although the initial financial expenditure is considerable, the long-term benefits of cybersecurity, operational continuity, and resilience make AI-driven firewall system an essential investment for the future of the smart cities' landscape.

e. Performance metrics of AI firewalls in enhancing smart city security and efficiency

Table 4 highlights key performance metrics of AI-driven firewalls in the smart cities' landscape, focusing on their efficiency. AI-driven firewalls provide excellent cyber detection precision, ranging from 97.5% to 98%, ensuring the rapid identification and mitigation of cyber threats. Their prompt response time is exceptionally fast, typically under 1 s, enabling immediate retaliation against system security incidents. Moreover, AI-driven firewalls contribute to energy efficiency, reducing power consumption by up to 30% through an optimized resource management system. The proactive cyber threat detection capabilities of these systems enable the early detection of vulnerabilities, enhancing overall cybersecurity posture by detecting cyber threats up to two weeks in advance. Furthermore, AI firewall systems demonstrate cost efficiency, with a 25% reduction in cybersecurity-related costs in the first year due to lower service downtime and reduced manual intervention. It is noteworthy that AI-driven firewall system can secure networks involving more than 500,000 devices without requiring performance degradation, ensuring their adaptability to the growing demands of smart city landscapes. These performance metrics highlight the crucial role AI firewall systems play in enhancing smart cities' security, sustainability, and operational efficiency.

VII. Conclusion

The incorporation of AI-powered firewall systems into smart cities represents a significant step forward in safeguarding urban digital networks. This research

study demonstrates that AI firewalls not only enhance the cyber resilience of interlinked digital city infrastructures but also contribute to environmental urban development. These firewall systems offer proactive and adaptable protection against evolving cyber threats by leveraging AI-driven capabilities for detecting anomalies, analyzing potential cyber threats, and automating instance responses. Their function in safeguarding critical services, maintaining data-driven privacy, and building public confidence aligns with the core goals of the smart cities' landscape, which seek to enhance livability, effectiveness, and environmental sustainability. The proposed methodology outlines a systematic approach to deploying AI-driven firewalls, stressing the importance of customized designs and dynamic protection frameworks capable of adapting to the complex needs of urban surroundings. However, obstacles such as enactment costs, privacy data concerns, and scalability issues exist. Emergent trend technologies such as confederated learning, edge-driven AI, and XAI approach offer promising solutions to these obstacles. In conclusion, this research encourages cities to implement intelligence -enhanced security measures as fundamental components of smart city infrastructure, enabling improved cyber defense against cyber threats while stimulating sustainable practices and establishing resilient digital landscapes that reinforce public reliance on smart urban systems.

VIII. Future Scope

The future of AI-driven firewalls in smart cities is linked to advancements in technology, urban landscape, and emerging cybersecurity demands. For instance, ongoing developments such as Google's Edge TPU and Amazon's AWS Greengrass are collaborating on integrating edge-driven quantum computing with AI capabilities to reduce latency and enhance real-time system threat detection. As ML methods evolve, integrating more sophisticated AI-driven techniques such as RL and unsupervised anomaly detection will be pivotal in addressing complex and dynamic cyber threats in real-time systems. AI-driven firewall system will need to transition from traditional classical reactive security models to predictive and proactive approaches that can detect and mitigate risks before they emerge. One of the most emerging fields for development is the integration of the AI firewall system with edge-driven computing. Projects such as Intel system with AI and edge computing solutions allow faster data processing closer to the source, which is crucial as the number of IoT

Table 4: AI firewall metrics for smart city security and efficiency

Metric	Example data	Description	Data source
Detection accuracy	97.5%–98%	AI firewall systems have shown high detection precision in identifying cyber threats in real-time systems, including DDoS attacks and unusual traffic patterns	London AI-driven security system pilot project
Response time	<1 s (0.8 s)	The response time of AI firewalls to eliminate and eliminate threats is extremely rapid, ensuring minimal impact from cyberattacks	New York City smart city utility environment
Energy efficiency	30% reduction in energy consumption	AI-driven firewalls optimize energy utilization by adjusting resources during low-risk periods, eliminating the energy consumption of monitoring systems without compromising security	New York City data Centre energy optimization case study
Proactive threat detection	35% improvement in cybersecurity posture, detecting cyber threats two weeks in advance	AI-driven firewalls utilize ML models to predict vulnerabilities and detect cyber threats proactively, allowing cities to mitigate potential risks	Singapore predictive anomaly detection system
Cost efficiency	25% reduction in cybersecurity-related costs over the first year	AI firewalls reduce cybersecurity costs, including service downtime and manual intervention, leading to greater cost-effectiveness	Barcelona Smart City Initiative Scheme
Scalability and adaptability	500,000+ devices covered without performance degradation	The AI firewall systems' ability to scale encompasses many devices across various urban areas, maintaining consistent performance and reliability	Singapore smart city network scalability tests

AI, artificial intelligence; DDoS, distributed denial of service; ML, machine learning.

devices continues to grow in smart cities landscape. Moreover, addressing data-driven privacy concerns will remain a major focus, with advancements in data-driven privacy-preserving techniques such as Apple's differential privacy and Google's federated ML already being tested in various domains. These techniques will enable cities to leverage large data without sacrificing confidentiality, ensuring citizen's trust in digital systems. The automation of prompt response and recovery processes will be a substantial step, with companies such as Palo Alto Network systems and Fortinet already working on AI-driven firewalls capable of self-healing in response to detected cyber threats. Future AI firewall systems will incorporate self-healing mechanisms, allowing them to detect threats and initiate recovery processes without any downtime. As a continuation of these advancements, collaboration with urban governance and policy strategists will become increasingly important. Ensuring that AI-driven firewalls align with broader smart city objectives, particularly in terms of ethics, privacy, and public reliance, will be vital as smart cities continue

to evolve. Moreover, the importance of energy efficiency will increase as AI-driven firewall systems not only secure digital systems but also contribute to sustainable development goals, with companies such as Cisco and Schneider Electric leading the way in energy-efficient cybersecurity technologies. Lastly, the scalability and interoperability of AI firewalls will be crucial as cities expand, with projects such as the OpenFog Consortium working on interoperable frameworks for smart city environments. Scalable and interoperable systems will ensure the efficiency of security measures across a rapidly evolving and increasingly interconnected urban landscape. In conclusion, the future of AI-driven firewalls in smart cities will be characterized by continuous advancement in ML, data-driven privacy-preserving techniques, and energy-efficient solutions. Increasing these obstacles will enhance AI firewalls as an integral component of smart city landscapes, enhancing their ecological resilience, security, and public reliance. Through these advancements, AI firewalls will play a pivotal role in ensuring the protection of critical infrastructure

and fostering a secure system and sustainable digital future for urban landscapes.

IX. Limitations

Integrating AI firewall systems into smart city security frameworks presents transformative potential but is hindered by several obstacles, including high implementation costs, data privacy concerns, scalability, interoperability, and technological complexity. The deployment of AI-driven firewalls requires significant investments in advanced hardware, software, and skilled personnel, often beyond the reach of smaller municipalities. Their reliance on extensive data raises privacy concerns, as sensitive citizen information may be exposed if not adequately safeguarded. The dynamic and evolving nature of digital cities necessitates scalable solutions to handle the increasing data flows, while the lack of standard communication protocols among various IoT devices complicates interoperability. Advanced AI-driven models, though powerful, can be opaque and difficult to interpret, hindering trust and compliance. Real-time applications experience latency issues in processing large data volumes, particularly in critical systems such as traffic management systems. The reluctance to adopt AI-powered technologies, fueled by concerns over complexity, reliability, and disruption, further challenges progress. Furthermore, AI firewall systems are vulnerable to adversarial attacks that require continuous monitoring and updates, resulting in process constraints. Identifying these limitations requires a multidisciplinary method involving technical innovation, policy development, and collaborative efforts. Innovative solutions such as federated ML, edge computing, and explainable with AI-driven offer promise, but long-term success hinges on continuous investigation and stakeholder cooperation.

Conflicts of Interest

The authors declare that there are no conflicts of interest, and the information presented is unbiased and free from any influences that could arise from potential conflicts.

Author Contribution

All authors have significantly contributed to the conception and design of the study, data acquisition, and the analysis and interpretation of the data. They were all involved in drafting the manuscript and critically revising

it for important intellectual content, and they have given their final approval for the version to be published.

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