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Information Communication Technology (ICT) Support Of Smart Cities Development

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- Role of ICT in Sustainable Urban Development.
- Characteristics of ICT-Based Environmental Activities in Selected Cities.
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AUTHOR’S STATEMENT

I declare:

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ANNOTATION

This thesis investigates the contribution of Information and Communication Technologies (ICT) to the development of smart cities, with a specific emphasis on environmental sustainability. The study examines how digital technologies, such as the Internet of Things (IoT), digital twins, and big data analytics, are applied in managing core urban systems, including energy, waste, water, and transportation. The analysis is based on seven international cities , Singapore, Amsterdam, Copenhagen, Oslo, Zurich, Dubai, and Cape Town, which have demonstrated significant progress in integrating ICT into environmental governance frameworks. The study adopts a qualitative multi-case design, structured around five analytical dimensions: environmental performance, technological innovation, digital governance, contextual adaptability, and long-term sustainability.

Results highlight ICT's role in promoting efficient use of resources and enhancing civic participation. At the same time, the analysis points to existing barriers, such as rising energy demands, unequal access to technology, and regulatory shortcomings. The thesis offers practical suggestions to support more effective, inclusive, and environmentally driven digital transformation in urban contexts.

KEYWORDS

smart city, ICT, environmental sustainability, urban governance, digital infrastructure, IoT, big data

ANOTACE

Tato práce zkoumá přínos informačních a komunikačních technologií (IKT) k rozvoji inteligentních měst, se zvláštním důrazem na environmentální udržitelnost. Studie zkoumá, jak jsou digitální technologie, jako je internet věcí (IoT), digitální dvojčata a analýza velkých dat, aplikovány při správě klíčových městských systémů, včetně energetiky, odpadového hospodářství, vodohospodářství a dopravy. Analýza je založena na sedmi mezinárodních případových studiích ze Singapuru, Amsterdamu, Kodaně, Osla, Curychu, Dubaje a Kapského Města, které prokázaly významný pokrok v integraci ICT do rámců environmentálního řízení. Studie využívá kvalitativní multi-case design, strukturovaný kolem pěti analytických dimenzí: environmentální výkonnost, technologická inovace, digitální správa, kontextová adaptabilita a dlouhodobá udržitelnost.

Výsledky zdůrazňují roli ICT při podpoře efektivního využívání zdrojů a posilování občanské participace. Zároveň analýza poukazuje na existující překážky, jako je rostoucí poptávka po energii, nerovný přístup k technologiím a nedostatky v regulaci. Práce nabízí praktické návrhy na podporu efektivnější, inkluzivnější a environmentálně orientované digitální transformace v městském kontextu.

KLÍČOVÁ SLOVA

chytré město, ICT, ekologická udržitelnost, správa měst, digitální infrastruktura, internet věcí, velká data.

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List of Abbreviations

Abbreviation	**Full Form**
AI	Artificial Intelligence
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
GIS	Geographic Information System
ICT	Information and Communication Technology
IoT	Internet of Things
MPC	Model-based Predictive Control
NO_2	Nitrogen Dioxide
O_3	Ozone
SO_2	Sulfur Dioxide
PM_{10}	Particulate Matter 10 micrometres or less
$PM_{2.5}$	Particulate Matter 2.5 micrometres or less
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
SDGs	Sustainable Development Goals

INTRODUCTION

Before the rise of digital infrastructure, cities relied on traditional systems to manage everyday services such as energy, water, waste, and transport. But as urban populations continue to grow, these systems face greater pressure. According to the United Nations (2018), nearly 70 percent of the world's population is expected to live in cities by 2050. This demographic shift creates urgent environmental challenges, including resource depletion, air pollution, and escalating carbon emissions.

In response to these challenges, many cities have embraced the concept of smart cities as a pathway to enhanced sustainability and efficiency. Central to this idea is Information and Communication Technology (ICT), which enables cities to collect real-time data, optimize service delivery, and inform environmental decision-making (Nghiem et al., 2021). Through advanced tools like the Internet of Things (IoT), digital twins, and big data, cities are now capable of tracking pollution, managing energy more wisely, and improving waste systems (Agrawal et al., 2024), as exemplified by applications in urban energy transitions and environmental monitoring. At the same time, this digital transition has introduced new concerns. ICT infrastructure, particularly data centers, demands significant energy and contributes to greenhouse gas emissions (Giudici, 2024). This creates a paradox: while ICT offers solutions to environmental problems, it can also exacerbate them.

This thesis, therefore, aims to explore how Information and Communication Technology (ICT) can support the development of smart cities, with a particular focus on fostering environmental sustainability. It looks at how digital tools can help address pressing ecological challenges while also contributing to the creation of more efficient, inclusive, and resilient urban systems.

1. SMART CITY

This chapter offers a clear and comprehensive introduction to the concept of smart cities and their historical evolution. It highlights the transition from a technology-focused perspective to an approach that emphasizes sustainability and participatory governance. The chapter reviews various definitions from both academic and practical viewpoints, emphasizing the core dimensions that define smart cities. Special attention is given to the increasing role of Information and Communication Technology (ICT) in promoting environmental sustainability. The purpose is to establish a solid theoretical foundation to support the applied analyses presented later.

1.1 The Historical Evolution of the Smart City

The idea of the smart city has developed in scope and meaning over the past few decades. While early visions centered on enhancing urban efficiency through technology, more recent approaches reflect a broader commitment to sustainability, inclusive governance, and social equity. Today, smart cities are no longer perceived as collections of disconnected technologies. Instead, they are understood as adaptive systems shaped by real-time data, artificial intelligence, and the Internet of Things. These technologies are used to improve service delivery, inform decision-making, and respond to the changing needs of urban populations. This change highlights a growing transformation in both digital innovation and the way urban actors engage with their environments (Albino et al., 2015).

The initial phase: The Technical Establishment (pre-2010)

The early vision of the smart city was driven primarily by the private sector, particularly large technology companies such as IBM and Cisco. During this stage, urban intelligence emerged as a key idea, centered on using live data and monitoring tools to optimize how city services function. The implementation of smart infrastructure such as automated lighting and traffic control systems was a defining feature of this period. However, these initiatives often overlooked local social dynamics and did not actively involve communities in their design or implementation (Batty, 2017).

San Jose in California was among the first cities to adopt this early model. The city partnered with tech firms to install extensive sensor networks for monitoring transport, energy consumption, and public lighting. Despite its technological sophistication, the model was criticized for its lack of community engagement and social responsiveness. Decision-making processes were largely guided by algorithms, which led scholars to describe the approach as a form of algorithmic governance where authority was transferred to data systems rather than shared with citizens (Janssen et al., 2020).

Phase Two - Digitalization and E-Government (2010 - 2015)

As limitations of the early model became evident, a second phase emerged that emphasized local context, governance, and social relevance. The term “existing smart cities” was introduced to describe real-world applications that were informed by the unique spatial and historical conditions of urban areas (Kitchin et al., 2018).

Dublin represents a clear example of this more integrated approach. The city implemented intelligent traffic systems based on local conditions and incorporated them into existing governance frameworks. This approach recognized the need for technology to adapt to each city's specific conditions instead of being implemented as a generic solution.

Barcelona advanced this model further by combining digital systems with participatory practices. Using the Sentilo open-source platform, the city gathered environmental and transportation data while also encouraging public involvement in budgeting and urban planning decisions. This represented a shift in how technology was used, evolving from a mechanism for control to a channel for citizen involvement and collaboration (Bakıcı et al., 2023).

Third phase: Participatory and Adaptive Maturity (2015 – 2020)

During the third phase, more attention was given to equity, public participation, and flexible planning approaches. Smart cities came to be seen as collaborative environments where various stakeholders (including local governments, civil society, private actors, and residents) contributed to shaping urban development. Coletta et al. (2019) suggest that this phase represents a shift from systems design to process design, where participation and flexibility are essential features.

Amsterdam provides a strong case for this approach. Its Smart City program includes initiatives such as the Smart Citizens Lab, which allows residents to co-develop and operate environmental sensors that monitor air and water quality. These efforts highlight the emergence of new governance models where authority is distributed and decisions are informed by collective input and lived experience (de Waal et al., 2021).

The fourth phase: Focus on sustainability and governance (2020-now)

In the most recent phase, smart cities have increasingly aligned themselves with long-term sustainability goals. Cities are now understood as experimental platforms for addressing global challenges such as climate change, mobility transitions, and social inclusion. This stage is defined by the integration of digital tools within broader urban strategies aimed at achieving environmental justice, efficient resource management, and inclusive policymaking (Valencia-Arias et al., 2025).

Singapore exemplifies this comprehensive vision. The city has effectively used IoT technologies across its urban infrastructure to enhance resilience and quality of life. Its governance model, known as GMSDIL, evaluates six key domains: governance, mobility, sustainability, economic development, intellectual capital, and quality of life. Even during the COVID-19 pandemic, this framework allowed Singapore to adapt and respond effectively to emerging needs while maintaining progress toward its broader development goals (Ferro-Escobar et al., 2022).

In summary, the smart city has moved beyond its original technical roots toward a broader and more inclusive urban vision. This transformation reflects a growing recognition that cities are shaped not only by infrastructure and data but also by the values, needs, and participation of their residents. The next section turns to the academic literature to explore how researchers define the smart city and the dimensions they consider most critical.

1.2 Defining Smart Cities

The idea of the smart city has attracted growing attention in both academic research and policy discussions. Despite its frequent use, there is still no single, agreed-upon definition. Earlier understandings tended to focus on how digital technologies and ICT tools could improve the efficiency of city services and infrastructure (Shi et al., 2023). Over time, this view has expanded. Smart cities are now seen as systems that are not only shaped by technology but also influenced by social dynamics, environmental challenges, and political decision-making. In this broader perspective, factors like citizen participation, transparent governance, and sustainability have become central to the concept (Bellini et al., 2022). Because of these diverse priorities, researchers have developed multiple definitions, each reflecting a unique angle, whether it is automation, collaborative planning, ecological goals, or institutional cooperation (Gracias et al., 2023). The next table summarizes selected academic definitions and the core themes that distinguish them.

Table 1 Definitions of Smart City from Selected Academic Sources (2012–2025)

Author(s)	Definition of Smart City	Key Focus	Summary and Interpretation
Stratigea (2012)	Smart cities are characterized as urban regions that make use of advanced technologies, including sensors, intelligent materials, and digital networks, to enhance the efficiency of their infrastructure.	Technological Integration	Highlights how digital systems and automation are used to enhance efficiency and public safety, often through private sector involvement.
Moura et al., (2021)	Smart cities are characterized by the integration of physical, digital, and human systems that collaborate to promote sustainable and inclusive urban growth.	Governance and Social Relevance	Emphasizes the role of local governance in shaping smart city strategies, with attention to equity and active community participation in urban decision-making.
Gracias et al. (2023)	Views smart cities as collaborative spaces where governments, businesses, and citizens work together to develop flexible and fair urban solutions.	Citizen Engagement and Flexibility	Highlights the shift from fixed systems to more adaptive and participatory urban approaches that reflect local needs.
Shao et al., (2025)	Smart cities are defined as environments that use data technologies to enhance and guide decision-making and digital services, residents' quality of life, and sustainability.	Sustainability and Inclusive Policy	Illustrates how digital systems can support inclusive governance and respond to global concerns like climate change through integrated policy frameworks.

Source: Compiled by the author based on Stratigea (2012); Moura et al. (2021); Gracias et al. (2023); Shao et al. (2025).

The definitions outlined in the table illustrate how the concept of the smart city continues to evolve across different academic and policy perspectives. While some sources prioritize technological advancement and operational efficiency, others highlight the importance of social equity, governance structures, or sustainability goals. This diversity points to the need for smart city strategies that not only integrate digital tools but also respond to the specific social, environmental, and institutional contexts in which they are applied. Recognizing these varied viewpoints is critical for building urban frameworks that are both adaptable and meaningful in practice.

Building on this foundation, the following section introduces six key dimensions that shape how smart cities are conceptualized and implemented in practice.

1.3 Smart City Dimensions

As the smart city concept has developed, both researchers and practitioners have moved toward a multidimensional understanding of urban innovation. This broader perspective incorporates social, economic, and environmental factors alongside technology, providing a more comprehensive approach to smart urban development (Albino et al., 2015; Ulya et al., 2024).

- **Conceptual Foundations of the Framework**

Giffinger et al. (2007) introduced one of the earliest and most influential models in this field. Their framework outlines six key dimensions of smart cities: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Developed through a study of mid-sized European cities, the model has since been widely applied across different contexts due to its flexibility (Giffinger et al., 2007).

Over time, this framework has been updated to reflect changes in digital infrastructure and public expectations. More recent studies emphasize not just technology, but also inclusivity, sustainability, and participatory governance (Albino et al., 2015; Parra-Pulido et al., 2024). To operationalize these dimensions, researchers have proposed a set of focus areas and indicators that reflect each domain's core characteristics and facilitate comparative evaluation, as summarized in the table below.

Table 2 Core Dimensions and common Indicators of Smart Cities

Dimension	Core Focus	Common Indicators
Smart Economy	Innovation and productivity	Start-up activity, employment rates, R&D investment
Smart People	Education and civic engagement	Educational attainment, digital skills, social capital
Smart Governance	Participation and digital services	Use of e-government, availability of open data
Smart Mobility	Accessibility and sustainable transit	Public transport use, traffic congestion
Smart Environment	Resource efficiency and pollution	Air quality, renewable energy, waste management

Source: Compiled by the author based on widely cited smart city frameworks, including Giffinger et al. (2007) and later adaptations.

While the complete framework includes six dimensions that together offer a broad view of smart urban development, this thesis focuses on three domains: smart environment, smart governance, and smart mobility. These were selected due to their strong relevance to the thesis objective**,** examining how ICT supports environmental sustainability in smart cities. Focusing on these specific areas allows the research to examine their features and challenges in greater depth. Each of the next sections looks at one dimension, with attention to how it has been addressed in recent studies, what difficulties exist in practice, and how ICT tools are being used to support sustainable outcomes.

- **ICT and Environmental Strategy Integration**

Among the six dimensions, smart environment is closely tied to sustainability goals. It focuses on the use of information and communication technologies (ICT) for environmental monitoring, efficient use of resources, and pollution control (Bibri, 2020). Internet of Things (IoT) devices, for example, are used to monitor air and water quality, manage waste collection, and improve energy use in real time (Bibri, 2020).

However, this dimension often depends on others to be effective. Governance systems need to support transparency and enforce regulations, while innovation in the economy drives the development of clean technologies (Parra-Pulido et al., 2024). These interlinkages highlight the need for integrated policy and technological approaches (Parra-Pulido et al., 2024).

1.3.1 Challenges and Practical Considerations

While the six-dimensional model is useful for analysis and planning, it also faces limitations. Cities with fewer resources may lack the infrastructure or administrative capacity to apply it effectively (Albino et al., 2015). Some indicators are highly context-specific, making comparisons across cities difficult. Definitions of governance, participation, or quality of life can vary widely depending on cultural or institutional factors (Ulya et al., 2024).

Another issue is the risk of overly technical planning that ignores social equity. This has been a common critique of early smart city projects, where digital solutions were implemented without adequate attention to inclusion (Bibri, 2020).

Despite these challenges, the model remains a valuable tool for evaluating smart city performance. This thesis uses it to assess ICT-based sustainability efforts in selected case cities, with a focus on smart environment, smart governance, and smart mobility. These dimensions are the most closely connected to environmental outcomes and digital integration (Ulya et al., 2024; Parra-Pulido et al., 2024).

In sum, the six-dimensional framework offers a robust structure for examining how cities align digital tools with goals of sustainability, innovation, and social well-being (Giffinger et al., 2007; Albino et al., 2015). It moves analysis beyond infrastructure to consider the complex interconnections between systems, policies, and technologies (Ulya et al., 2024). Importantly, progress in one dimension often relies on advancements in others, especially in resource efficiency, transparent governance, and digital integration (Parra-Pulido et al., 2024; Bibri, 2020).

Building on this foundation, the present thesis applies the six-dimension model to analyse ICT-enabled environmental sustainability in selected cities. It focuses on smart environment, smart governance, and smart mobility, domains closely linked to ecological outcomes and digital strategy (Ulya et al., 2024). Through this approach, the research aims to translate theory into practice, showing how different urban contexts implement smart city principles to drive sustainable change (Parra-Pulido et al., 2024; Bibri, 2020).

1.3.2 Evolving Academic Insights

Recent scholarship highlights the need for coordination among dimensions. Ulya et al. (2024) found that many smart city initiatives fail when cities focus on one area in isolation. Their research argues for a systems-based approach in which progress in one domain supports the others (Ulya et al., 2024).

Prioritization of dimensions also varies by region. European cities tend to focus on environmental and governance issues, while Latin American cities often prioritize public safety and access to essential services due to different social needs (Parra-Pulido et al., 2024).

In addition, emerging issues like cybersecurity, climate adaptation, and digital inclusion are now being considered across all six dimensions. This signals a shift toward more flexible and forward-looking urban strategies (Parra-Pulido et al., 2024).

1.4 Dimensions of Sustainability in ICT-Enabled Smart Cities

Sustainability in smart cities requires a balanced focus on environmental, economic, and social dimensions. These interconnected pillars provide a foundation for comprehensive and inclusive urban development. Rather than treating them separately, smart city strategies must integrate all three to ensure long-term resilience and equity. Toli et al. (2020) emphasize that sustainable urban systems emerge from this integration, fostering inclusive and adaptable environments. Similarly, Parra-Pulido et al. (2024) call for multidimensional frameworks to effectively assess and implement sustainability in smart city initiatives. The sections below explore each of these dimensions in turn.

- **Environmental Sustainability**

Environmental sustainability in smart cities centers on reducing ecological impact through green technologies and data-driven solutions. Bibri (2020) highlights the potential of eco-cities, where integrating renewable energy systems with smart infrastructure can significantly cut energy use and pollution. A notable example is the Stockholm Royal Seaport, where such technologies have been successfully implemented to support sustainability goals.

Parra-Pulido et al. (2024) identify key environmental indicators in their systematic review, including air quality, renewable energy adoption, and waste management performance. These indicators are crucial for tracking progress and shaping effective environmental policies in urban settings.

- **Economic Sustainability**

Economic sustainability involves enabling smart cities to support innovation, growth, and the efficient use of resources. Tura et al. (2022) highlight the role of sustainability-oriented innovations (SOIs), showing how technological and organizational advancements contribute to urban economic development. Their research underscores the importance of SOIs in driving both economic competitiveness and sustainability.

Parra-Pulido et al. (2024) further identify key economic indicators such as employment in green industries, investment in sustainable infrastructure, and the emergence of eco-conscious businesses. These metrics help evaluate the economic resilience and sustainability of smart cities.

- **Social Sustainability**

Social sustainability in smart cities focuses on inclusion, equity, and citizen engagement. Toli et al. (2020) note that many definitions of smart cities increasingly prioritize social factors, especially access to services and public participation. However, they also warn that technological advances may unintentionally exclude marginalized groups if not carefully designed.

Reyes-Rubiano et al. (2021) explore how smart transportation systems can promote social inclusion by improving mobility, shortening travel times, and increasing access to urban services. These innovations contribute to more equitable and connected urban communities.

In conclusion, Sustainability in smart cities depends on the coordinated integration of environmental, economic, and social priorities. Addressing these dimensions together allows cities to develop in ways that are efficient, inclusive, and future-ready.

While the previous section clarified how sustainability in smart cities relies on the balance of environmental, economic, and social dimensions, it is equally important to understand how these goals are practically supported and enabled by digital innovation.
To build on this foundation, the next section turns to the role of ICT as the backbone of digital innovation in sustainable smart cities.

2. ICT AND SUSTAINABLE SMART CITIES

This chapter continues the theoretical and practical framework introduced in the previous chapter, which discussed the concept of smart cities and their six dimensions. The focus here is on the central role of digital infrastructure in making this urban model a reality. It analyses key tools and technologies such as cloud computing, 5G networks, open data, and cybersecurity.

The chapter also explores how information and communication technologies (ICT) are applied in environmental management, including real-world examples from leading cities like Singapore, Amsterdam, and Barcelona. These examples highlight how ICT is used to manage air quality, energy, waste, water, and green spaces. The discussion then turns to the role of artificial intelligence and big data in enhancing environmental decision-making and urban planning.

In addition, the chapter addresses the challenges of using these technologies, such as high energy consumption in data centers, the carbon footprint of digital systems, and the digital divide. Finally, it shows how ICT supports the dimensions of smart cities, particularly environment, governance, and mobility, promoting inclusive and sustainable urban development.

2.1 Digital Infrastructure for Smart Cities

Digital infrastructure forms a central pillar in the development of smart cities, serving as the medium through which goals such as sustainability, operational efficiency, and improved urban quality of life are realized. This infrastructure includes technologies such as cloud computing, 5G networks, open data, cybersecurity, and digital twins. Together, these tools enable cities to address environmental, economic, and social challenges in a cohesive and effective manner (Das, 2024; Gryshchenko et al., 2022).

- **Cloud Computing as an Enabler of Smart Operations**

Cloud computing acts as a central platform for data processing and digital resource management. It enables smart cities to store, analyse, and integrate various urban systems efficiently (Tahirkheli et al., 2021). This technology allows for operational flexibility, reduces the cost of traditional infrastructure, and provides real-time access to data, supporting faster and more informed decision-making. Within the six smart city dimensions, cloud computing contributes to smart governance and smart living by enhancing digital services and user experiences.

- **5G Networks and Real-Time Connectivity**

5G networks offer unprecedented data speeds, high device density, and low latency, which are essential for smart transportation, the Internet of Things, and digital twins (Gohar et al., 2021; Mahomed et al., 2025). These networks connect billions of devices simultaneously, supporting smart mobility and smart economy by strengthening digital infrastructure and fostering innovation.

- **Open Data and Its Role in Public Participation and Governance**

Open data is a cornerstone of transparency and citizen empowerment. It allows residents to participate in shaping urban policy and enables knowledge-based solutions. Cities use open data to analyse trends and make evidence-based decisions (Das, 2024). This directly supports the smart people and smart governance dimensions by spreading knowledge and enhancing accountability.

- **Cybersecurity as the Foundation of Digital Sustainability**

Cybersecurity is essential for safeguarding personal information and guaranteeing continuous services as cities become more reliant on digital systems (Houichi et al., 2024). Advanced security measures that employ machine learning and artificial intelligence to identify and address threats are necessary for smart cities. By fostering trust and facilitating safe online communication between residents and urban systems, cybersecurity promotes smart living and smart governance.

- **Digital Twins for Better Urban Decision-Making**

Digital twins provide urban planners and policymakers with dynamic visual models of infrastructure and services. These digital replicas simulate real-world scenarios, allowing cities to assess potential impacts before implementation (Mahomed et al., 2025). This technology reduces risks and improves preventive maintenance, closely aligning with the smart environment and smart living dimensions.

- **Integrating Digital Infrastructure to Support Sustainable Development**

Studies such as Gryshchenko et al. (2022) emphasize the importance of integrating digital infrastructure components to achieve sustainable development goals. Combining cloud computing, 5G, cybersecurity, and open data creates a cohesive digital ecosystem that enhances urban resilience, environmental performance, and social responsiveness.

2.2 ICT in Urban Environmental Management

Application of information and communication technologies (ICT) has become a key enabler for sustainable environmental management in smart cities as urban areas face growing environmental pressures from climate change, rapid population growth, and limited resources. The way municipalities plan, monitor, and manage their environmental infrastructure is changing as a result of technologies like digital twins, Internet of Things (IoT) sensors, Geographic Information Systems (GIS), and predictive control systems (Batty et al., 2012; Kitchin, 2014). By using real-time data collection, spatial analysis, and algorithmic decision-making, these tools enable cities to transition from reactive to proactive environmental strategies.

This paragraph introduces the role of ICT in five key areas of urban environmental management: green space accessibility, air quality monitoring, energy systems, waste management, and water infrastructure. The discussion includes examples from cities such as Singapore, Barcelona, and Amsterdam to illustrate practical applications and policy implications.

One key application of ICT in environmental planning is the use of Geographic Information Systems (GIS) to assess spatial inequalities in access to green and blue space.

Geographic Information Systems (GIS) and spatial data analysis are widely used to identify disparities in access to urban natural resources such as parks, rivers, and recreational zones. These tools provide planners with detailed spatial visualizations that inform inclusive design strategies to improve environmental equity. This supports both the Smart Environment and Smart Governance objectives (Nghiem et al., 2021).

- **Singapore Case**: GIS-based spatial analysis revealed geographic inequalities in access to green and blue spaces across various districts. In response, planners implemented targeted interventions to enhance accessibility for marginalized neighborhoods (Nghiem et al., 2021).
- **Barcelona Case**: The 22@ innovation district employs digital monitoring to manage its green infrastructure. These tools ensure that ecological considerations are embedded in urban redevelopment, thereby aligning urban growth with environmental sustainability goals (Gianoli et al., 2020).

ICT-Based Real-Time Air Quality Monitoring

IoT-based air monitoring systems are increasingly deployed to provide continuous, real-time data on urban air pollutants such as PM2.5, NO_2, and O_3. These platforms enable local governments to identify pollution hotspots, adapt traffic flow, issue health alerts, and design evidence-based policies. This improves the Smart Environment by enhancing public health and supports Smart Governance through policy transparency (Veloso et al., 2024).

- **Barcelona Case**: The city's IoT sensor network transmits air quality data to a centralized dashboard. Decision-makers use this information to implement targeted interventions like traffic limitations in high-pollution zones (Veloso et al., 2024).
- **Singapore Case**: The "Virtual Singapore" platform utilizes a digital twin to simulate pollutant dispersion patterns based on topography and wind flows. These insights guide urban ventilation design and the placement of ecological corridors (Ignatius et al., 2019).

Smart Energy Systems and Citizen Participation

ICT underpins the development of smart energy systems that optimize the production, distribution, and consumption of renewable energy. These systems use data analytics, decentralized energy platforms, and real-time control systems to reduce emissions and enhance energy efficiency. Importantly, ICT also facilitates community participation, allowing residents to manage or trade energy locally. This supports both the Smart Environment and Smart Governance dimensions (Noori et al., 2025).

- **Amsterdam Case**: The LIFE project links neighbourhood solar panels and batteries through a digital platform, enabling peer-to-peer energy trading and greater local energy independence (Noori et al., 2025).
- **Barcelona Case**: In the 22@ district, real-time energy management systems control the operation of waste-to-energy plants and district heating networks to minimize carbon emissions and operational costs (Gianoli et al., 2020).

ICT-Enabled Waste Management Optimization

ICT applications in waste management are evolving toward Smart Waste Management 4.0. In this approach, artificial intelligence and big data analytics are employed to predict waste generation, monitor bin capacity, and optimize collection routes. These technologies reduce environmental impact by lowering emissions, cutting operational costs, and improving recycling efficiency. They contribute to the Smart Environment and Smart Mobility goals (Kannan et al., 2024).

- **Example**: The Smart Waste Management 4.0 framework integrates sensors, citizens, businesses, and public services via a centralized digital platform. When bins reach predefined thresholds, the system dynamically adjusts collection schedules, ensuring timely and resource-efficient operations (Kannan et al., 2024).

Predictive Water Management in Smart Cities

ICT-based water systems utilize Model-Based Predictive Control (MPC) and sensor networks to improve water conservation, detect leakages, and reduce operational costs. These systems enhance the Smart Environment through sustainable water usage and support Smart Governance by enabling public participation and greater accountability (Ocampo-Martínez et al., 2009).

- **Barcelona Case**: An MPC system monitors water consumption and dynamically adjusts pump activity according to demand forecasts, achieving up to a 25 percent reduction in water loss (Ocampo-Martínez et al., 2009).
- **Singapore Case**: In Bishan-Ang Mo Kio Park, real-time water-level sensors are used for irrigation control and public awareness as part of the ABC Waters programme. This initiative combines ICT with nature-based solutions (Wang et al., 2024).

In sum across the five domains discussed, ICT emerges as a transformative enabler of urban environmental management. From spatial equity in green space access to predictive control in water systems, the integration of ICT ensures not only technical efficiency but also democratic participation, sustainability, and transparency. These capabilities advance multiple dimensions of smart cities, particularly Smart Environment and Smart Governance, by embedding intelligence and responsiveness into urban infrastructure and policy. As demonstrated in cities such as Singapore, Barcelona, and Amsterdam, ICT-driven environmental solutions represent a scalable and adaptable pathway toward climate-resilient and citizen-centred urban futures.

2.3 AI and Big Data in Sustainable Smart Cities

The accelerating pace of urbanization, coupled with mounting environmental pressures, has increased the need for smarter, data-driven approaches to city governance. In this context, **Artificial Intelligence (AI)** and **Big Data** have emerged as central technologies enabling a new model of urban management, one that emphasizes predictive insights, real-time responsiveness, and sustainability.

AI refers to computational systems capable of analysing data, learning from patterns, and making decisions with minimal human input. Big Data encompasses vast, fast, and diverse datasets collected from sensors, transportation systems, mobile devices, and environmental monitoring platforms (Yao, 2022). The integration of these technologies allows decision-makers to better understand complex urban systems and formulate adaptive and equitable policies (Ejaz et al., 2025).

- Enhancing Predictive and Responsive Urban Planning

These technologies support anticipatory governance through predictive modelling, risk analysis, and improved resource allocation. In environmental monitoring, AI can analyse real-time data on air and water quality, helping cities identify pollution sources and take immediate action (Yao, 2022). Machine learning also supports long-term planning by forecasting trends in urban development and environmental degradation (Santos et al., 2025).

Several global examples illustrate the practical benefits. Barcelona uses a city-wide Big Data platform to monitor air quality, traffic, and energy consumption. This enables targeted responses to congestion and pollution (Yao, 2022). Singapore applies AI to optimize traffic flow and reduce carbon emissions, improving mobility and air quality (Ejaz et al., 2025). Amsterdam employs participatory platforms that let residents contribute environmental data, promoting inclusivity and justice in local decision-making (Mark et al., 2019).

- Practical Gains and Ethical Considerations

AI and Big Data have improved efficiency in areas such as waste management, infrastructure planning, and service delivery. They also support public accountability by enabling transparent access to environmental metrics for both officials and citizens (Santos et al.,, 2025).

However, the deployment of these technologies brings challenges. Key concerns include data privacy, ownership of user-generated data, and algorithmic bias. Without ethical oversight, AI systems may reinforce inequality through biased inputs or opaque decision-making processes (Mark et al., 2019). Smaller cities may also struggle to implement advanced infrastructure due to financial or technical limitations (Qurbonova et al., 2023).

To ensure equitable outcomes, ethical frameworks must be established. These should promote transparency, accountability, and citizen inclusion at every stage of technological implementation (Santos et al., 2025).

- Integrating Spatial Data and Environmental Modelling

The use of AI and Big Data with Geographic Information Systems (GIS) is advancing spatial planning and urban resilience. GIS platforms, powered by machine learning, help simulate urban growth, assess environmental impact, and guide green infrastructure distribution (Yao, 2022).

These tools also enable participatory planning by offering public dashboards and visualizations, allowing citizens and officials to collaborate more effectively on sustainable development goals (Santos et al., 2025).

In Conclusion, AI and Big Data are reshaping how cities manage environmental and urban challenges. While their potential is significant, realizing it requires thoughtful governance, inclusive participation, and strong ethical oversight. With the right frameworks in place, these technologies can support the creation of more sustainable, responsive, and just urban environments.

2.4 Challenges Associated with the Use of ICT

Information and Communication Technologies (ICT) have become deeply embedded in economic systems, governance, education, and daily life. Their role in enhancing productivity, enabling innovation, and expanding access to services is widely acknowledged (Ayers et al., 2024). However, the environmental and social implications of their growing footprint are increasingly difficult to ignore. The ICT sector already accounts for 2% to 4% of global greenhouse gas (GHG) emissions and could reach 14% by 2040 if current growth continues unchecked (Belkhir et al., 2018). These figures underscore the paradox of digital progress: while ICT drives sustainable development, it simultaneously contributes to climate stress and deepens existing inequalities. This paradox becomes especially visible in smart cities, where the reliance on digital infrastructure must align with environmental goals and inclusive urban planning. Three core challenges highlight this contradiction: the carbon emissions of data centres, rising energy consumption, and persistent digital exclusion.

1. The Carbon Footprint of Data Centres

One of the most urgent environmental concerns in the digital era is the growing carbon footprint of data centres. As reliance on cloud computing, artificial intelligence, and big data continues to expand, these facilities require increasingly high energy inputs for server operation and cooling. Data centres currently account for approximately 16% of total ICT sector emissions, and projections suggest this share could rise significantly by 2030 if demand trends persist (Aslan et al., 2025). In Germany, for example, carbon emissions from data centres are expected to increase by 13% during the current decade, despite improvements in infrastructure efficiency (Aslan et al., 2025). These emissions are not limited to electricity use alone (Scope 2) but also include indirect emissions (Scope 3) from the manufacturing of servers and storage devices. Producing just one server can emit more than 1,200 kilograms of CO_2 (Aslan et al., 2025). These figures highlight the need for a comprehensive strategy that addresses the full life cycle of ICT equipment, especially given the current gaps in environmental monitoring systems in many countries (Ayers et al., 2024).

2. Increasing Energy Demand in the ICT Sector

The ICT sector has seen a sharp increase in energy consumption due to the exponential growth of digital infrastructure and online services. According to Aslan et al. (2025), despite advancements in efficiency technology, data centers' global energy usage increased by 6% between 2010 and 2018. By 2030, demand may increase to 3,000 terawatt-hours, according to future projections (Ewim et al., 2023). Efficiency gains alone cannot counteract this level of consumption. Even though contemporary equipment may consume less energy for each task, these savings are negligible due to the ongoing growth in the volume of digital processing. Reliance on coal and gas-powered power systems, which increase emissions per kilowatt-hour used, makes the problem worse in poorer nations. As a result, some data center operators in North America and Europe have started reusing server-generated heat and incorporating renewable energy sources. Nevertheless, these practices are still small-scale and have not yet gained global adoption (Aslan et al., 2025; Ayers et al., 2024). The gap between wealthy smart cities that have started incorporating sustainable energy solutions and developing cities that still mainly rely on fossil fuel-based grids and are unable to retrofit for green is even more pronounced.

The Digital Divide and Unequal Access

While digital technologies are expanding rapidly in urban and high-income areas, many rural and low-income regions remain underserved. This disparity, known as the digital divide, prevents millions from accessing education, job opportunities, and essential services. For instance, research in China revealed that regions with poor internet infrastructure struggled to implement digital learning during the COVID-19 pandemic, resulting in significant educational gaps (Wang et al., 2024). Moreover, digital exclusion is not only geographic. Within the same country, older adults, women, and low-income groups often face additional barriers due to affordability and lack of digital skills (Ayers et al., 2024). Globally, over 2.7 billion people remain offline, most of whom live in the Global South (Ayers et al., 2024). Bridging this divide requires not only expanding infrastructure but also implementing inclusive policies that ensure affordability and promote digital literacy.

Addressing the sustainability of ICT is no longer optional but essential to digital policy frameworks**.** These three challenges make clear that the digital transition is neither environmentally neutral nor socially equitable. If left unmanaged, it could worsen inequality and intensify environmental strain. Addressing the carbon impact of ICT, managing its growing energy use, and closing the digital access gap requires coordinated policies that combine technical solutions with regulatory and educational strategies. Only through such an integrated approach can ICT become a tool for advancing sustainable development rather than a barrier to it. Such integrated approaches are already being applied: for example, Stockholm enforces strict energy efficiency standards in its data centres, while Singapore's Smart Nation program enhances digital equity through subsidized internet access and national literacy campaigns (Ewim et al., 2023; Ayers et al., 2024).

2.5 The Relationship Between Smart City Dimensions and the Role of ICT

One of the main factors facilitating the creation of smart cities is information and communication technology, or ICT. It promotes vital urban elements like mobility, governance, and environmental sustainability. When combined with ICT tools and systems, these interconnected dimensions become more effective (Albino et al., 2015). First, in smart cities, ICT plays a major role in environmental management. City officials can precisely track waste flows, energy consumption, and pollution levels thanks to technologies like sensors and real-time monitoring systems. According to Gu et al. (2024), these tools assist cities in creating more sustainable policies and responding swiftly to environmental issues. For instance, smart energy grids adjust electricity flows based on actual demand, which reduces energy waste. Buildings with automated systems can also lower emissions by managing heating and cooling more efficiently. However, while ICT offers solutions for environmental sustainability, it also raises environmental concerns of its own. Research shows that the ICT sector's global carbon footprint is growing steadily, and by 2040, it could contribute up to 14% of total emissions if not managed responsibly (Belkhir et al., 2018). This highlights the need for green ICT strategies that reduce emissions from data centers, networks, and digital devices while supporting environmental goals. Therefore, smart environmental solutions must balance innovation with responsibility to avoid unintended consequences.

Second, ICT enhances governance by making city administrations more transparent, responsive, and citizen-focused. Platforms that support e-services, online consultations, and feedback mechanisms increase public participation in decision-making. This helps governments understand public needs better and deliver services more efficiently (Kaiser, 2024). Data analytics also enable better monitoring of urban performance, helping cities adapt policies in real time. The use of ICT in governance creates systems that are not only efficient but also inclusive, allowing more people to be involved in shaping the city. Like environmental systems, smart governance depends on accurate, real-time data to function effectively, which makes ICT a shared foundation between both dimensions (Angelidou, 2014).

Third, ICT plays a transformative role in urban mobility. Smart transportation systems use digital infrastructure to improve traffic flow, reduce congestion, and support sustainable mobility. Technologies such as vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication help manage road conditions dynamically and reduce accidents (Mahrez et al., 2021). Public transport routes can be adjusted based on passenger demand collected through mobile apps and GPS data. Additionally, ICT supports electric vehicle charging networks and car-sharing services, helping cities reduce their transport emissions (Mohammadi et al., 2022). Smart mobility also relies on data from other city systems, including energy and environment, to operate efficiently. This further demonstrates how ICT acts as the common link between multiple city functions.

In conclusion, ICT is not simply a supporting tool. It is the system that connects and empowers the different elements of a smart city. It enables better environmental monitoring, more democratic governance, and cleaner urban mobility. While ICT opens up many opportunities, it also comes with responsibilities, especially in terms of its environmental footprint. Therefore, the integration of ICT must be done with care, ensuring that technological solutions support sustainability rather than create new problems. This understanding is central to this theis, which focuses on the role of ICT in building smarter, more sustainable, and inclusive urban environments (Albino et al., 2015; Belkhir et al.,2018; Gu et al., 2024; Kaiser, 2024).

2.6 Future Trends for Smart Cities – Early Predictions and Their Evolution By 2024

Digital technologies are becoming more and more important in influencing urban development as the population of cities continues to grow. Previously regarded as theoretical concepts, smart cities have developed into functional urban models. These days, smart cities use cutting-edge technology to boost sustainability objectives, increase operational effectiveness, and improve urban life quality. In recent years, scholars and urban planners have put forth several predictions about how smart cities will develop, especially in areas like mobility, infrastructure, governance, and environmental management. Many of these forecasts have come true, but others faced unforeseen difficulties that necessitated tactical changes.

The incorporation of Internet of Things (IoT) technologies to facilitate real-time environmental management is one of the most important trends. Pielli et al. (2015) emphasize that the success of IoT systems depends not only on sensor deployment but also on the robustness of platforms and communication protocols. Their research highlights the importance of scalable and energy-efficient IoT architectures for enabling environmental applications such as air quality monitoring, smart waste systems, and adaptive traffic control. Rather than focusing on isolated devices, their systems-level perspective stresses interoperability, standardized protocols, and reliable data transmission, which are essential for large-scale urban implementation.

The following examples illustrate how some of the early expectations surrounding smart city development have unfolded in practice by 2024, highlighting both successful implementations and ongoing challenges.

- **Artificail Intelligence and Autonomous Governance**

2020 Predictions

Toli et al. (2020) anticipated that artificial intelligence (AI) would play a major role in enhancing environmental governance in smart cities. They argued that AI could enable real-time monitoring, predictive planning, and automated service delivery. Their emphasis was on embedding sustainability into both infrastructure and governance structures.

2024 Reality

By 2024, cities like Singapore have begun implementing AI-based systems to manage environmental data and transportation infrastructure. These implementations emphasize a balanced approach that integrates AI tools with human oversight to ensure ethical considerations, maintain public trust, and address accountability in algorithmic decision-making. This hybrid model helps mitigate biases and promotes responsible urban management (Das et al., 2024). which reinforces the emphasis by Toli et al. (2020) on inclusive, sustainability-oriented governance.

- **Decentralized Smart Infrastructure**

2022 Predictions

Blockchain technology is increasingly projected to support decentralized renewable energy systems by enabling peer-to-peer microgrids, where households can directly generate, share, and trade solar power. This model reduces dependency on centralized utilities and contributes to lower environmental impacts by promoting local clean energy exchange (Nepal et al., 2022).

2024 Reality

By 2024, cities such as Copenhagen and Los Angeles initiated the deployment of blockchain-enabled microgrids. These systems aim to improve local energy reliability and minimize transmission losses. While offering potential environmental and technical advantages through decentralized energy management, their widespread adoption faces obstacles. These include issues concerning system interoperability and compliance with existing national energy regulations. Overcoming these challenges is crucial for effectively integrating blockchain technology into urban energy infrastructures (Wang et al., 2023).

- **Smart Cities and the Sustainability Agenda**

2020 Predictions

According to Bibri (2020), smart cities will be crucial to reaching the Sustainable Development Goals (SDGs) of the UN, especially through resource efficiency and intelligent waste reduction. Their research focused on how big data, AI, and IoT sensors support circular economy models.

2024 Reality

In 2024, many cities have made progress in deploying smart waste management systems. However, the focus has shifted toward influencing household-level behaviour. For instance, Wang et al. (2024) developed a model that integrates the Analytic Hierarchy Process (AHP) with the TRIZ methodology to reduce household food waste. This approach illustrates a broader shift in smart city thinking, from automation alone to citizen-centered engagement. Nevertheless, issues such as behavioural resistance, rising e-waste, and fragmented systems remain ongoing concerns.

- **AI-Driven Digital Twins**

2023 Predictions

Attaran et al.(2023) envisioned the use of digital twins, virtual models of physical urban systems, to support real-time environmental simulations for challenges such as flooding, pollution, and energy consumption.

2024 Reality

By 2024, cities like Helsinki and Shanghai have started using AI-powered digital twins for infrastructure planning and environmental monitoring. These systems are applied to simulate air quality fluctuations and manage energy demand. However, most applications remain sector-specific due to challenges like data standardization, high implementation costs, and platform integration difficulties (Mazzetto, 2024)

Addressing Technology Adoption Challenges

While digital technologies offer significant potential for addressing urban environmental issues, their deployment often encounters major barriers. Ali et al. (2024) identify three main categories of obstacles: technical complexity, stakeholder resistance, and regulatory uncertainty. Their review suggests that building effective smart cities requires more than technological investment. It also involves cross-sector collaboration, user-focused strategies, and educational initiatives to enhance digital literacy and community participation.

For example, many urban areas struggle to integrate new AI and IoT systems with aging infrastructure, leading to inefficiencies and inconsistent data flows. Furthermore, public resistance and limited awareness often undermine the sustainability impact of these projects. To overcome these barriers, Ali et al. (2024) propose an integrated framework combining technical innovation, policy reform, and trust-building with local communities.

In sum, the contrast between early forecasts and current developments reveals that while technological advancements have been significant, the path toward sustainable smart cities remains complex. Tools such as AI, blockchain, and digital twins are increasingly used in environmental management, but their widespread adoption is hindered by ethical, infrastructural, and policy-related challenges. As cities continue to digitalize their systems for energy, waste, and transport, deeper integration between technological solutions and inclusive governance will be essential to ensure that smart urban development is both sustainable and socially just.

Therefore, even while technology innovation is advancing, how much of an influence it has on sustainability will rely on how well digital tools are integrated into long-term policy planning, cross-sectoral strategies, and inclusive governance. Building on the conceptual foundations and analytical elements discussed in the previous chapters, the following section transitions from theory to methodology. It outlines the thesis design, case selection criteria, and data sources for a scientific investigation of how ICT promotes environmental sustainability in smart cities. By transforming theoretical ideas into a systematic comparative analysis, this chapter establishes the methodological framework for evaluating real-world applications in diverse urban contexts.

3. METHODOLOGY AND RESEARCH DESIGN

Building on the theoretical framework laid out in the preceding chapter, which examined the conceptual aspects, historical development, and strategic significance of ICT in smart cities, this chapter outlines the methodological framework utilized to analyse the role of these technologies in promoting environmental sustainability. A qualitative, multi-case research design was chosen, informed by globally recognized smart city indicators and performance metrics. This methodology provides both contextual richness and rigorous analysis.

To achieve a deeper understanding of how digital tools are integrated into urban environmental systems, a qualitative research approach was deemed most suitable. This type of research prioritizes the interpretation of social and technological phenomena within their unique contexts, enabling researchers to investigate intricate relationships, meanings, and processes that quantitative methods may not effectively capture.

As Takona (2024) explains, the qualitative approach is particularly valuable when the aim is to understand how and why certain practices or systems operate in real-world conditions, especially when the variables are dynamic and context dependent.

To address the research objectives, this thesis applies a multiple-case study design to compare selected smart cities that have implemented ICT-based environmental strategies. This design enables the analysis of different approaches used by cities to manage environmental challenges such as pollution, waste, energy use, and water resources through digital technologies. It also supports the identification of shared patterns, innovative solutions, and unique local constraints. Given the diverse nature of environmental initiatives across cities, which span different timeframes and address distinct issues, this study focuses on an in-depth qualitative comparison rather than an extensive statistical analysis. The inherent variability in how cities develop and report their data means that rigorous statistical modelling would not be the primary method for interpreting findings

The thesis relies entirely on secondary data drawn from academic literature, official government reports, and municipal open-data platforms. These sources were analysed using thematic analysis to identify recurring ideas and insights across the selected cases. The aim is not to produce generalizations but to offer a contextual and comparative understanding of how ICT is used to address environmental goals in diverse urban settings. Choosing a qualitative, multi-case approach allows the thesis to reflect the complexity of smart city development while maintaining a focused exploration of the environmental dimension. It provides a flexible and in-depth means of understanding how local governance, policy frameworks, and digital infrastructure interact to shape sustainable urban transitions.

3.1 Research Objectives

This thesis aims to examine the role of Information and Communication Technology (ICT) in advancing smart city development, with a specific focus on how these technologies contribute to achieving environmental sustainability. To achieve this, the following research objectives were formulated:

1. The aim is to understand how Information and Communication Technologies (ICT) can help make cities more environmentally friendly. This will look at how ICT can help with air quality, energy, waste, and water management.
2. The thesis looks at how some cities use high-tech digital tools like the Internet of Things (IoT), artificial intelligence (AI), and big data to make the environment better.
3. To understand the problems, limits, and differences in the environment that affect the success of ICT-based environmental strategies.
4. The aim is to suggest some real-life solutions that will help city planners and the people who make laws to reduce the environmental impact of ICT in smart cities in the future.

By setting these objectives, the research aims to offer a comparative yet practical understanding of how smart cities apply ICT in pursuit of sustainability, while also identifying opportunities to improve the design and adaptation of digital solutions for diverse urban contexts.

3.2 Analytical Framework

To ensure a strict as well as consistent evaluation of how Information and Communication Technology (ICT) supports environmental sustainability within smart cities, this thesis analyses through a framework five dimensions. From 2015 to 2024, this framework is grounded within a thorough narrative review of some academic studies. The reviewed literature does cover key fields such as digital governance and environmental monitoring. It includes ICT systems focused on citizens and smart infrastructure.

Three core principles guide the selection of the five analytical dimensions. First, the framework must maintain a clear focus on environmental sustainability. Second, it should reflect the diversity of urban contexts and their varying ecological challenges. Third, it must enable comparative analysis across different case studies. Present-day academic thought stresses integrated evaluations of smart cities' technical, environmental, and social aspects consistent with these tenets (Albino et al., 2015; Bibri, 2020).

Based on these considerations, the thesis defines five key dimensions as follows:

D1: Environmental Effectiveness

This dimension evaluates the extent to which ICT tools produce tangible and measurable environmental improvements. These improvements may include reductions in CO_2 emissions, better air and water quality, higher recycling rates, and increased energy and water efficiency. Technologies such as IoT sensors, real-time monitoring systems, and automated dashboards play a central role in enabling these outcomes. Practical examples from cities like Oslo and Amsterdam show how smart waste systems and air quality monitoring have led to measurable environmental gains (Allam et al., 2022).

D2: Technological Innovation

This dimension focuses on the level of advancement and integration of digital technologies. It includes the application of emerging tools such as artificial intelligence (AI), digital twins, blockchain, edge computing, and big data analytics to address environmental issues. As noted by Bibri et al. (2020), cities that embrace innovative and scalable technologies are more capable of adapting to complex urban sustainability challenges.

D3: Digital Governance and Public Engagement

This dimension examines how ICT enhances transparency, institutional accountability, and citizen participation in environmental governance. It includes the use of digital platforms such as open data portals, participatory apps, and reporting tools that foster two-way communication between citizens and government. Research highlights the importance of digital tools in enabling inclusive and responsive governance systems (Bastos et al., 2022).

D4: Contextual Adaptability

Given that cities vary in their environmental, social, and institutional conditions, this dimension assesses how well ICT solutions are adapted to local contexts. Instead of replicating standard models, effective smart city strategies tailor digital interventions to meet local needs. Cape Town, for instance, implemented mobile apps and sensor systems suited to informal and resource-constrained areas during its 2018 water crisis (Paul et al., 2019).

D5: Long-term Impact and Integrated Sustainability

This dimension considers the sustainability of ICT strategies over time. It focuses on factors such as funding continuity, institutional integration, long-term policy alignment, and the contribution of ICT solutions to broader goals like economic resilience and social inclusion. Cities like Copenhagen and Singapore illustrate this dimension through their integration of digital tools within long-term climate and sustainability strategies (Abu-Rayash et al., 2021; Ferro-Escobar et al., 2022).

3.3 Research Questions

To support the aim of this thesis and ensure a focused analysis, a set of research questions has been formulated. These questions were developed in direct alignment with the thesis's objectives and are designed to reflect the five key analytical dimensions used in evaluating the selected smart cities.

RQ1: In the cities analysed, what are the main environmental changes that have emerged as a result of using of ICTs? How has this affected areas such as energy, air quality, water and waste management?

RQ2: What digital tools are these cities adopting, such as the Internet of Things or Artificial Intelligence, and what role do these tools play in supporting environmental sustainability plans?

RQ3: What challenges do cities face when implementing digital strategies to protect the environment? Do these challenges vary according to local conditions and available capacities?

RQ4: By comparing different experiences, what ideas or lessons can be learnt to develop the use of ICT in long-term and effective environmental planning?

Together, these questions guide the structure of the analysis and provide a consistent basis for comparing the selected smart cities. They also support the development of practical insights that can inform future ICT strategies aimed at promoting environmental sustainability in urban settings.

Table 3 shows the alignment of the research questions with the analytical dimensions:

Table 3 The alignment of the research questions with the analytical dimensions

Research Question	**Analytical Dimension**
RQ1: What environmental changes have resulted from ICT use in these domains?	Environmental Effectiveness **(D1)**
RQ2: What tools are adopted and what roles do they play in sustainability efforts?	Technological Innovation **(D2)**
RQ3: What challenges do cities face, and how do these vary by context?	Digital Governance and Public Engagement & Contextual Adaptability **(D3 & D4)**
RQ4: What lessons can be learned to support long-term environmental planning with ICT?	Long-term Impact and Integrated Sustainability **(D5)**

Source: Author's creation

3.4 Research Structure

The thesis is structured into eight main chapters:

Chapter 1: Smart City

This chapter provides an overview of the historical development of smart cities, definitions from various perspectives, and different dimensions of smart cities. It also explores evolving academic insights, challenges, and the concept of sustainability in ICT-enabled cities.

Chapter 2: ICT and Sustainable Smart Cities

This chapter focuses on the role of digital infrastructure in smart cities, particularly in urban environmental management. It discusses technologies such as artificial intelligence and big data, addresses associated challenges, and examines the relationship between ICT and smart city dimensions. Future trends and predictions are also included.

Chapter 3: Methodology and Research Design

This chapter outlines the research objectives, questions, and design. It also presents the analytical framework, evaluation indicators, and the rationale for selecting the seven cities case study.

Chapter 4: Findings from the Selected Smart Cities (Case study)

This chapter presents findings from each of the seven cities: Copenhagen, Amsterdam, Dubai, Singapore, Zurich, Cape Town, and Oslo. It highlights their ICT-enabled environmental transitions.

Chapter 5: Results

This chapter organizes the findings according to five analytical dimensions:

- Environmental Effectiveness
- Technological Innovation
- Digital Governance
- Contextual Adaptability
- Integrated Long-Term Sustainability

Chapter 6 – Discussion

This chapter interprets the results in the context of existing literature, using the same five analytical dimensions as sub-sections to reflect on the significance and implications of the findings.

Chapter 7: Conclusion and Recommendations

This chapter summarizes the thesis's key contributions. It includes policy recommendations, acknowledges limitations, and proposes directions for future research.

3.5 Smart City Evaluation Indicators and Case Selection Criteria

To ensure methodological rigor and relevance, this research adopts a structured and indicator-based approach for evaluating and selecting smart cities as a case study. While the concept of a smart city is often associated with digital innovation, this thesis adopts a broader definition. A smart city is understood as a data-informed, environmentally responsible, and socially inclusive urban system. Its intelligence reflects not only the presence of digital infrastructure but also the integration of effective governance, sustainable energy, efficient mobility, and active citizen participation (Albino et al., 2015).

Several international institutions and academic researchers have developed frameworks to assess smart city performance. These frameworks vary in their scope, methodology, and areas of focus. Giffinger et al. (2007) introduced a six-dimensional model that includes smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. In a more recent contribution, Abu-Rayash et al. (2021) proposed a Smart City Index that includes eight domains. These domains are economy, environment, governance, infrastructure, energy, transport, society, and resilience, and they are closely aligned with the United Nations Sustainable Development Goals.

To provide a strong analytical basis for this research, three major global indices were selected for comparison. The Table 4 summarizes their key dimensions, data sources, and reference authors to ensure transparency and academic credibility.

Table 4 Overview of Selected Smart City Indexes and Their Relevance to Case Study Selection

Relevance to Case Cities	Key Dimensions Used in Case Selection	Source	Smart City Index / Framework
Amsterdam, Zurich, Copenhagen	Smart Environment, Smart Mobility, Smart Governance, Smart Living, Smart Economy, Smart People	Lai et al., (2023)	Giffinger Model (6 dimensions)
Singapore, Dubai, Oslo	Health & Safety, Mobility, Governance, Activities, Opportunities	Toh (2022)	IMD Smart City Index (SCI)
Cape Town, Dubai, Singapore	Environment, Energy, Governance, Infrastructure, Society, Transport	Abu-Rayash et al., (2021)	Abu-Rayash & Dincer Framework

Source: Developed by the author based on Lai et al., (2023), Toh (2022), and Abu-Rayash et al., (2021) These indexes form the basis for evaluating city performance across various dimensions, ensuring that the case selection in this thesis is rooted in measurable and internationally validated standards. While each index has its unique focus and methodology, they collectively offer a comprehensive lens for assessing urban smartness in the context of environmental and technological advancement.

3.6 Case Study Selection

Seven cities were selected for this thesis based on their consistent appearance and high performance in the global indexes outlined above. Each city demonstrates active engagement with ICT tools to address environmental sustainability, although the approaches and local contexts differ.

The inclusion of **Singapore** in this thesis is based on its leadership in digital governance at the national level. It ranks consistently high in the IMD-SUTD Smart City Index and demonstrates full integration of ICT in areas such as mobility, water management, energy systems, and digital services. Its Smart Nation initiative has positioned Singapore as a global model of comprehensive smart governance (Toh, 2022).

The inclusion of **Amsterdam** is based on its strong emphasis on participatory governance and open digital infrastructure. The city is known for promoting citizen-led innovation and decentralized environmental monitoring. As reported by Albino et al. (2015) and Lim et al. (2024), Amsterdam performs well in the CIMI index, especially in areas related to mobility, data transparency, and sustainable urban services.

The inclusion of **Copenhagen** reflects its global leadership in sustainability. The city applies advanced data analytics and smart technologies to support its target of becoming carbon-neutral by 2030. Its performance in the SCI and CIMI indexes is linked to its ICT-supported environmental planning and mobility policies (Abu-Rayash et al., 2021).

The inclusion of **Oslo** is based on its innovative use of ICT in energy management. The city employs real-time data to monitor emissions and regulate district heating systems. It also ranks highly in environmental and governance categories in both the IMD and CIMI indexes (Toh, 2022).

The inclusion of **Zurich** is based on its strong institutional commitment to transparency and smart infrastructure. The city has implemented ICT in waste collection, public transport, and urban monitoring. According to Albino et al. (2015) and Lai et al. (2023), Zurich performs exceptionally well in digital governance and public participation.

The inclusion of **Dubai** introduces a perspective from the Global South. Dubai is recognized for its rapid adoption of advanced technologies such as artificial intelligence, blockchain, and smart grids. It ranks highly in the IMD-SUTD and SCI indexes and is guided by national policies including Smart Dubai and the Dubai Clean Energy Strategy 2050 (Toh, 2022; Lim et al., 2024).

The inclusion of **Cape Town** reflects the relevance of studying smart city initiatives in resource-constrained settings. Despite infrastructure limitations, Cape Town has adopted smart water systems, solar energy solutions, and environmental data platforms. It adds geographical diversity and highlights the adaptability of ICT in the Global South (Lai et al., 2023).

By selecting cities that represent different regions, development levels, and governance models, this thesis offers a broad yet focused comparison. These cases allow the thesis to identify adaptable strategies, scalable innovations, and context-sensitive challenges in applying ICT for environmental sustainability in urban settings.

4. FINDINGS FROM THE SELECTED SMART CITIES

Comparative overview of selected cities has grounded in a multifaceted theoretical framework and a context-responsive methodological approach, this analysis examines how prominent global cities utilize digital technologies to promote environmental sustainability. By investigating the incorporation of ICT tools within urban systems, the thesis provides a systematic comparison across various socio-economic and geographic contexts.

The evaluation is structured around five primary analytical dimensions: environmental efficacy, technological advancement, digital governance, contextual flexibility, and integration of long-term sustainability. These dimensions are utilized to assess how cities incorporate instruments such as the Internet of Things, digital twins, open data platforms, smart grids, and artificial intelligence into their environmental policies, infrastructure development, and operational practices.

The chosen case study (Copenhagen, Amsterdam, Dubai, Singapore, Zurich, Cape Town, and Oslo) reflect a wide array of digital maturity levels, governance approaches, and environmental priorities. Their selection highlights both the international scope of ICT-driven environmental innovation and the local adaptations influenced by institutional capabilities, climatic factors, and urban growth trajectories.

This analysis relies on credible secondary sources including official governmental publications, publicly accessible urban data platforms, and scholarly peer-reviewed articles. Quantitative metrics and visual aids are employed to illustrate measurable advancements in areas like carbon emission reduction, increased use of renewable energy sources, improved air quality standards, and the establishment of low-emission infrastructure.

The **detailed case studies for each city** are provided in **Appendix A: Comprehensive City Examples.**

Instead of merely cataloguing digital advancements, this chapter underscores the dynamic interplay among technology, governance structures, and environmental planning. It demonstrates how ICT systems can act as strategic catalysts for more sustainable, inclusive, and adaptable urban transformations when customized to fit local governance frameworks and urban demands. Ultimately, the insights gained provide a framework for cities aiming to leverage digital technologies in their quest for sustainable and resilient urban futures.

The following table provides a comparative overview of how these smart cities leverage various ICT applications for environmental sustainability

Table 5 Comparative ICT Applications for Environmental Sustainability Across the Selected Smart Cities

City	Strategic Environmental Vision	Focused Environmental Domains	Key ICT Tools and Platforms	Unique Sustainability Approach
Copenhagen (2019-2023)	Climate neutrality by 2025 through integrated urban planning and green infrastructure.	Energy, Mobility, Waste, Public Engagement	IoT-based data collection, Urban data platform, Intelligent traffic systems, AI for waste collection	Strong policy-tech alignment and real-time urban monitoring
Amsterdam (2019-2023)	Digital-first transition toward circular economy and resilient energy use.	Energy transition, Emissions, Transport, Citizen participation	Decentralized energy platforms, Blockchain for local energy exchange, Smart meters, AI-driven analytics	Community co-design and digital civic platforms
Dubai (2021-2024)	Achieve Smart and Sustainable City status via large-scale ICT investments.	Energy, Water, Emissions, Waste, Air Quality	Big Data, AI-driven digital twins, IoT sensors, Integrated dashboards	High reliance on predictive analytics for resource management
Singapore (2018-2023)	Smart Nation strategy focusing on liveability, sustainability, and resilience.	Air Quality, Water, Waste, Green spaces, Biodiversity	Nationwide IoT infrastructure, AI-based water monitoring, Satellite urban data, Smart waste bins	Holistic, city-wide digital governance approach
Zurich (2018-2024)	Sustainability-driven smart urbanism integrated with citizen feedback loops.	Emissions, Transport, Biodiversity, Waste	Smart grids, Traffic control systems, IoT waste management, Digital twin infrastructure	Data-informed decision making with public accountability
Cape Town (2018-2025)	Climate-responsive digital urban services to address resource scarcity.	Water, Waste, Energy, Emissions	Smart metering, GIS water management, Remote sensing, public participation tools	Adaptive ICT use in low-resource settings
Oslo (2018-2023)	Achieve zero-emission urban mobility and net-zero carbon by 2030.	Mobility, Energy, Emissions, Urban greenery	Smart traffic platforms, green mobility apps, Air quality sensors, Smart lighting	Leadership in ICT-enabled sustainable transport systems

Source: Compiled by the author, based on detailed case studies presented in Appendix A: Comprehensive City Examples

It's important to recognize that, while this study offers a comparative analysis of smart cities' environmental efforts, the underlying data presents inherent complexities. The selected cities address diverse environmental challenges, operate within distinct policy frameworks, and implement ICT initiatives over varying timelines. This means that direct, perfectly aligned comparisons are challenging, as specific patterns and overlapping periods may not be uniform across all cases. For instance, while this study generally covers data from 2018 to 2025 (or specific periods as noted for each city), urban contexts evolve rapidly, and some information may have shifted since its collection. Nevertheless, deliberate efforts were made to harmonize and present the data as comparably as possible, allowing for the identification of core patterns and ICT-driven strategies contributing to environmental sustainability in different urban settings.

The following **summary** outlines the main environmental achievements and persistent challenges observed in each of the seven case study cities

Copenhagen achieved substantial reductions in CO_2 equivalent emissions and increased its share of renewable energy, positioning itself firmly on track to meet its 2025 carbon neutrality goal. ICT played a central role in optimizing energy use and enhancing transparency. While no major setbacks are mentioned, the key challenge remains sustaining this decarbonization pace and ensuring sectoral alignment across the city.

Amsterdam's transition between 2019 and 2023 featured a notable decline in energy demand and a sharp increase in renewable energy uptake, supported by digital platforms and participatory initiatives. However, the reliance on pilot-stage decentralized technologies (e.g., blockchain energy trading) presents a challenge for system-wide scalability and integration.

Dubai advanced its environmental agenda through clean energy integration and improved utility efficiency, driven by ICT systems and strategic planning. However, carbon emissions rebounded by 2024 due to post-pandemic economic growth, highlighting the challenge of decoupling emissions from rapid development in high-consumption settings.

Singapore demonstrated progress across multiple environmental indicators, including emissions, waste, and air quality, through deep ICT integration. Still, implementation costs and data limitations in certain industrial sectors remain significant barriers to system-wide environmental intelligence.

Zurich consistently reduced energy use and emissions while improving air quality, benefiting from a cohesive ICT-enabled strategy and active public involvement. The ongoing task is to ensure the adaptability of its “2000 Watt Society” model to technological changes and evolving public expectations.

Cape Town effectively addressed a severe water crisis through a mix of infrastructure investment, digital monitoring, and public mobilization. While the immediate threat was mitigated, the city faces a continued challenge in maintaining long-term water security under climate stress and population growth.

Oslo achieved strong outcomes in reducing transport-related emissions, expanding electric vehicle adoption, and enhancing waste recycling through a comprehensive digital transition. However, meeting its ambitious 2030 net-zero target requires further behavioural shifts and broader citizen engagement beyond early adopters

5. RESULTS

This chapter presents detailed findings from a comparative study of how smart cities are using information and communication technologies (ICTs) to support environmental sustainability. The results aim to answer the main research questions (RQ1–RQ4) and explore how digital innovation and environmental change interact in different urban settings.

The findings are organized around a five-part analytical framework used in the thesis: Environmental Effectiveness (D1), Technological Innovation (D2), Contextual Adaptation (D3), Digital Governance (D4), and Integrated Long-term Sustainability (D5). Each section of this chapter focuses on a specific research question and highlights key insights from seven cities: Copenhagen, Singapore, Zurich, Amsterdam, Dubai, Oslo, and Cape Town.

The chapter starts by examining the actual environmental improvements that resulted from using ICTs (RQ1). It then looks at the digital tools adopted and their impact on sustainability (RQ2). After that, it addresses the challenges cities faced and how these varied by local context (RQ3). Finally, the chapter shares lessons learned and suggestions for how ICTs can be used in long-term environmental planning (RQ4). These insights set the foundation for the deeper analysis provided in the following chapter.

5.1 RQ1 Answer

The findings show that using information and communication technologies (ICT) has led to real, measurable environmental improvements in the seven smart cities studied. These improvements were assessed through four key indicators: lower CO_2 emissions, higher renewable energy production, better air quality, and changes in recycling rates.

Figure 1 offers a comparison of how each city performed on these indicators. It also highlights how the results differ depending on each city’s local institutions and socio-economic conditions. This variation reflects the influence of geography and governance on environmental outcomes.

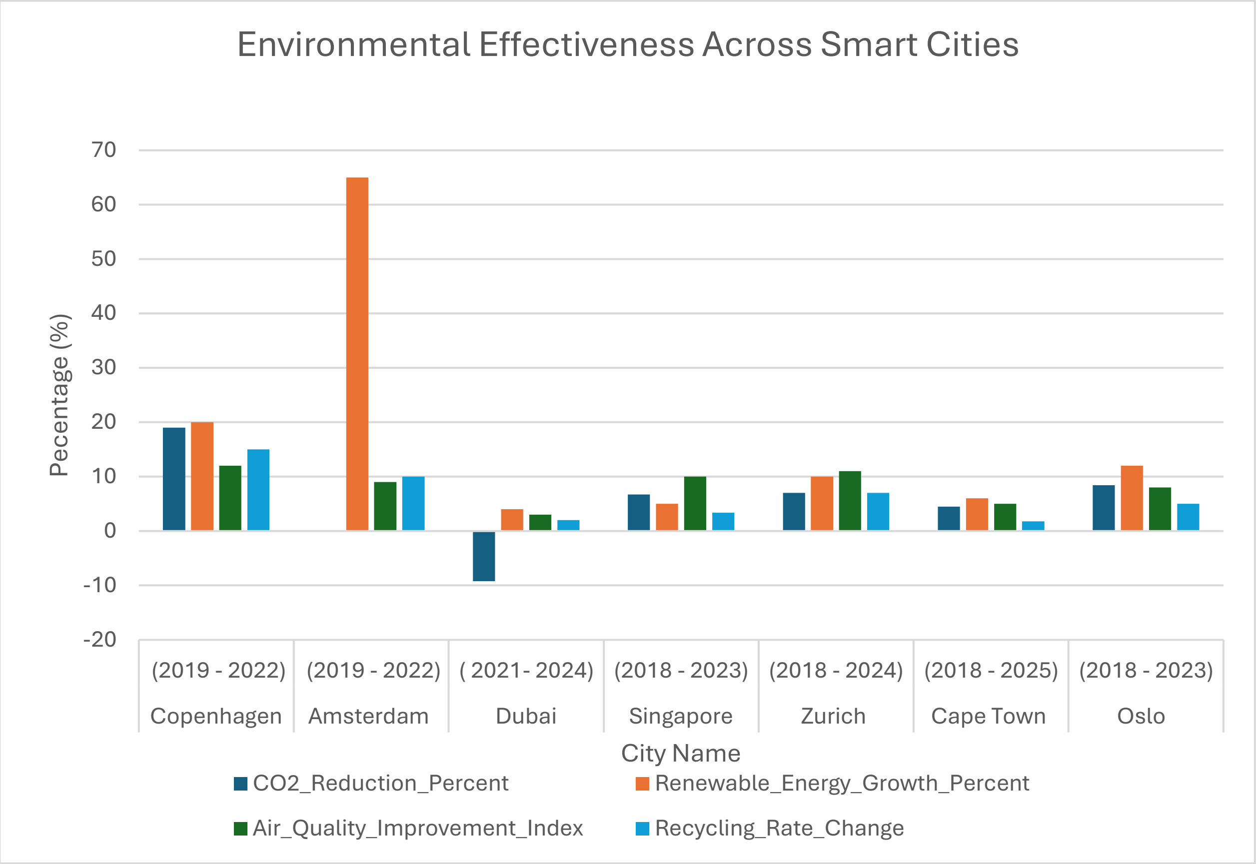

Figure 1 Environmental Effectiveness Across Smart Cities

Source: Author's elaboration based on detailed case studies presented in Appendix A: Comprehensive City Example

Key environmental changes by city

Copenhagen made the most progress in cutting emissions. Between 2019 and 2022, the city reduced its carbon dioxide emissions by 19%. This success came from using smart grid systems, heat-balancing technologies backed by data analytics, and a 20% increase in renewable energy for district heating. These actions show how digital tools can lead to real environmental benefits when applied to infrastructure.

Amsterdam kept its emission levels steady during the same period between 2019 and 2022, but made major progress in renewable energy, with a 65% increase in production. This was made possible by digitally managing decentralized energy systems and using blockchain-based electricity trading. While emissions didn't drop, the city made important advances in energy efficiency and system flexibility.

Dubai experienced a 9.2% rise in emissions from 2021 to 2024, even after adding 433 MW of solar power. The increase is linked to economic recovery after the pandemic and ongoing urban development, both of which drive up energy use. Although digital systems like district cooling and energy demand management were in place, they weren't enough to balance out the high energy consumption.

Singapore (2018 to 2023), Zurich (2018 to 2024), and Oslo (2018 to 2023):

These cities showed steady improvements across several indicators.

- **Singapore** cut greenhouse gas emissions by 6.7% and also reduced nitrogen and sulphur oxides. This was supported by sensor networks and systems that forecast air quality.
- **Zurich** improved air quality and recycling with the help of smart meters and citizen-focused digital platforms.
- **Oslo** saw a big drop in transport emissions, with the transport sector’s share falling from 68% to 54%, thanks to a rise in electric vehicle use from 25% to 70%.

Despite difficult conditions, **Cape Town** in the period from 2018 to 2025 applied ICT tools in solar energy and waste management. However, the environmental gains were modest. This suggests that digital solutions alone aren’t enough; they need strong policies and funding to be fully effective.

To understand the relationship between increased renewable energy use and reduced carbon emissions, a Pearson correlation analysis was performed using data from six of the cities (as shown in the **Figure 2**).

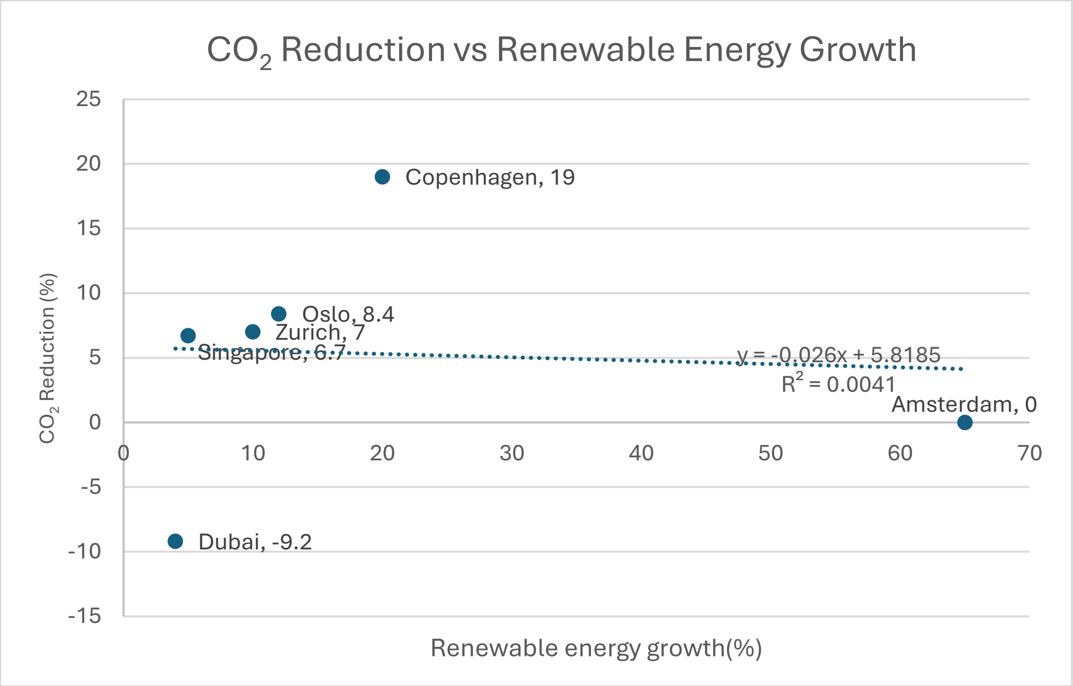

Figure 2 CO_2 Reduction vs Renewable Energy Growth

Source: Author’s elaboration based on detailed case studies presented in Appendix A: Comprehensive City Examples

The figure shows that there's no clear pattern between increasing renewable energy and reducing emissions. In fact, the data (including a very low correlation score of $R^2 = 0.0041$) suggests a slight negative link. This means that just because a city produces more renewable energy, it doesn’t always lead to lower emissions. For example, Amsterdam made big progress in renewable energy but didn’t cut emissions. Meanwhile, Dubai added solar power but still saw emissions go up.

This shows that improving the environment in smart cities isn't just about adding new technologies. What really matters is how those technologies fit with each city’s energy system, policies, and planning. Digital tools are powerful, but they need to be used in the right way, coordinated across sectors and adapted to each city’s unique situation. The different results from each city in this thesis prove that a one-size-fits-all approach doesn’t work.

In other words, having digital systems in place isn’t enough on its own. Cities need to connect technology with clear environmental goals, strong leadership, and good planning. **Copenhagen, Singapore, and Zurich** have seen real improvements because they combine digital tools with smart policies and data-driven planning. They treat technology as part of a larger, well-organized system.

But in cities like **Dubai and Cape Town**, even advanced digital tools didn’t lead to strong environmental outcomes, mainly because of gaps in policies, coordination, or resources. **Amsterdam,** while not seeing immediate emission cuts, showed promising steps with fast growth in renewable energy and new energy trading platforms. This could lead to future benefits.

So, **in response to the (RQ1)**, yes, digital technologies can help cities become more environmentally sustainable. But this only happens when those tools are supported by clear policies, good institutions, and thoughtful planning. Technology alone isn’t enough—it must be part of a bigger picture that includes people, systems, and goals all working together.

5.2 RQ 2 Answer

These findings show how several smart cities are using advanced digital technologies to tackle environmental challenges, focusing on the area of technological innovation (D2). The analysis looks at tools like artificial intelligence (AI), blockchain, the Internet of Things (IoT), digital twins, and sensor networks. These aren't just technical upgrades, they represent a real change in how cities manage environmental issues and make decisions.

This part answers Research Question 2 (RQ2) by showing how new ICT tools are being used to support environmental goals in cities. It also helps explain how different kinds of technologies work together to achieve real environmental improvements.

Key technologies and how cities are using them

Singapore stands out as a leader. The city has invested heavily in AI-based systems, digital twins, and predictive analytics to monitor and forecast environmental changes in real time. Through its "Smart Nation" initiative, it encourages data sharing between sectors and public involvement through interactive digital platforms. This helps the city plan proactively using accurate, real-time data.

Amsterdam is also doing well in using technology. It has applied blockchain in its local energy systems, allowing people to trade electricity directly within communities. This supports decentralized energy systems and increases transparency. The city also uses IoT for smart buildings and circular economy models, showing how digital tools are used across different sectors.

Copenhagen has focused on using AI in public services, especially in energy and transportation. The city uses sensors to monitor its heating systems and smart traffic management to reduce emissions. These innovations help improve efficiency and link directly to climate policies.

Zurich benefits from strong institutions that support its tech efforts. The city uses smart meters to track energy use and digital platforms that involve citizens in sustainability projects. Zurich's "positive energy zones" act as test areas to combine renewable energy with digital optimization.

Dubai takes a large-scale approach, with high-profile projects like autonomous vehicles, smart building policies, and AI-driven water and energy systems. These innovations are gradually being included in official regulations, such as the "Saafat" green building code. Dubai also offers a "Smart Life" dashboard that helps residents monitor their energy and water use in real time.

Oslo focuses on smart transportation and cutting emissions. The city uses AI for traffic control, has planning tools for electric vehicles, and has placed environmental sensors throughout its transport system. These tools help reduce emissions by making mobility more efficient and responsive to changing conditions.

Cape Town, although facing resource limitations, has launched creative solutions that fit its local context. It uses mobile apps and satellite data to support water conservation and track environmental indicators. Low-cost sensor projects allow communities to monitor local waste, rainfall, and pollution. These efforts show how technology can be adapted to local needs.

Table 6 below compares how each city uses these technologies across different environmental areas.

Table 6 Matrix comparing the application of advanced digital technologies in environmental domains across the selected smart cities

City	**Artificial Intelligence (AI)**	**Block-chain**	**Internet of Things (IoT)**	**Digital Twins**	**Smart Metering / Sensors**	**Citizen Platforms**
Singapore	High	Low	High	High	High	High
Amsterdam	Medium	High	High	Low	Medium	High
Copenhagen	Medium	Low	High	None	Medium	Medium
Zurich	Low	Low	Medium	Low	High	High
Dubai	Medium	Low	Medium	Low	Medium	Medium
Oslo	Medium	Low	Medium	Low	Medium	Medium
Cape Town	Low	No data	Low	No data	Low	Low

Source: Author's elaboration based on detailed case studies presented in Appendix A: Comprehensive City Example

Among all the cities compared, Singapore clearly stands out. It received a "High" rating in almost all technologies shown in the table: AI, IoT, digital twins, smart metering, and citizen platforms. This shows how Singapore uses digital tools not just for isolated projects, but as part of a larger strategy for managing the environment through data and technology.

For example, Singapore is the only city with a high rating in digital twins. These tools allow the government to build real-time 3D models of the city and run simulations to plan for pollution, energy use, and more. This helps them act before problems happen, not just after.

However, blockchain remains a weaker area. Although Singapore started some pilot project, like a platform in 2019 that let people trade solar energy directly, these efforts stayed small and didn't expand. Complex rules and high costs made it hard to use blockchain widely. This shows that even in highly digital cities, not every new technology fits easily or grows fast.

When comparing cities, it becomes clear that innovation is not just about having advanced tools, it is about how those tools are applied. This table provides a comparison of the selected smart cities' application of advanced digital technologies in environmental areas, in response to the second research question (RQ2) that focuses on the second dimension (D2): Technological Innovation. The extent to which each technology (AI, blockchain, IoT, digital twins, smart meters/sensors, and citizen platforms) was assessed based on a qualitative analysis of the information contained in the descriptive sections of each city, according to the following criteria:

High: Awarded to cities that demonstrate widespread, advanced, and integrated use of this technology, with concrete examples of its significant contribution to environmental goals.

A prominent example is Singapore, which has invested heavily in artificial intelligence systems, digital twins, and predictive analytics to monitor and anticipate environmental changes in real time.

Medium: Indicates a notable use of technology, but it may be less comprehensive or advanced compared to the "High" rating or applied in specific sectors. An example is Amsterdam, which has ‘implemented blockchain in local energy systems.

Low: Reflects limited or experimental use of the technology, or no prominent mention of it in the analytical text. This applies to Cape Town, which focuses on creative solutions suited to its local context, such as mobile applications and satellite data.

None: Used when the text clearly states that there is no use of this technology in the context of the city in question, such as digital twins in Copenhagen.

When comparing cities, it becomes clear that innovation is not just about having advanced tools, it is about how those tools are applied. Cities such as Singapore and Amsterdam show how innovation can be systemic, participatory, and policy-driven. Other cities, such as Cape Town, show that even modest tools can have a significant impact when rooted in local realities.

Beyond technological innovation, the real value of digital tools lies in their ability to reshape environmental management systems. Whether through predictive analytics, decentralised energy markets, or community-based monitoring, what matters most is how technology is woven into the city's broader environmental vision.

In response to the (RQ2), the results show that the digital tools adopted by smart cities are diverse in form but unified in purpose. Technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, and digital twins are not simply applied for the sake of efficiency, they are increasingly integrated into how cities think, plan, and act on environmental issues. However, their effectiveness is not determined by the technology itself, but by how carefully it is applied.

The wave of technological innovation has helped reveal not only the tools being used, but how cities are using them differently. In places like Singapore and Copenhagen, digital tools have been part of a broader system of governance and planning, enabling real-time monitoring, early intervention, and data-informed decision-making. In contrast, cities such as Cape Town focused on locally affordable and socially accessible tools, demonstrating that innovation can take many forms when rooted in context.

More importantly, the cities that achieved promising results were not those with the most advanced tools, but those where technology was aligned with clear environmental goals, comprehensive policies, and citizen participation. This suggests that innovation, when guided by local needs and supported by institutional structures, can be a powerful driver of environmental transformation.

5.3 RQ3 Answer

The findings reveal that smart cities encounter a wide range of environmental challenges, and their responses differ based on local circumstances (Dimension D3: Contextual Adaptation) and the strength of their digital governance systems (Dimension D4: Digital Governance). These differences are not shaped by technology alone, but by how well it fits into each city's institutional setup, social dynamics, and public engagement levels.

Each city offers a distinct example of how challenges are handled and solutions adapted:

Cape Town stands out for how it adapted during a major water crisis in 2018. After facing the threat of “Day Zero,” the city switched from a reactive approach to a digitally supported, proactive water system. Tools like real-time dashboards, mobile alerts, and public monitoring platforms helped residents track water levels and reduce their own use. Even with limited infrastructure, this open and community-centered strategy restored trust and stabilized water reserves. It shows how digital tools, when built around local risks, can improve resilience.

Dubai In a region with scarce natural resources, Dubai developed a tech-driven model that fits its environmental limitations. The city deployed over two million smart meters, introduced AI-based cooling, and applied predictive planning to manage urban expansion. Large projects like the Hatta Hydroelectric Station and solar energy initiatives reflect an approach that blends innovation with environmental constraints.

Zurich illustrates how strong institutions help cities connect digital tools across sectors. Its energy, air quality, and water systems are linked through smart meters and environmental sensors, all supported by coordinated policy and citizen involvement. Projects like its “positive energy zones” show how well-planned digital strategies can meet both technical and environmental goals.

Singapore uses pilot areas and centralized systems to scale digital solutions citywide. As part of the “Smart Nation” initiative, it integrates digital tools into public services for transport, energy, water, and waste. Test areas like Tenga and Punggol allow real-time experimentation, while coordination between agencies ensures that solutions grow without losing local relevance.

Amsterdam takes a community-focused approach. In districts like Buikslot, people use modular energy systems, open dashboards, and behavioral incentives. The goal isn’t just better performance, but making sure these technologies fit with daily life. This bottom-up method suits cities that prioritize democratic values and social inclusion.

Copenhagen links digital technology directly with policy goals. It tracks emissions in real time, uses smart waste systems, and manages traffic adaptively. Its circular economy model promotes open data and feedback loops that turn digital information into action. This strong link between citizens, data, and planning improves transparency and policy support.

Oslo builds its digital strategy around inclusion. By combining smart energy systems, adaptive transport, and open environmental data, it creates a decision-making process that considers equity and environmental goals. The focus on access and local relevance makes sure that digital progress benefits all groups—not just those with technical expertise.

Tables 7 and 8 summarize these strategies. Table 7 compares key governance features like access to open data, real-time feedback, and integration with environmental policy. Table 8 highlights how each city adapts to local conditions, including crisis response, alignment with geography, policy integration, and public engagement.

Table 7 Comparative overview of digital governance features in selected smart cities

City	Open Data Platforms	Citizen Feedback Systems	Real-Time Dashboards	E-Government Integration	Environmental Policy Linkage	Level of Civic Participation
Singapore	Yes	Yes	Yes	Full	Strong	High
Amsterdam	Yes	Yes	Yes	Moderate	Strong	High
Copenhagen	Yes	Yes	Yes	Moderate	Strong	Moderate
Zurich	Yes	Yes	Yes	Full	Strong	Moderate
Dubai	Yes	Limited	Yes	Full	Moderate	Low
Oslo	Yes	Yes	Yes	Moderate	Moderate	Moderate
Cape Town	Yes	Yes	Yes	Basic	Moderate	Moderate

Source: Author's elaboration based on detailed case studies presented in Appendix A: Comprehensive City Example

Table 9 shows the features of digital governance in the selected smart cities, in response to the third research question (RQ3) that addresses the fourth dimension (D4): Digital Governance. Each feature was assessed based on the qualitative analysis of the cities' descriptive texts, according to the following criteria:

Open Data Platforms, Citizen Feedback Systems, Real-Time Dashboards:

Yes: If the text indicates the existence or use of these platforms/systems/dashboards, such as Copenhagen, which promotes open data and feedback loops.

No: If the text does not mention these platforms/systems/panels.

Limited: Used if there is a mention, but it is limited or does not rise to the level of a full 'yes' (e.g., Dubai on citizen feedback systems).

E-Government Integration:

Full: Indicates a high level of digitisation and integration of government services across sectors, as in Singapore, where 'most public services are already digitised'.

Moderate: Indicates a good level of digitisation and integration but may not be as comprehensive.

Basic: Indicates that some services are digitised, but may be sporadic or not highly integrated, as in Cape Town, which faces infrastructure challenges.

Environmental Policy Linkage:

Strong: For cities that demonstrate a direct and clear link between the use of digital technologies and overarching environmental goals and policies, such as Copenhagen, which links digital technology directly to policy goals.

Moderate: Indicates connectivity but may not be as deep or comprehensive as in cities with a 'strong' rating.

Level of Civic Participation:

High: For cities that demonstrate strong and ongoing citizen engagement initiatives, such as Amsterdam, which takes a community-centred approach.

Moderate: For cities that show a level of engagement, but it may not be as deep or comprehensive.

Low: For cities where citizen engagement does not feature prominently in the analytical text, such as Dubai.

Table 8 Comparative Assessment of context adaptability across the selected smart cities

City	Crisis Response Capacity	Adaptation to Climate/Geography	Integration with Local Policy	Community Engagement Level	Use of Localized Data
Cape Town	High	High	Moderate	High	Moderate
Dubai	Moderate	High	High	Low	High
Zurich	Low	Moderate	High	Moderate	High
Singapore	Moderate	Moderate	High	Moderate	High
Amsterdam	Moderate	Moderate	Moderate	High	High
Copenhagen	Low	Moderate	High	Moderate	Moderate
Oslo	Moderate	High	High	Moderate	High

elaboration based on detailed case studies presented in Appendix A: Comprehensive City Example

Table 8 provides a comparative assessment of the contextual adaptability of the selected smart cities, in response to the third research question (RQ3), focusing on the third dimension (D3):

Contextual Adaptation. Each dimension (crisis response capacity, climate/geographical adaptation, integration with local policies, level of community participation, and use of local data) was assessed based on the qualitative analysis of the cities' descriptive texts, according to the following criteria:

High: Awarded to cities that have demonstrated exceptional capacity or strong focus in this aspect, with clear examples from the text.

Moderate: For cities that have demonstrated significant capacity, but perhaps not to the same level of comprehensiveness or impact as the “High” rating.

Low: For cities where the text does not prominently emphasise this aspect or demonstrates limited capacity.

Apply the criteria to the selected columns:

Crisis Response Capacity:

High: For cities such as Cape Town that ‘stood out in how it adapted during a major water crisis in 2018’, shifting from a reactive approach to a proactive digitally supported water system.

Moderate: For cities that have shown some ability to respond or adapt to disruptions, such as Singapore, which continued to achieve its environmental goals by rapidly shifting resources.

Low: For cities where the text does not mention an outstanding response to crises from a contextual adaptation perspective.

Adaptation to Climate/Geography:

High: For cities that have implemented digital solutions specifically suited to their unique climate or geographic challenges, such as Dubai, which has developed a technology-driven model that fits its environmental constraints.

Moderate: For cities that have shown some adaptation, but perhaps not to the same degree of specialisation or centrality.

Integration with Local Policy:

High: For cities that show strong integration of digital technologies into local policies and regulations, reflecting an integrated approach, such as Dubai, where these innovations are gradually embedded in official regulations.

Moderate: For cities that show some integration but may not be as comprehensive or mandatory.

Community Engagement Level:

High: For cities that demonstrate strong and sustained community engagement in the context of contextual adaptation, such as Cape Town, which has adopted an open and community-based strategy.

Low: For cities where the text places less emphasis on community engagement, such as Dubai.

Use of Localised Data:

High: For cities that use data from local or community-level sources to support decisions and adaptation, such as Cape Town, which uses mobile phone apps and satellite data to support water conservation and track environmental indicators.

Moderate: For cities that utilise data but may not have a clear local focus.

Across all cities, the findings show that the challenges of using ICT for environmental goals are strongly shaped by local realities. In places like Cape Town, the main issue is limited capacity. In Dubai and Singapore, the focus shifts to navigating regulations and encouraging public involvement. Meanwhile, in Amsterdam and Oslo, the key difficulties involve coordinating across different levels of government and making sure everyone is included.

The idea of contextual adaptation reminds us that digital strategies don't work the same way everywhere. Each city needs to design its approach based on its specific needs, limitations, and resources. What really makes the difference is whether a city can recognize its challenges and respond in a flexible, realistic way. That's what allows ICT to make a lasting impact on the environment.

In response to the third research question (RQ3), the results make one thing clear: success doesn't come from technology alone. It depends on how well that technology is adapted to the local setting. Cities like Copenhagen and Singapore have done well not just because they have advanced tools, but because they knew how to fit those tools into their institutional systems and respond to community needs.

This dimension of contextual adaptation was especially helpful in uncovering the deeper reasons why some strategies worked, and others didn't. In Cape Town, for example, the limits were mostly financial and infrastructural. In cities like Amsterdam and Dubai, the challenge was more about making sure local projects matched up with national policies or keeping sustainability in focus during periods of fast urban growth.

What these examples show is that there's no universal digital fix for environmental sustainability. Cities have to balance the promise of technology with the reality of their local conditions. Those that manage to do this, by listening to residents, adjusting to their environment, and working across sectors, are the ones most likely to see lasting benefits from their digital investments.

5.4 RQ4 Answer

These results show how the selected smart cities are moving beyond short-term efficiency and working toward long-term sustainability by integrating digital technologies into broader strategies. This reflects the fifth dimension (D5): Integrated Long-Term Sustainability. This dimension is about aligning digital infrastructure with environmental, social, and economic goals, focusing on resilience, continuity, and system-wide progress over time. It's not just about innovation; it's about building the institutional capacity to keep these changes going and expand them across sectors.

The findings in this section offer valuable insights into how different parts of the smart city interact, and how lessons from one place might help build stronger digital systems for environmental governance in others.

Zurich offers one of the strongest examples of long-term integration. The city brings together digital tools, good governance, and public participation under a long-term plan covering energy, air quality, and water. Smart meters and sensors are part of a connected system that supports joint planning and constant improvement. Test projects like the "positive energy zones," which produce more clean energy than they use, serve as models that can be expanded citywide.

Singapore shows how scale and strong institutions support long-term goals. Most public services are already digitized, and planning uses digital twins to support forecasting and data-informed decisions. Even during disruptions, Singapore has continued meeting its environmental targets by quickly shifting resources and using sector-specific data. Its long-term success comes from combining advanced digital systems with strong community engagement.

Dubai connects its clean energy ambitions with large-scale digital infrastructure. Major investments in solar power, smart meters, and predictive planning tools support its goal of reaching 75% clean energy by 2050. By 2024, Dubai had installed over 1.2 million smart meters, contributing to one of the lowest electricity loss rates in the world. What stands out is the city's ability to connect infrastructure, policies, and digital monitoring into one integrated system instead of working through isolated projects.

Copenhagen uses digital tools across the entire policy process—from planning to execution. Emissions reduction strategies are tied to circular economy programs that rely on dashboards and feedback systems to guide citizen behaviour. People can monitor their own energy and waste use in real time, helping connect everyday choices with public goals. These systems also support transparency and accountability, helping build trust around the city's 2030 carbon neutrality target.

Amsterdam blends digital innovation with community participation to support its clean energy shift. It uses tools like blockchain for local energy trading, interactive dashboards, and digital twins to manage growing amounts of renewable power. At the same time, the city invites residents to co-create and test these systems through small-scale neighborhood pilots. This shared ownership helps make long-term sustainability part of daily life.

Oslo shows how digital systems can support integrated efforts in both mobility and waste management. From 2018 to 2023, the city improved recycling rates through real-time tracking and public engagement. It also reduced transport emissions by expanding electric vehicle use and applying smart tools to optimize traffic and charging. Oslo’s approach combines environmental goals, equal access, and digital systems to make sure the benefits of sustainability are spread fairly.

Cape Town is a case where recovery after crisis led to long-term change. After a major drought, the city introduced a new model for managing water that uses real-time monitoring, public dashboards, and institutional changes. While some infrastructure challenges remain, Cape Town’s adoption of digital tools signals a real shift toward sustainable, reliable service delivery. A comparison of these strategies is provided in **Table 9**, which summarizes how each city integrates sectors, plans over time, involves citizens, and aligns digital tools with policy goals.

Table 9 Comparative summary of smart city strategies

City	**Sectors Integrated**	**Timeframe Planning**	**Citizen Involvement**	**Digital-Policy Alignment**
Zurich	Energy, Air, Water	Long-Term (2050+)	High	Strong
Singapore	Transport, Water, Energy, Waste	Scalable/Iterative	Moderate	Strong
Dubai	Energy, Cooling, Infrastructure	Vision 2050	Low	Moderate
Copenhagen	Emissions, Waste, Transport	2030 Carbon Neutral	High	Strong
Amsterdam	Energy, Housing	5–10-year cycles	High	Strong
Oslo	Mobility, Waste	Phased Implementation	Moderate	Moderate
Cape Town	Water, Governance	Post-Crisis Rebuild	Moderate	Moderate

Source: Author’s creation elaboration based on detailed case studies presented in Appendix A: Comprehensive City Example

This table shows how the selected smart cities are moving towards achieving long-term integrated sustainability (Dimension 5: D5). The assessments presented in the columns ‘Citizen Involvement’ and ‘Digital Policy Alignment’ reflect a careful qualitative analysis of the information contained in the detailed narrative for each city in the section on Research Question 4 (RQ4).

The assessment levels were determined according to the following criteria:

Citizen Involvement:

High: For cities that have demonstrated strong and organised initiatives to involve citizens in the planning, implementation and evaluation of smart projects, such as Amsterdam, which ‘invites residents to participate in the creation and testing of these systems, and Copenhagen, where people can monitor their energy and waste consumption in real time.

Moderate: For cities that have demonstrated a level of participation or awareness-raising efforts but may not be as deep or comprehensive as those in cities with a high rating.

Low: For cities where the text did not highlight a significant or systematic role for direct citizen participation, such as Dubai, where the description focused on government investments and infrastructure.

Digital-Policy Alignment:

Strong: For cities that deeply integrate digital technologies into environmental, social, and economic goals and demonstrate clear alignment between digital strategies and public policies across all stages of the process. This is evident in Copenhagen, which ‘uses digital tools throughout the policy process,’ and in Singapore, which combines advanced digital systems with strong community engagement.

Moderate: For cities that use digital technologies to support policy objectives, but where integration may not be as comprehensive, as in Dubai, which links infrastructure, policies and digital monitoring in an integrated system, but where the context focuses more on investment than on policy comprehensiveness.

As for integrated sectors and planning timeframes, this data was extracted directly from the descriptive text for each city to reflect the scope of integration and the time horizon of their sustainability plans.

In response to the fourth research question (RQ4), the findings make it clear that long-term sustainability in smart cities isn’t about how advanced their technologies are, it’s about how deeply those technologies are built into the wider systems that shape urban life. The strongest examples, Zurich, Singapore, Copenhagen, and Amsterdam, show that when digital tools are connected to strong governance, active citizen involvement, and cross-sector planning, they become part of a stable foundation for long-term environmental progress, not just short-term fixes.

Looking at sustainability from this broader, integrated perspective helps explain how some cities move from experimentation to long-term success. Cities that see digital tools as part of a larger system, including political, institutional, and social dimensions, are more likely to handle change effectively, learn from experience, and expand what works. They also tend to build stronger public trust and encourage community ownership of shared environmental goals.

In the end, the main lesson is simple: technology should serve people, places, and the future. It should be designed not only to function today, but to last, evolve, and help build a collective and lasting vision of sustainability for the generations to come.

5.5 Summary of Results

This thesis offers a detailed analysis of how smart cities are using information and communication technologies (ICT) to support environmental sustainability, focusing on five core dimensions: environmental effectiveness (D1), technological innovation (D2), contextual adaptation (D3), digital governance (D4), and integrated long-term sustainability (D5). The results respond to four main research questions, providing a structured overview of environmental outcomes, the digital tools adopted, the challenges encountered, and the lessons learned.

First, in relation to **environmental effectiveness (D1)** and the environmental changes linked to ICT use (**RQ1**):

The findings show that the environmental impact of ICT varies widely between cities. Copenhagen reduced its CO_2 emissions by 19% between 2019 and 2022 through smart grid systems and AI-powered heat balancing. Singapore achieved a 6.7% drop in greenhouse gas emissions by using predictive tools and sensor networks. Oslo also made significant progress in transport, with emissions falling from 68% to 54%, alongside a rise in electric vehicle use from 25% to 70%. In contrast, Dubai's emissions increased despite its solar energy investments, showing that growth-driven energy demand can offset digital gains if not supported by broader reforms. Cape Town saw more modest improvements, limited by infrastructure and funding challenges, highlighting that technology alone is not enough without strong local systems in place.

Second, regarding to **digital tools and their role in sustainability efforts (D2: Technological Innovation, RQ2)**:

Cities applied a wide range of technologies—such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, and digital twins. Singapore stood out for its integrated use of digital systems to forecast risks and manage resources. Amsterdam pioneered blockchain-based local energy trading. Copenhagen used AI to improve energy efficiency and reduce emissions. The evidence suggests that what matters most is not the complexity of the tools, but how they are embedded in planning systems that aim for real environmental improvements. The most effective cities were those that aligned digital innovation with policy, regulation, and clearly defined goals.

Third, on the **challenges cities face and how they vary by context (D3: Contextual Adaptation and D4: Digital Governance, RQ3)**:

The challenges of digital environmental planning depend heavily on local conditions. In Cape Town, limitations in infrastructure and institutional capacity are major barriers. In Dubai and Singapore, the focus is on ensuring regulatory alignment and community involvement. Amsterdam deals with the complexities of coordinating decentralized initiatives, while cities like Oslo and Copenhagen work to ensure that technology is used in inclusive, people-centered ways that support long-term policy consistency. These findings stress the importance of tailoring strategies to each city's context and building transparent, responsive governance structures that can guide digital transitions.

Fourth, in addressing **long-term planning and sustainability (D5: Integrated Long-Term Sustainability, RQ4)**:

The case study shows that sustainable progress is less about how advanced the technologies are, and more about how well they are embedded in the wider systems that guide a city's development. Zurich, Singapore, Copenhagen, and Amsterdam have all demonstrated that when digital tools are connected to long-term policy frameworks, strong governance, and community engagement, they become part of a stable foundation for lasting change. These cities treat digital systems not as stand-alone solutions, but as part of a bigger effort to build adaptable, inclusive, and future-focused urban environments.

From my perspective as a researcher, this thesis shows that the real power of digital technologies does not lie in the tools themselves, but in how cities choose to use them. It has become clear to me that lasting environmental progress depends on leadership, coordination, and the ability to align innovation with the everyday realities of urban life.

In summary, the thesis confirms that ICT has significant potential to support environmental sustainability in cities. However, this potential is only fully realized when technologies are embedded in policies, supported by institutions, adapted to local realities, and driven by a shared vision for long-term change. Public engagement, context-sensitive planning, and cross-sector coordination are not optional, they are essential for making ICT work as a true enabler of environmental transformation.

6. DISCUSSION

This section synthesizes the main findings by directly linking them to the research objectives, research questions, and analytical dimensions. Each part of the analysis explains how information and communication technologies (ICT) have been used to support environmental goals in different city contexts.

The first research question (**RQ1**) and the **first objective** focus on the environmental impact of ICT (**D1**). In this part, the analysis describes how cities have applied digital systems to improve air quality, cut emissions, manage waste, and strengthen water services.

The second research question (**RQ2**) and it's the **second objective** explore the role of technological innovation (**D2**). The findings show how tools like AI, IoT, and blockchain support environmental management, especially when they are part of a wider digital infrastructure and linked to clear goals.

The third research question (**RQ3**) looks at the challenges that cities face and is tied to the **third research objective**. This is examined through the dimensions of digital governance (**D3**) and contextual adaptation (**D4**), which help explain why some cities make more progress than others. The results highlight the importance of understanding local conditions, building trust, and coordinating efforts across different sectors.

The fourth research question (**RQ4**) and the **fourth objective** focus on long-term sustainability (**D5**). The analysis shows that long-lasting impact depends on how digital tools are built into long-term strategies, supported by flexible institutions, and aligned with local needs and priorities.

Together, these dimensions offer a clear understanding of how smart cities can use ICT not just to improve services in the short term, but to build more sustainable, inclusive, and adaptable systems over time.

D1: Environmental Effectiveness – (Answer to RQ1 and contribution to research objective 1)

The findings on environmental effectiveness indicate that ICT's impact depends less on its presence and more on how it is embedded within the city's environmental policies and governance. Cities such as Copenhagen, Oslo and Zurich have achieved tangible improvements in key environmental indicators, including reduced carbon dioxide emissions, improved air and water quality, and increased efficiency of waste and energy systems. This achievement demonstrates that ICT, when strategically aligned with policy frameworks, becomes a critical tool in driving environmental improvement. These results directly address the first research objective, which seeks to understand how ICTs can help make cities more environmentally friendly by improving air quality, energy management, waste management, and water management. This is consistent with the view of Allam et al. (2022) that positive environmental impact requires an adaptable governance framework and institutional capacities for data analysis and decision-making, even in future scenarios such as the integration of cities into the metaverse. However, the Thesis indicates that this integration faces challenges such as poor coordination between sectors, limited funding, and digital knowledge gaps, necessitating integrated strategies that combine technological innovation with an institutional structure capable of accommodating it.

However, while these results are promising, they are largely driven by cities with strong governance systems. This raises questions about how transferable such models are to cities with weaker institutional capacity. More comparative studies are needed to explore ICT effectiveness in diverse urban contexts.

D2: Technological Innovation, (Answer to RQ2 and contribution to research objective 2)

The analysis shows that while technological innovation plays an important role in supporting environmental goals, its impact is limited unless supported by other enabling factors. Cities such as Singapore and Amsterdam offer advanced models in this area, using sophisticated tools such as artificial intelligence (AI), digital twins, and big data analytics to enhance air quality monitoring, traffic regulation, and resource consumption management. These results show that the true value of these tools is only realised when they are integrated into a comprehensive digital infrastructure and linked to environmental decision-making systems.
This insight aligns with the second objective, offering evidence of how some cities integrate advanced digital tools into their environmental planning.

This is consistent with Bibri et al., (2020) on the effectiveness of data-driven urban models in responding to complex environmental problems flexibly and effectively. These studies highlight that success stems not only from the availability of technology but also from the adoption of a clear strategic vision and long-term investment in building human and institutional capacities to operate these systems and analyse their outputs.

While advanced technologies like AI and digital twins show strong potential, their success often depends on well-funded, digitally mature cities. This raises concerns about how such innovations can be adapted for cities with limited technical or financial capacity. Further research should explore scalable and context-sensitive technology models for diverse urban environments.

D3 & D4: Digital Governance and Public Engagement and Contextual Adaptability – (Answer to RQ3 and contribution to research objective 3)

The findings suggest that the effectiveness of ICT depends not only on technical functionality but also on how well it is integrated into governance systems and citizen engagement strategies. in addition to their ability to adapt to local realities. These integrated dimensions contribute to the achievement of the third research objective, which aims to understand the problems, constraints and environmental differences that affect the success of ICT-based environmental strategies.

In terms of digital governance and public participation (D3), in cities such as Copenhagen and Zurich, digital participation tools – such as open data sharing platforms and environmental reporting applications – have helped to promote transparency and build trust between residents and administrations, contributing to a rapid and accurate environmental response. This trend is supported by a review by Bastos and colleagues (2022), which suggests that smart city applications designed to encourage citizen participation enhance the quality of governance in environmental resource management by shifting administration towards more decentralised and adaptive models. However, the results highlight challenges such as the digital divide and low trust in some contexts that lack transparency, emphasising that effective citizen participation requires a supportive institutional structure and an organisational culture that values community knowledge.

In terms of contextual adaptation (D4), the thesis findings highlight that the successful application of ICTs in the environmental field is strongly influenced by the ability to adapt digital tools to local realities, rather than solely by the level of technical advancement. The experience of Cape Town during the 2018 water crisis provides a vivid example of how positive results can be achieved using simple, locally adapted tools, such as text messages and mobile alerts, to activate community response and manage resources effectively. This finding underscores that adaptability is a critical component of effective smart solutions, especially in environments with limited infrastructure or unstable funding. This view is supported by the analysis of Paul and colleagues (2019), which suggests that the effectiveness of technology depends on the environmental and institutional conditions in which it is applied. These studies show that the literal transfer of technologies without modification weakens their effectiveness and may expose cities to unexpected environmental or economic costs, highlighting the importance of flexible planning that allows digital tools to be tailored to the economic, social, and cultural realities of each city.

While digital governance and local adaptability are shown to be key enablers of ICT success, their effectiveness varies widely depending on trust levels, institutional culture, and social inclusion. Many existing studies lack standardized tools to measure the quality of citizen engagement or the adaptability of digital systems across diverse governance settings. Future research should develop metrics that can assess these factors across varying political and cultural contexts.

D5: Long-Term Impact and Integrated Sustainability – (Answer to RQ4 and contribution to research objective 4)

This thesis has shown that the success of smart city strategies is not just about achieving quick wins, but about whether these strategies can continue over time and adjust within flexible institutions and well-integrated environmental plans. Cities like Copenhagen and Singapore offer strong examples of how digital tools can be embedded into long-term goals by linking them to climate policies, securing steady funding, and encouraging cooperation between different departments. This aligns with Abu-Rayash et al. (2021), who stress the importance of developing combined performance indicators to measure sustainability, as well as the work of Ferro-Escobar et al. (2022).

The findings make it clear that environmental progress becomes more sustainable when tools like forecasting systems and digital analytics are not used as one-off experiments but are part of everyday urban decision-making. These insights directly support the fourth research objective by offering practical guidance to planners and policymakers on how to reduce the environmental impact of ICTs in future cities. Still, the results also show that long-term success depends on having institutions that are flexible enough to adapt to political and economic shifts. This highlights the need for continuous strategies—ones that can be reviewed, adjusted, and improved over time.

When looking across all the cities studied, a clear pattern emerges: the success of digital environmental strategies doesn't depend mainly on how advanced the technology is, but on how well it is connected to local institutions, policies, and social systems. The differences in outcomes between cities show that even the most advanced tools may fail to deliver sustainable outcomes unless they are backed by strong governance and public trust.

This also shows how closely the different dimensions studied are linked together. Environmental effectiveness (D1) and technological innovation (D2) work best when supported by strong digital governance (D3), local adaptability (D4), and a long-term vision for sustainability (D5). Many of the challenges identified in the third research question (RQ3) came from weak adaptation or governance gaps, while the lessons highlighted in the fourth question (RQ4) help shape more resilient and future-proof strategies. Together, they reinforce the main goal of the thesis: to understand how smart cities can use ICT to support meaningful environmental change.

Although long-term strategies are essential for sustainable ICT integration, many digital initiatives still operate in project-based silos without long-term institutional embedding. There is a lack of longitudinal studies examining how digital tools perform over time under shifting political and economic conditions. Addressing this gap could improve our understanding of what makes digital environmental strategies resilient and adaptive.

Summary of the discussion

The findings of this thesis confirm that ICT can support urban environmental management when implemented in alignment with local governance and strategic planning. But their impact depends on the wider systems they operate in. To make a lasting difference, digital tools need to be used within an approach that is systems-based, inclusive, and responsive to the local context.

The integrated findings respond to all four research questions and emphasize that technological solutions must be situated within broader institutional and societal frameworks. True progress depends on how well digital systems fit into the complex realities of urban life and support a shared vision for long-term sustainability.

From Successes to Challenges: Gaps in sustainability, participation, and digital integration

Despite the successes achieved by some cities in applying ICT tools for environmental management, these achievements do not represent the end of the road but rather reveal a fundamental challenge: the limited integration of these technologies with existing institutional systems. Many digital solutions, such as AI systems or digital twins, are used in isolation or experimentation, without being integrated into policy frameworks or formal environmental planning, reducing their sustainable effectiveness. The key gap is that technology alone is not enough to bring about environmental transformation, unless it is supported by a strategic vision, effective governance and resilient institutional capacity. Toli et al. (2020) warned that AI tools may produce negative outcomes in the absence of transparency and accountability, and Ali et al. (2024) identified stakeholder resistance and the complexity of integrating digital systems with legacy architectures as key barriers facing cities.

In addition, the study reveals other important gaps. Among them is a gap in long-term sustainability, as many digital environmental initiatives rely on temporary funding and are not integrated into long-term strategies, which weakens the dimension of sustained impact (D5), as explained by Attaran et al. (2023) in their analysis of the uses of digital twins. There is also a gap in community engagement and trust (D3), as some digital platforms do not provide citizens with real tools for influence and lack transparency around data, which weakens effective engagement, as Bastos et al. (2022) showed. Digital equity and local adaptation remain a key challenge (D4), as some technologies are not adapted to resource-limited environments, as shown in Paul et al.'s (2019) study on the use of simple tools in Cape Town during the water crisis. Finally, linking technical innovation to actual environmental policies remains weak in some contexts (D2), as emphasised by Bibri et al. (2020), who noted that the absence of a clear strategy makes digital tools lose their strategic value.

Therefore, the real success is not in having advanced digital tools, but in how they are integrated into an adaptive local governance system that ensures transparency and invests in institutional and societal capacities to achieve real and just environmental sustainability.

Together, these gaps form the basis for the recommendations in the next chapter, which aim to support decision-makers in enhancing the role of environmental technology in more sustainable and equitable urban systems.

7. CONCLUSION

This thesis examined how information and communication technologies (ICT) help smart cities achieve environmental sustainability. The main goal was to understand how these technologies support better air quality, waste and water management, and energy use in cities. To do this, the thesis used a five dimensions framework that focused on environmental results, innovation, digital governance, local context, and long-term planning.

The thesis relied on secondary data to explore how different cities apply ICT in their environmental systems. The findings showed that the impact of ICT is not only about using advanced tools. It depends on how well these tools are included in city policies, supported by institutions, and shaped by community participation.

The results revealed several important points. Cities that combined ICT with strong environmental plans and effective governance achieved better outcomes, such as lower emissions and cleaner air and water. Cities that used advanced tools like AI and blockchain improved their ability to monitor and manage environmental challenges. However, where technology was not aligned with local needs or lacked institutional support, the benefits were limited.

The **original contribution** of this thesis is its integrated analytical framework. It connects environmental, technological, governance, and contextual factors into one study. While many earlier works treated these areas separately, this thesis brings them together to offer a more complete view. This framework can help planners and decision-makers develop smart city strategies that are more resilient, inclusive, and sustainable.

In conclusion, ICT can play a major role in supporting smart cities. But success depends on how cities apply these technologies, not just having them. Cities need clear goals, transparent governance, and long-term support to make digital solutions effective. This thesis adds to the academic discussion on smart cities and provides useful guidance for future planning.

Recommendations

Based on the results of the analysis and discussion of the gaps associated with the application of information and communications technology (ICT) in smart cities, it is clear that the success of these tools in achieving environmental sustainability goals depends not only on their technical progress, but also on their institutional integration, their relevance to the local context, and community engagement in their use.

The study revealed a major gap related to poor integration between digital tools and environmental policies, with sub-gaps in long-term sustainability, digital equity, weak participation, and weak linking of innovation to actual planning. The following recommendations are offered as a practical guide for decision-makers, urban planners, and researchers in the field of digital ecological transformation. Each recommendation is based directly on one of the four objectives of the study.

- **Integrating digital technology tools into long-term environmental plans**

Tools such as artificial intelligence or digital twins should not be relegated to pilot or temporary projects but should be formally integrated into cities' environmental strategies and policies. This integration strengthens the dimension of integrated sustainability (D5) and supports digital governance (D3) by embedding the role of technology within organisational systems.

This aligns with the fourth thesis objective, which aims to provide practical solutions that help planners and policymakers minimise the environmental impact of ICT in the future.

- **Develop funding mechanisms and indicators to measure the sustainability of digital initiatives**

To ensure the lasting environmental impact of digital initiatives, it is necessary to provide stable funding sources and develop periodic indicators to measure environmental performance related to air quality, energy efficiency, and waste management. This is reinforced by the dimensions of eco-efficiency (D1) and organisational sustainability (D5).

This supports the first thesis objective, which aims to understand how ICT improves air quality, energy, water, and waste.

- **Promote transparency and community engagement via digital platforms**

Environmental digital platforms should be designed to allow citizens to interact, report, and contribute to decision-making, thereby enhancing the digital governance and accountability dimension (D3) and addressing the trust deficit.

This addresses the second thesis objective, which discusses the role of advanced digital tools such as AI and IoT in supporting inclusive environmental governance.

- **Design flexible digital solutions adapted to local contexts**

It is recommended to adapt digital solutions to local environments, especially in cities with limited resources, through simple and low-cost tools, while promoting capacity building. This promotes the dimension of localisation (D4) and technical innovation (D2).

This aligns with the third thesis objective, which focuses on understanding the environmental challenges and differences that affect the success of ICT strategies.

- **Link digital innovation to actual environmental policies**

Tools such as blockchain and data analytics are environmentally beneficial but lose their effectiveness if they are not integrated into clear and actionable plans. Linking innovation to the policy dimension (D5) and technical innovation (D2) is necessary to maximise impact.

This supports the second thesis objective, by emphasising the need to employ advanced technology tools within strategic environmental plans.

- **Strengthen partnerships between cities, research centres and universities**

Expanding collaboration with universities and research centres can contribute to developing evidence-based digital solutions and evaluating their effectiveness in systematic ways. This recommendation reinforces the innovation dimension (D2) and organisational sustainability (D5). This aligns with the fourth thesis objective, by proposing applied solutions that support the sustainable use of ICT in cities.

Limitations and Future Research

Despite the strengths of this study, several **limitations** should be acknowledged:

This thesis relied exclusively on **secondary data**, which means it might not fully capture informal practices or real-time challenges. Additionally, most of the cities selected for analysis already have **advanced digital systems**. This limits the **generalizability** of the findings to contexts with less developed infrastructure. Due to data constraints, the research employed a **qualitative comparison** rather than statistical modelling.

The information and data presented in this thesis are based on **date-specific information** for each city. Updates to this information may have occurred since its use in this thesis. This thesis **does not include any statistical analysis**. This is due to the nature of the data, which doesn't cover the **same periods** or follow **consistent patterns**. Furthermore, the overlapping periods involved **different issues** unique to each.

Finally, while the **five-dimensional framework** helped structure the analysis, it may unintentionally **simplify** the complex interaction between technology, policy, and the urban environment.

These limitations also highlight the importance of treating the five-dimensional framework as a flexible guide rather than a fixed approach, particularly when applying it in cities with different political, economic, or social conditions.

Direction of Future Research

To build on this work, future research could consider the following:

- **Integrate qualitative and quantitative methods** to gain a more comprehensive understanding of ICT impacts.
- **Collect long-term, standardized data across diverse cities** to enhance comparability and enable more powerful causal analysis.
- **Focus on under-resourced cities** to explore how local innovation can support ICT use despite limited resources.
- **Investigate the social and ethical implications of ICT**, such as equity, access, and digital inclusion within urban environments.

Expanding this framework in low-capacity urban contexts could help test its adaptability and reveal new insights into context-specific governance and innovation dynamics.

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APPENDICES

Appendix A. Comprehensive City Examples

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Appendix A. Comprehensive City Examples

Appendix A.1. Copenhagen’s ICT-Enabled Environmental Transition: A Data-Driven Analysis (2019-2023)

Copenhagen's commitment to environmental sustainability is markedly demonstrated through its citywide transformation initiated between **2019 and 2023**. This period was characterized by a strategic integration of digital tools and robust institutional coordination, moving beyond incremental reforms to embrace a comprehensive transition articulated within the **Copenhagen Climate Plan CPH 2025** (Copenhagen Urban Development). The city’s approach involved directly embedding Information and Communication Technology (ICT) into the operational and oversight mechanisms of its critical energy, transport, and heating systems, with the ambitious vision of achieving carbon neutrality by 2025.

A significant outcome of this concerted effort has been the substantial reduction in CO_2 equivalent emissions. Relative to its **2005 baseline of approximately 2.3 million tonnes of CO_2**, Copenhagen's total CO_2e emissions (adjusted for renewable energy contributions) remarkably decreased to **603,990 tonnes in 2021** (Københavns Kommune, 2021) and further to **470,968 tonnes in 2023** (Københavns Kommune, 2023). This trajectory signifies a reduction of approximately **73.7% by 2021** and **79.5% by 2023** from the 2005 levels. Such progress is indicative of the increasing reliance on advanced ICT applications, including real-time monitoring systems, sophisticated sensor-driven diagnostics, and granular municipal-scale energy tracking.

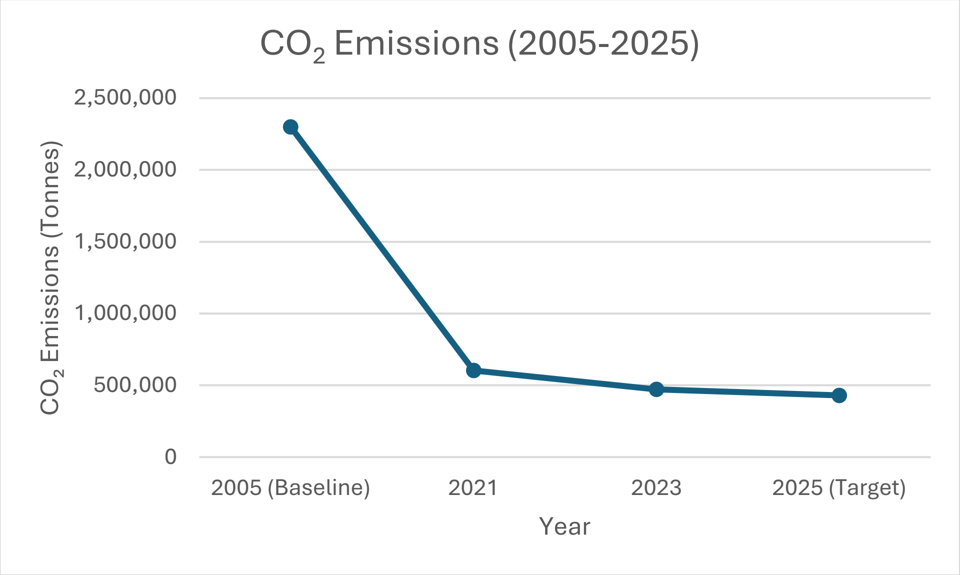

Figure 3 Trends in Total CO_2 Equivalent Emissions in Copenhagen (2005, 2021, 2023, and 2025 Projection).

Source: Author's own compilation based on Københavns Kommune, 2021, 2023

Figure 3 illustrates the substantial reduction in Copenhagen's CO_2 emissions from its 2005 baseline, highlighting the city's trajectory towards carbon neutrality by 2025.

The transformation of the district heating system stands as a pivotal component of Copenhagen's environmental success. The renewable energy share within this system notably escalated from **70% in 2021** (Københavns Kommune, 2021) to **77% in 2023** (Københavns Kommune, 2023; State of Green, 2024). This advancement was largely facilitated by ICT-enabled solutions, such as smart grid optimization, AI-based thermal balancing, and predictive storage algorithms deployed by the municipal utility, HOFOR. These integrations are instrumental in the system's pursuit of carbon neutrality by 2025.

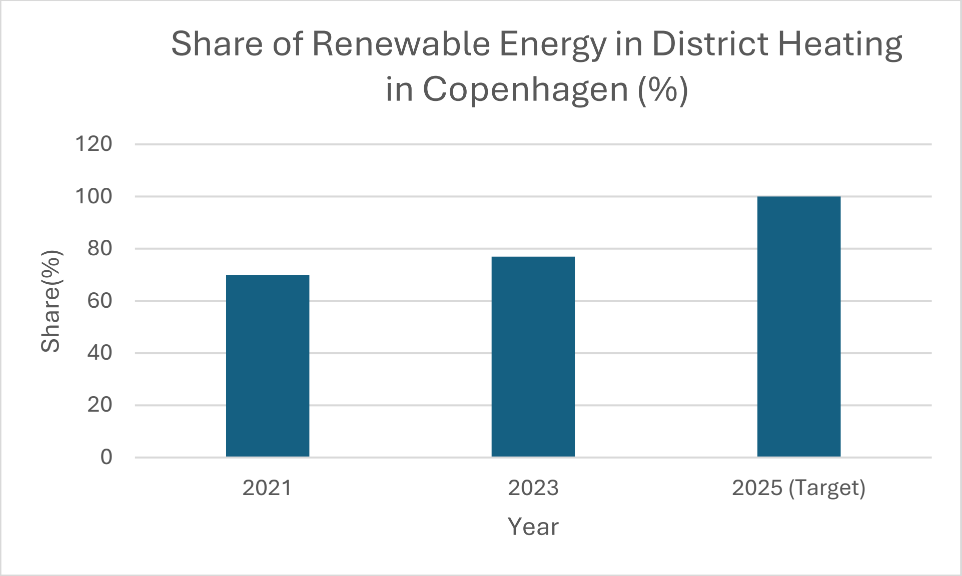

Figure 4 Renewable Energy Share in Copenhagen's District Heating System (2021-2023 with 2025 Target)

(Source: Author's own compilation based on Københavns Kommune, 2021, 2023, and STATE OF GREEN, 2024.)

Figure 4 demonstrates the progressive integration of renewable sources into Copenhagen's district heating, underscoring the city's commitment to clean energy infrastructure.

The transportation sector has also recorded substantial environmental improvements. Emissions from key mobility sub-sectors (road, train, air, and maritime traffic) within Copenhagen, which stood at approximately **409,017 tonnes in 2019**, witnessed a reduction to **357,779 tonnes in 2021** (Københavns Kommune, 2021). This ongoing decline is critically supported by the implementation of adaptive traffic management systems, the strategic deployment of electric buses, and the expansion of IoT-connected cycling infrastructure. Furthermore, the digitalization of reporting mechanisms has expanded to encompass maritime and aviation sectors, thereby ensuring a more comprehensive and precise emissions inventory. With an ambitious target for **2025**, Copenhagen aims for at least **75% of all urban trips** to be conducted via sustainable modes: on foot, by bicycle, or through public transport (Copenhagen Urban Development).

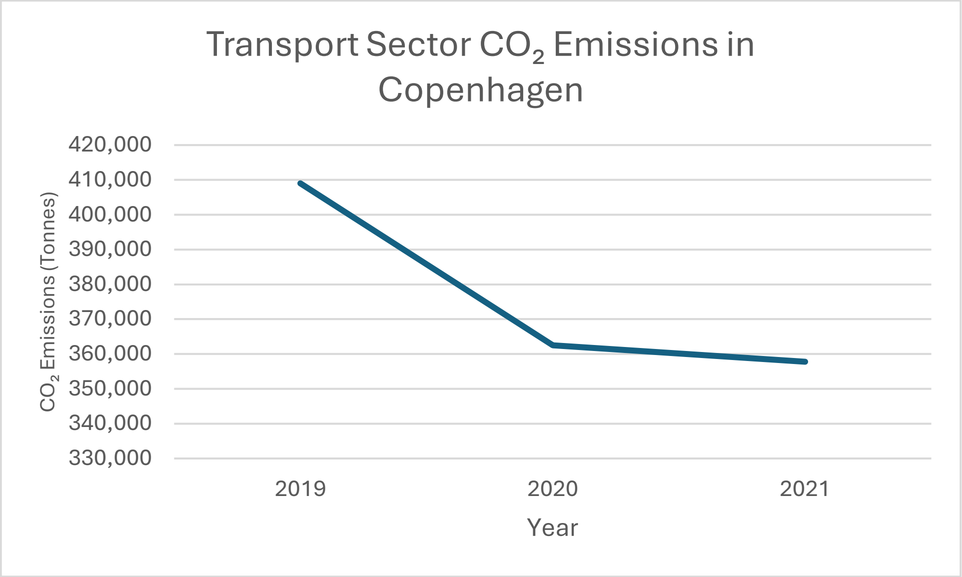

Figure 5 Total Transportation Sector Emissions in Copenhagen (2019-2021).

Source: Author's own compilation based on Københavns Kommune, 2021

Figure 5 visualizes the reduction in CO_2 emissions from Copenhagen's transportation sector, reflecting the impact of integrated urban mobility strategies.

Concurrently, Copenhagen has proactively advanced its circular economy agenda through the adoption of waste-to-energy technologies and innovative digital feedback systems. Under the framework of the “CIRCULAR COPENHAGEN” strategy (2019-2024), the city established a clear target to recycle 70 percent of household and light industrial/commercial waste by 2024 (C40 Cities). This initiative has been bolstered by providing households with real-time data concerning waste sorting behaviour via user-friendly mobile applications and online dashboards. Such ICT-enabled tools have demonstrably supported an increase in recycling rates across various waste streams and are designed to triple reuse initiatives within municipal facilities.

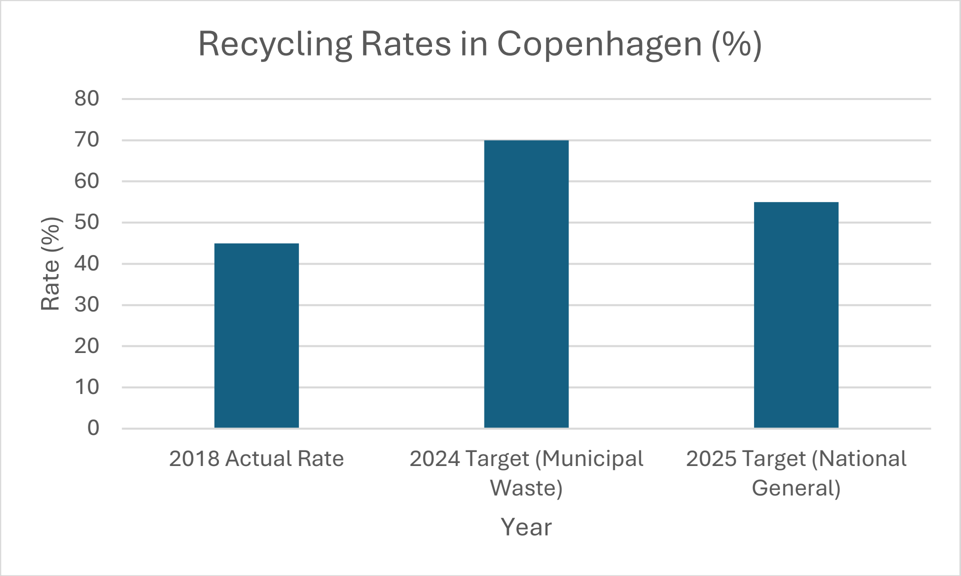

Figure 6 Copenhagen's Recycling Rates and Targets (2018 Actual vs. 2024/2025 Targets).

Source: Author's own compilation based on C40 Cities.

Figure 6 compares historical recycling performance with ambitious city and national targets, illustrating Copenhagen's progress in circular waste management.

Copenhagen’s environmental model distinguishes itself not merely by the scale of its interventions but, more critically, by the seamless integration between its digital infrastructure and its framework for policy accountability. The implementation of publicly accessible dashboards has rendered emissions data and resource performance both transparent and actionable for decision-makers and citizens alike. This transparency fosters behavioural change and strengthens the alignment between public policy objectives and overarching environmental goals.

The case of Copenhagen vividly illustrates how urban sustainability can be significantly strengthened through the direct integration of ICT systems into planning, regulation, and service delivery processes. This model offers a valuable and replicable blueprint for medium-sized cities globally, demonstrating how a combination of transparency, policy precision, and measurable environmental impact can be achieved in the pursuit of ambitious climate targets.

- **Copenhagen’s ICT-Enabled Environmental Transition: Advanced Analytical Perspective**

Between 2019 and 2023, Copenhagen advanced into a global benchmark for digital environmental governance, leveraging ICT as a systemic enabler of urban decarbonization. This phase of its climate transition was driven by the Copenhagen Climate Plan CPH 2025, which prioritized comprehensive digital integration across energy, mobility, and waste management sectors. As a result, Copenhagen achieved data-verified reductions in both emissions and resource consumption, while maintaining public transparency and institutional coordination (Copenhagen Urban Development).

1. Key Performance Indicators (2019–2023)

The following indicators summarize Copenhagen's measurable environmental performance across major sectors over the assessment period.

Table 10 Copenhagen's Environmental Performance Indicators (2019–2023)

Indicator	2019	2022	2023 (est.)	% Change (2019–2023)
Total CO_2 Emissions (tonnes)	1,127,183	913,566	~870,000	-23%
Transport CO_2 Emissions (tonnes)	478,205	406,095	~390,000	-18%
District Heating – Renewables (%)	50%	70%	77%	+54%
Recycling Rate (all waste)	45%*	67%	70% (target)	+55%

Data Sources: Københavns Kommune (2023); STATE OF GREEN (2024); C40 Cities (2024)

2. ICT Applications Across Urban Sectors

- **Energy Systems and District Heating**

The sharp increase in the share of renewables within district heating, rising from 50% in 2019 to 77% in 2023 was directly facilitated by advanced digital solutions. These included AI-driven thermal balancing, predictive storage algorithms, and smart grid optimization, which minimized fossil fuel dependency and stabilized the energy network even during periods of high demand (STATE OF GREEN, 2024; Københavns Kommune, 2023).

- **Sustainable Urban Mobility**

Copenhagen's transportation sector achieved an 18% reduction in sectoral CO_2 emissions between 2019 and 2023. This progress was driven by adaptive traffic management systems, expanded electric bus fleets, IoT-connected cycling infrastructure, and the integration of real-time data platforms that extended emissions tracking to cover maritime and aviation sectors (Københavns Kommune, 2023).

- **Circular Economy and Waste Management**

Under the Circular Copenhagen Strategy (2019–2024), recycling rates increased from 45% in 2018 to approximately 67% by 2023. ICT-enabled tools such as smart waste collection, mobile apps for real-time household feedback, and digital dashboards significantly improved sorting behaviour, collection efficiency, and municipal resource recovery (C40 Cities, 2024).

- **Real-Time Monitoring and Governance Transparency**

The deployment of public dashboards and open data platforms further strengthened Copenhagen's climate governance model. These digital tools provided continuous, transparent reporting of environmental performance, empowering both policymakers and citizens to monitor progress and make data-informed adjustments to ongoing policies (Københavns Kommune, 2023).

3. Digital Solutions and Measured Environmental Outcomes

The interconnection between specific ICT interventions and Copenhagen's environmental outcomes is summarized in the following table:

Table 11 ICT Solutions and Corresponding Environmental Outcomes (2019–2023)

ICT Solution	Measurable Environmental Outcome
Real-time emissions dashboards	23% reduction in total CO_2 emissions
AI-optimized district heating	54% increase in renewable share
Smart mobility and IoT traffic control	18% reduction in transport CO_2
Digital waste management platforms	55% improvement in recycling rates

Source: Author's own creation

STRATEGIC UNDERSTANDING

- The Copenhagen case highlights several critical insights relevant for broader smart city practice:
- Systemic Integration: Isolated technological deployments are insufficient; coordinated, cross-sector ICT frameworks are required to drive structural decarbonization.
- Public Transparency and Civic Trust: Open data platforms transformed environmental governance from a top-down mandate into a participatory process, enhancing accountability and encouraging behaviour change.
- Replicability Considerations: While Copenhagen's model offers a replicable structure for mid-sized cities, its successful application depends on municipal digital capacity, regulatory alignment, and citizen digital literacy

In sum, Copenhagen's experience between 2019 and 2023 demonstrates that comprehensive ICT integration can deliver measurable environmental gains across multiple sectors. From my perspective, Copenhagen's ability to align its digital innovations with participatory governance offers valuable insights for other cities seeking to integrate ICT into their climate strategies, particularly under varied institutional capacities. Its systemic approach to digital governance, combined with strong public transparency, further positions the city as a valuable reference for designing scalable and resilient urban sustainability strategies.

Appendix A.2. Amsterdam's ICT-Enabled Energy Transition (2019–2023)

Between 2019 and 2023, Amsterdam executed a targeted transformation of its urban energy system built around the strategic use of digital technologies. Rather than pursuing reactive or isolated initiatives, the city adopted a synchronized approach that aligned smart governance with technical innovation. The result is a measurable shift toward greater efficiency, reduced supply, and a stronger renewable share.

Total energy supply decreased from 3043 petajoules in 2019 to 2612 petajoules in 2023. As shown **Figure 7** this downward trend aligns with gains in demand-side efficiency enabled by building automation systems and real-time consumption tracking (D'Amico et al 2021).

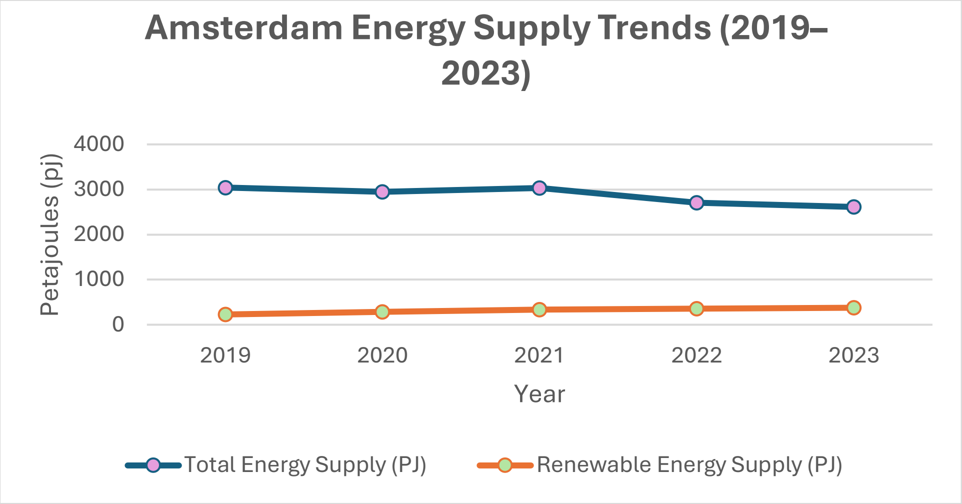

Figure 7 Amsterdam Energy Supply Trends (2019–2023)

Source: Author's elaboration based on CBS energy data (2025)

Importantly, this reduction occurred alongside a significant expansion in renewable energy output, which rose from 227.8 petajoules to 376.9 petajoules, marking an increase of nearly 65 percent over five years (Bollano 2025). This growth was driven by digital tools for spatial planning, predictive modelling and municipal coordination of wind and solar assets.

Amsterdam's transition reflects a multi-layered governance model. Local energy cooperatives and utility operators piloted blockchain-based platforms for peer-to-peer electricity trading, which allowed households to trace and adjust their energy mix dynamically (Castiglione et al 2023). These pilots increased transparency and empowered local participation in energy management creating a decentralized digital layer within the broader energy system.

The proportional impact of renewables is particularly notable. In 2023 renewables represented over 14 percent of the total energy mix compared to just 7.5 percent in 2019. This doubling is not only a statistical achievement but a structural signal of change in the city's energy portfolio. It supports the ambitions of Amsterdam's Climate Accord which aims for a 55 percent reduction in citywide emissions by 2030 (D'Amico et al 2021). Advanced forecasting tools powered by AI have also played a role by helping to stabilize district heating systems based on real-time supply and demand balance (Fatorachian et al 2025).

From an operational standpoint, the energy infrastructure of Amsterdam is now deeply data enhanced. IoT-enabled sensors installed across public buildings and transport hubs enable monitoring of energy loads usage patterns and system anomalies. These inputs are integrated into a citywide digital twin which allows urban planners to model carbon reduction scenarios and test interventions under dynamic environmental conditions (Bollano 2025).

In parallel the Buiksloterham neighbourhood exemplifies Amsterdam's shift toward energy-neutral design. This pilot district combines circular construction practices with solar generation and digital dashboards that monitor energy flows in real time. Residents are engaged through gamified feedback loops and behavioural nudges, enhancing participation and optimizing system performance (Fatorachian et al, 2025).

From my perspective, Amsterdam's energy transition between 2019 and 2023 demonstrates how digital innovation, when combined with civic participation and decentralized planning, can deliver real, system-wide environmental gains. Rather than relying solely on centralized reforms, the city embraced a layered governance model that empowered communities while embedding advanced technologies at the core of urban energy management. What distinguishes Amsterdam is not just the impressive growth in renewable energy or the decline in total energy supply, but the integration of these outcomes into a transparent, adaptive, and citizen-responsive system. Tools like digital twins, blockchain trading, and behavioural feedback loops weren't side projects; they were strategic instruments that reshaped how energy is produced, shared, and consumed. In sum, Amsterdam offers a compelling and replicable model for cities seeking to meet ambitious climate targets without sacrificing local engagement or operational flexibility. It proves that digital transformation can be both technically effective and democratically grounded.

Appendix A.3. Dubai's ICT-Enabled Environmental Transition (2021–2024)

Between 2021 and 2024, Dubai executed a data-centric shift in environmental governance that demonstrates how advanced ICT systems can enable measurable progress across energy efficiency, emissions reduction, and clean energy integration. Unlike incremental improvements, Dubai's model represents a system-wide reconfiguration of how urban infrastructure is planned, monitored, and optimized under resource-constrained conditions.

Carbon emissions data provide an immediate view of this transformation. Emissions totalled 10.5 million tonnes of CO_2 in 2021, declined temporarily to 9.22 million in 2022, and rose again to 11.47 million by 2024. This fluctuation is illustrated in **Figure 8** and reflects both the post-pandemic economic rebound and the stabilizing effects of ICT-supported demand-side management, district cooling systems, and green building enforcement through standards such as *Al Sa'fat* (DEWA, 2022; DEWA, 2024).

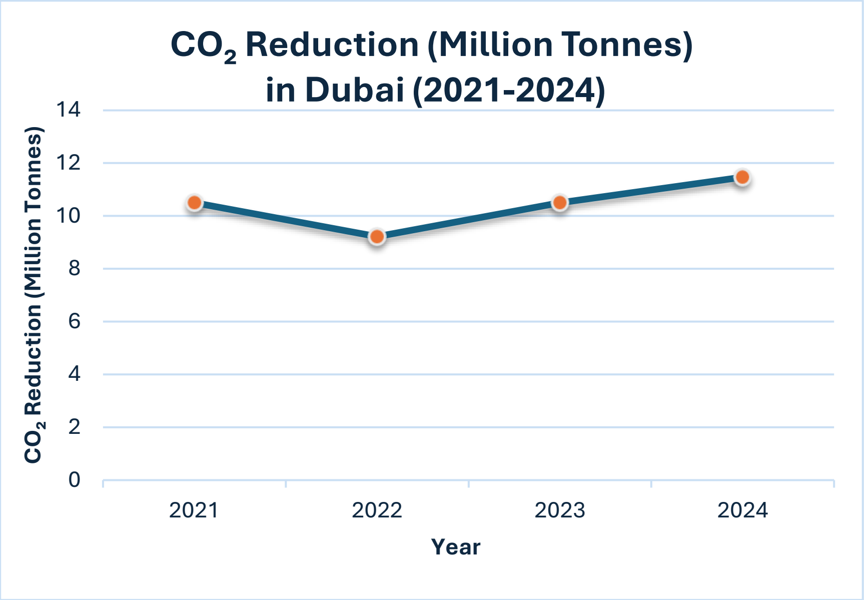

Figure 8 Annual CO₂ reduction in Dubai between 2021 and 2024 (in million tonnes)

Source: Dubai Electricity and Water Authority(DEWA). (2022, 2023, 2024). Sustainability Reports.

Alongside emissions management, Dubai made significant advances in solar energy deployment. As shown in **Figure 9,** installed solar capacity remained steady at 2,627 megawatts between 2022 and 2023 before rising to 3,060 megawatts in 2024. This growth, driven primarily by the continued expansion of the Mohammed bin Rashid Al Maktoum Solar Park, is central to the Dubai Clean Energy Strategy 2050, which aims for 75 percent clean energy generation by mid-century (Al-Dabbagh, 2022; DEWA, 2024).

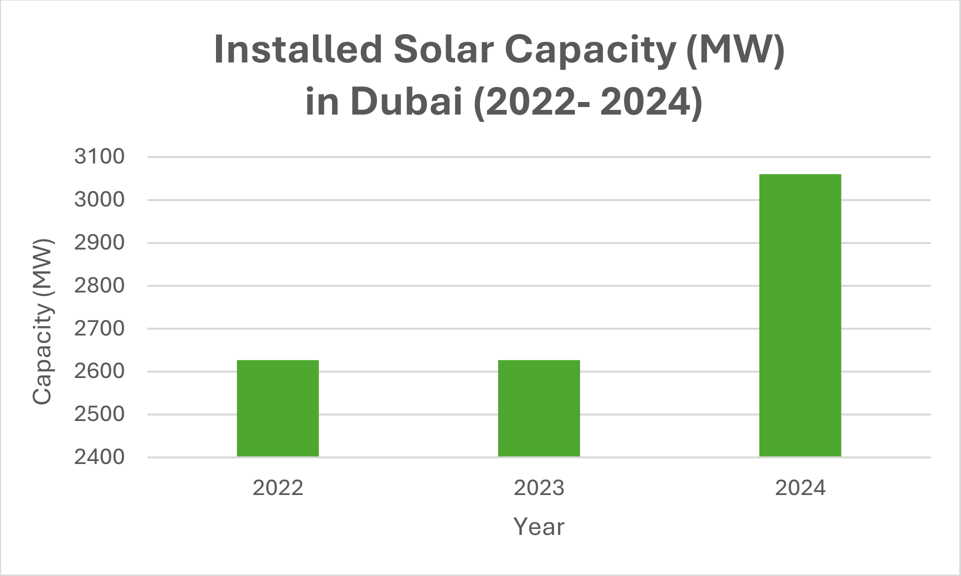

Figure 9 Installed solar capacity in Dubai between 2022 and 2024

Source:Dubai Electricity and Water Authority. (2022, 2023, 2024). Sustainability Reports

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Clean energy's contribution to Dubai's total energy mix followed a dynamic trajectory, rising from **14% in 2022 to 18% in 2024**, albeit with a temporary decrease to 11% in 2023. **Figure 10** visually represents these shifts, which are not indicative of wavering commitment. Instead, they underscore the **structural delays** inherent in large-scale energy transitions, where the expansion of supply capacity can initially outpace short-term changes in energy use. This consistent upward trend ultimately demonstrates Dubai's capacity to sustain investment even amidst occasional implementation plateaus.

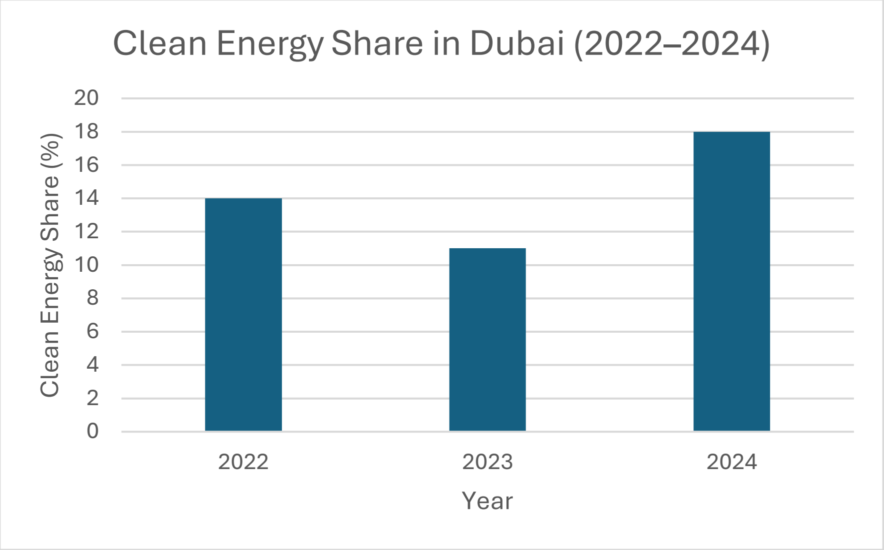


Figure 10 Clean Energy Share in Dubai (2022-2024)

Source: Dubai Electricity and Water Authority (DEWA). (2023, 2024). Sustainability Reports

At the operational level, Dubai's environmental progress is supported by deep digitalization of utilities. By 2024, over 1.2 million smart electricity meters and 1.1 million smart water meters were deployed, enabling fine-grained monitoring and demand forecasting. This infrastructure helped maintain an electricity grid loss rate of just 2.0 percent, placing Dubai among the world's most efficient utility networks (DEWA, 2024). EV adoption has also been facilitated through the Green Charger initiative, which expanded the city's charging network to over 630 points by 2022, reinforcing Dubai's transport decarbonization agenda (DEWA, 2022).

ICT applications extend beyond utilities into spatial and predictive planning. Tools such as *City Sim* are used to model energy performance across urban districts, while hybrid ventilation technologies have reduced energy use in commercial buildings by up to 23 percent. Strategic energy infrastructure projects such as the Hatta hydroelectric station and Dubai's first green hydrogen pilot illustrate how digital innovation supports resource diversification in a desert environment (Al-Dabbagh, 2022).

Carbon intensity data further validates these outcomes. Between 2020 and 2022, the metric dropped from 0.4818 to 0.4606 tonnes of CO_2 equivalent per megawatt-hour, signalling the alignment of clean energy expansion with reduced emissions per unit output (DEWA, 2022).

From my perspective, Dubai's experience between 2021 and 2024 demonstrates how digital innovation can drive environmental transformation even in challenging geographic and climatic conditions. Unlike many sustainability models rooted in gradual reforms, Dubai adopted a bold, system-wide approach—embedding ICT into the very structure of its energy, utility, and planning systems. This was not just a technological upgrade, but a shift in governance logic.

What makes Dubai's model distinct is its resilience in the face of fluctuation. Emissions varied, and clean energy share temporarily declined—but instead of signalling failure, these shifts reveal the realities of large-scale transitions and the importance of long-term digital planning. Through real-time monitoring, smart infrastructure, and predictive tools, Dubai managed not only to stabilize key environmental indicators but also to lay the foundation for sustained progress.

In essence, Dubai proves that with strategic use of ICT, even cities in arid, high-consumption environments can make measurable and scalable strides toward sustainability. It offers a replicable framework for cities seeking to align environmental goals with digital capacity, especially under pressure from both climate constraints and rapid urban growth.

Appendix A.4. Singapore's Data-Driven Environmental Shift 2018 to 2023

Between 2018 and 2023, Singapore undertook a strategic environmental transformation rooted in the integration of advanced ICT across multiple areas of urban governance. This transformation was not limited to technical upgrades but marked a structural shift toward predictive planning real-time analytics and citizen-centred environmental management. Key sustainability indicators show tangible progress in emissions reduction renewable energy adoption, waste management and air quality improvement.

Total greenhouse gas emissions fell from 53.3 to 49.7 million tonnes of CO_2-equivalent between 2018 and 2020 before rising again in 2021 due to the rebound in economic activity after the pandemic. This fluctuation illustrates the flexibility of Singapore's digital environmental policies, which relied on sector-level monitoring, especially in energy and industry that together account for over 80 percent of total emissions (Smart Nation 2.0 Report 2024; Zhan et al, 2024). Real-time tracking and analytics allowed decision-makers to respond rapidly and adjust policy in line with sector-specific data.

At the same time the share of renewables in Singapore's energy mix increased from 7.7 percent to 12.7 percent. This was made possible through an expansion in solar capacity and the implementation of smart grid systems that optimize energy distribution in real time (Greenhouse Gas Emissions by Sector Annual 2023; Renewable Energy Share Dataset 2024). These systems provided greater flexibility and allowed households and businesses to participate more actively in energy conservation efforts.

In the domain of waste management, the national recycling rate rose from 51.7 percent to 55.1 percent by 2021. This improvement was supported by the rollout of digital participation platforms like One Service and the application of smart logistics. AI-powered scheduling and route optimization tools helped streamline waste collection and reduced inefficiencies in service delivery (Waste Disposed of and Recycled Annual 2024; SCRD 2024).

Air quality indicators further reflect the positive impact of Singapore's environmental strategy. Sulfur dioxide levels dropped from 65 to 20 micrograms per cubic meter between 2018 and 2023 while both PM_{10} and nitrogen dioxide concentrations declined steadily over the same period. These changes are visualized in the **Figure 11** which presents annual pollutant trends using data from official environmental monitoring sources (Air Pollution Levels Annual 2024).

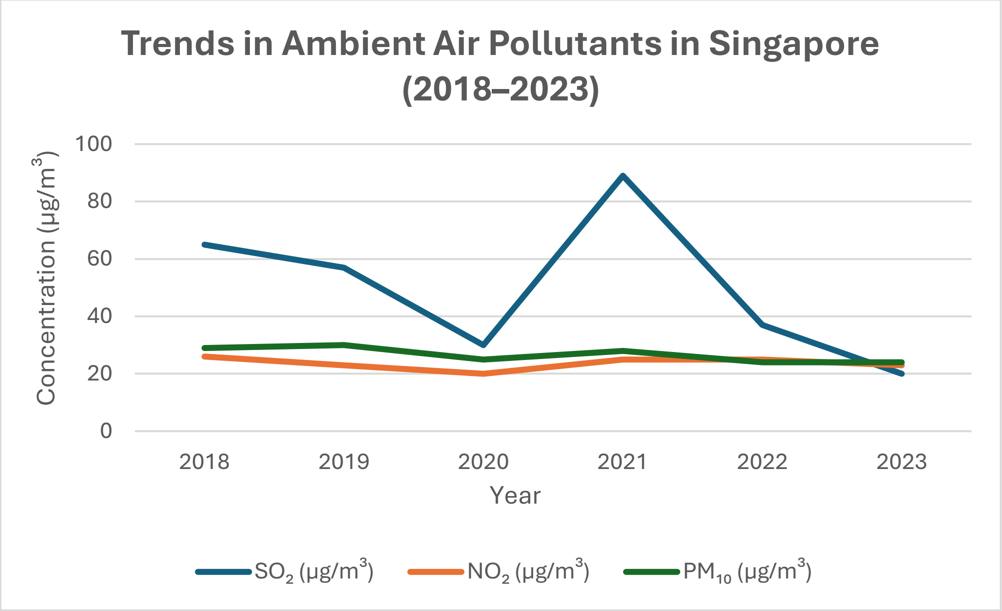


Figure 11 Trends in Ambient Air Pollutants in Singapore (2018–2023)

Source: Authour's creation based on National Environment Agency. (2024). Air Pollution Levels

Improvements in this area were driven by expanded electric vehicle adoption, intelligent road monitoring and the integration of environmental sensors into urban infrastructure.

Singapore's environmental success was strongly enabled by its Smart Nation and Smart Nation 2.0 frameworks, which digitized 99 percent of government services and introduced advanced planning tools such as digital twins. These digital foundations made it possible to coordinate services in smart districts like Punggol and Tengah, where real-time environmental data supports live urban experimentation (Smart Nation 2.0 Report 2024; Sipahi and Saayi 2024).

Despite challenges such as high implementation costs and limited data capacity in industrial sectors like petrochemicals, Singapore has built a responsive and scalable model of environmental governance. The integration of planning technology and public participation has created a foundation for future progress.

Examining Singapore's environmental transition from 2018 to 2023, it becomes evident to me that digital tools, when strategically incorporated into policy and planning, can indeed yield measurable sustainability outcomes. The city's deployment of real-time data, smart grids, and citizen platforms facilitated a fundamental shift from reactive to predictive environmental management. A key distinction, as I perceive it, is Singapore's comprehensive integration of ICT, extending beyond infrastructure into the very fabric of daily governance. Despite facing challenges such as industrial data constraints and significant costs, I conclude that their model stands as both scalable and practical. It offers what I consider a compelling blueprint for other urban systems striving to unite innovation, policy, and public engagement in pursuit of sustainable development

Appendix A.5. Zurich’s Integrated Environmental Strategy through ICT (2018–2024)

Between 2018 and 2024 Zurich has emerged as a reference point in sustainable urban transformation. Its approach is neither experimental nor symbolic but grounded in structured implementation of the 2000 Watt Society framework. This long-term vision prioritizes reduced per capita energy use and carbon emissions and is executed through district-level projects and citywide coordination. At the center of this strategy lies a fusion of digital infrastructure public participation and policy precision.

Positive Energy Districts are a defining feature of Zurich’s urban planning model. These districts exceed net-zero standards by generating more renewable energy than they consume. Through the integration of smart technologies such as real-time energy management systems and participatory digital platforms these districts demonstrate how environmental goals can be achieved without compromising comfort or functionality. They operate as testbeds for larger-scale replication and offer insight into how neighborhood-level resilience can feed into citywide outcomes.

Zurich’s broader energy transition reflects a deliberate alignment between technical systems and behavioural change. Smart metering and real-time monitoring tools have enabled more responsive demand management while incentives and regulatory frameworks have supported the decentralization of renewable generation. The Energy Strategy 2050 provides a binding policy backdrop and ensures coherence across departments and timelines. Data is not simply collected but operationalized in ways that inform planning and drive iterative improvements.

Environmental air quality data illustrate the results of this integrated strategy. This trend is visualized in **Figure 12,** which presents the annual mean concentrations of NO_2 and PM_{10} based on Zurich's official air quality records. The graph highlights not only the steady decline in both pollutants but also the consistency of environmental improvement across consecutive years.

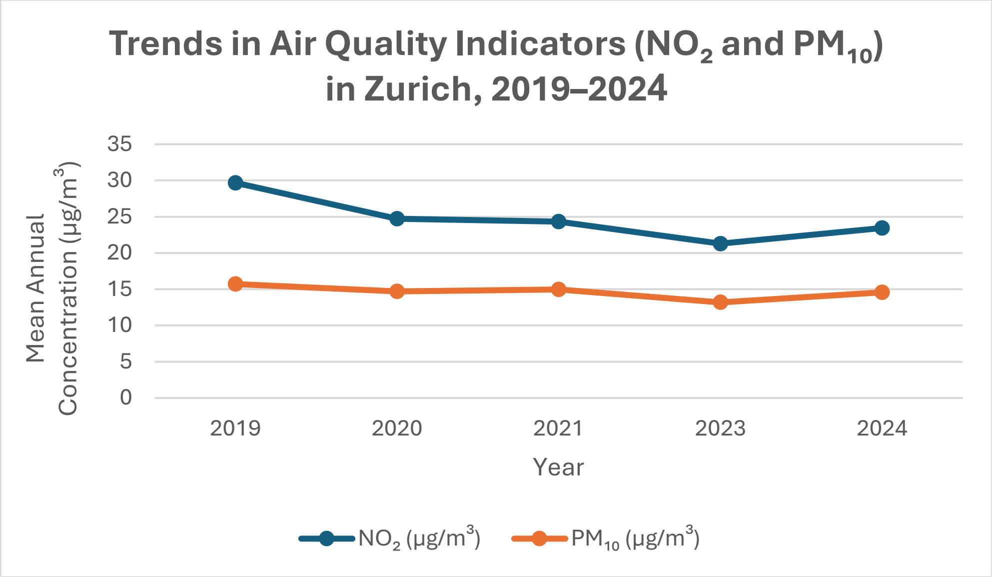


Figure 12 Trends in annual mean concentrations of NO_2 and PM_{10} in Zurich, 2019–2024

Source: Author's own elaboration based on data from Eberwein et al. (2015), Haase (2021), Menendez et al. (2022), and Zapata Riveros et al. (2024).

According to municipal records annual mean NO_2 concentrations dropped from 29.68 to 23.43 micrograms per cubic meter while PM_{10} declined from 15.71 to 14.56. These results underscore the combined effect of reducing traffic emissions promoting clean energy and shifting transport habits through expanded public transit and active mobility infrastructure.

Water management reinforces this model of environmental coherence. Through smart metering leak detection and adaptive consumption tracking Zurich has safeguarded water quality and availability despite growing climate pressures. Data transparency and clear regulatory oversight have allowed the city to reduce system losses maintain stable reserves and ensure equitable service delivery across all districts.

What sets Zurich apart is not only the quality of its technical systems but also the integration between sectors. Energy air and water are treated not as isolated challenges, but as interconnected systems governed by unified strategies. This has enabled the city to maintain a high level of environmental performance while adapting to shifting social and climatic demands.

Zurich's experience from 2018 to 2025 offers a concrete example of how digital tools, regulatory clarity and civic collaboration can produce measurable outcomes. It affirms that sustainability is not just a matter of policy intent but of institutional capacity operational discipline and ongoing public trust.

From my perspective as a researcher, Zurich presents a strong model of how cities can combine advanced digital technologies, clear regulations, and active citizen participation to achieve long-term environmental sustainability. What stands out in Zurich's case is its ability to treat energy, air, and water not as separate challenges but as connected systems managed under one coordinated strategy. In my view, this integrated approach demonstrates that real sustainability depends not only on having policies but on building stable institutions, using high-quality data in daily decisions, and maintaining strong public trust over time.

Appendix A.6. Cape Town's Adaptive Water Governance through ICT (2018–2025)

Between 2018 and 2025 Cape Town moved from a position of acute vulnerability to one of relative resilience in water management. This shift came in the aftermath of the Day Zero crisis and reflects a coordinated effort to stabilize supply systems through physical investment digital oversight and strong public engagement. Examining key water indicators shows how the city transitioned from reactive measures to an increasingly integrated and adaptive model of urban resource governance.

One of the clearest indicators of this transformation is the trend in dam storage across Cape Town's six major reservoirs. In 2018 average storage levels were just 46 percent with some dams dropping below 20 percent. By contrast from 2021 to 2025 average dam levels remained consistently above 59 percent. This trend is illustrated in Figure X which presents a year-by-year view of average minimum and maximum storage levels based on official municipal records. The visual makes clear the severity of the 2018 drought and the scale of recovery that followed.

While rainfall did improve in certain years the long-term rebound in storage cannot be explained by climate variability alone. Cape Town implemented wide-reaching water demand management strategies including behavioural campaigns tighter restrictions and extensive upgrades to its water and sanitation networks. According to municipal reports these interventions helped maintain higher minimum storage thresholds even in years of moderate precipitation.

Equally significant was the city's shift toward integrated digital water governance. Real-time dashboards and public-facing data tools gave residents visibility into dam levels usage rates and restrictions. The Water and Sanitation department doubled its operational budget in 2023 to expand monitoring capabilities improve catchment resilience and ensure more accurate forecasting. This investment in digital and institutional capacity became a core pillar of Cape Town's broader resilience strategy.

At the same time the data reveal unresolved challenges. Pollution remains a concern in several catchment zones and infrastructure inequities persist in lower-income districts. Reports also point to ongoing tensions in balancing ecological protection with urban demand. These issues are being addressed through scenario planning risk mapping and policies that emphasize social equity and shared responsibility.

Taken together the dam storage trajectory shown in the **Figure 13** represents more than hydrological recovery it reflects the outcome of policy coherence technological integration and public accountability. Cape Town's experience shows how cities facing environmental stress can move toward resilience through adaptive governance and long-term investment rather than short-term fixes.

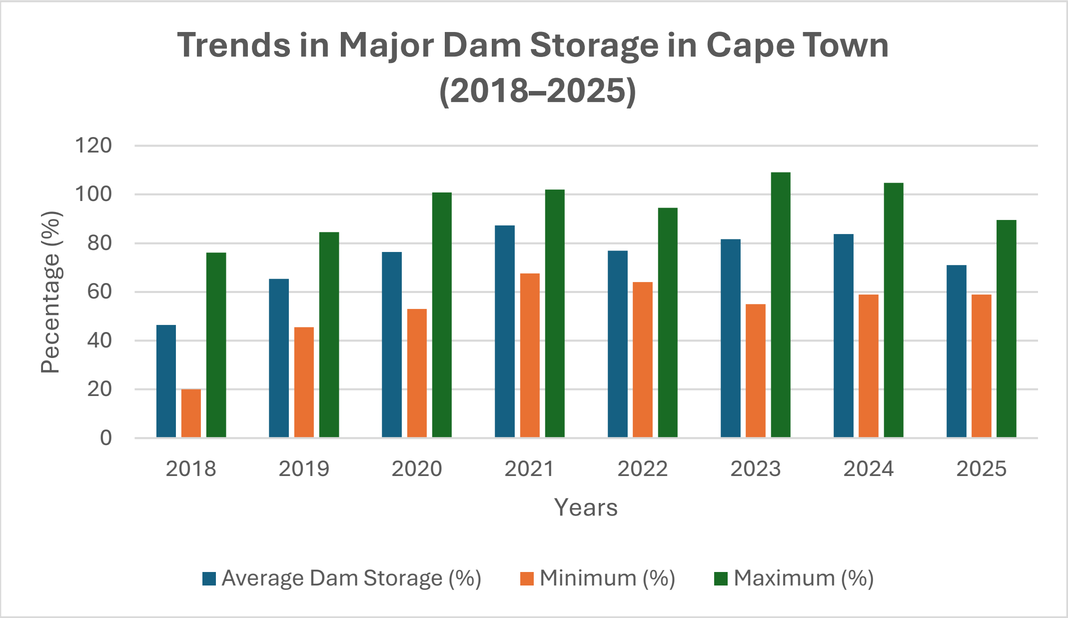


Figure 13 Trends in average, minimum, and maximum storage of major dams in Cape Town (2018–2025)

Source: Author's own elaboration based on data from City of Cape Town (2025, 2024, 2023) and Rodina, l (2019).

From my research perspective, Cape Town provides a valuable example of how cities can build long-term resilience after severe environmental crises. The integration of real-time digital monitoring, public transparency, and institutional investment has allowed the city to manage water scarcity more effectively. In my view, Cape Town's experience shows that resilience is not achieved only by infrastructure, but by continuously involving citizens, improving data-driven decision-making, and adapting governance frameworks to address both environmental and social challenges over time.

Appendix A.7. Oslo's Digital Environmental Transformation 2018 to 2023

Between 2018 and 2023 Oslo experienced a measurable shift in its environmental performance closely tied to the integration of digital tools and ICT-based governance. This shift is most clearly reflected in three interconnected indicators the share of transport-related emissions the percentage of new electric vehicle registrations and the municipal recycling rate. These indicators do more than track environmental progress they illustrate Oslo's capacity to embed technological innovation into its broader climate strategy.

First, the proportion of transport-related greenhouse gas emissions decreased from 68% to 54%. This reduction is attributed to Oslo's adoption of zero-emission vehicles and the implementation of smart transport systems. Tools like real-time fleet tracking and automated route optimization helped city officials identify inefficiencies, reduce fuel use, and move towards sustainable mobility.

Second, the percentage of new electric vehicle registrations dramatically increased from 25% to 70%. This growth reflects strong public incentives and the development of supporting digital infrastructure. Mobile apps and IoT-based services improved access to charging points, enabled dynamic pricing, and supported shared mobility platforms, making the shift to clean technologies practical and appealing for citizens.

Finally, Oslo's municipal recycling rate improved from 45% to 61%. This progress was partly due to the digitalization of waste management through participatory platforms and real-time data analytics. By tracking waste streams, providing household feedback, and optimizing collection logistics, the city enhanced transparency and boosted community involvement in circular economy practices.

These three indicators are presented in **Figure 14** which summarizes Oslo's environmental trajectory and shows the parallel progress in emissions reduction electric vehicle adoption and recycling efficiency

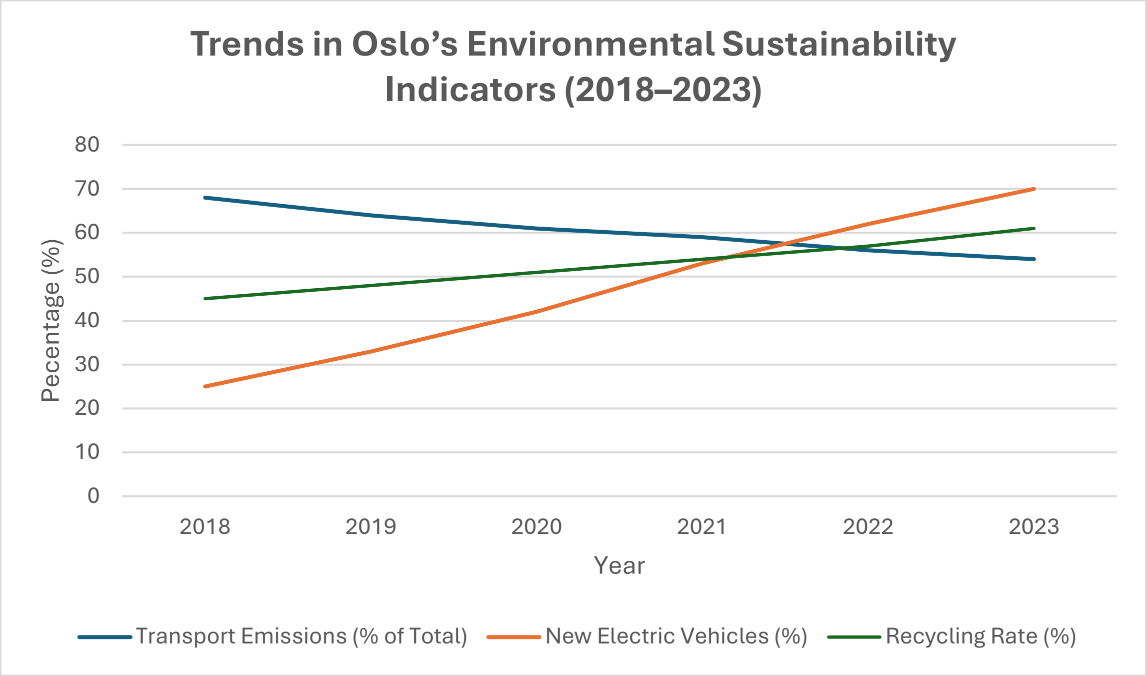


Figure 14 Oslo’s Key Environmental Sustainability Indicators (2018–2023)

Source: *Author’s own elaboration based on data from City of Oslo (2022); Karjalainen et al. (2024); Resourceful Cities (2019).*

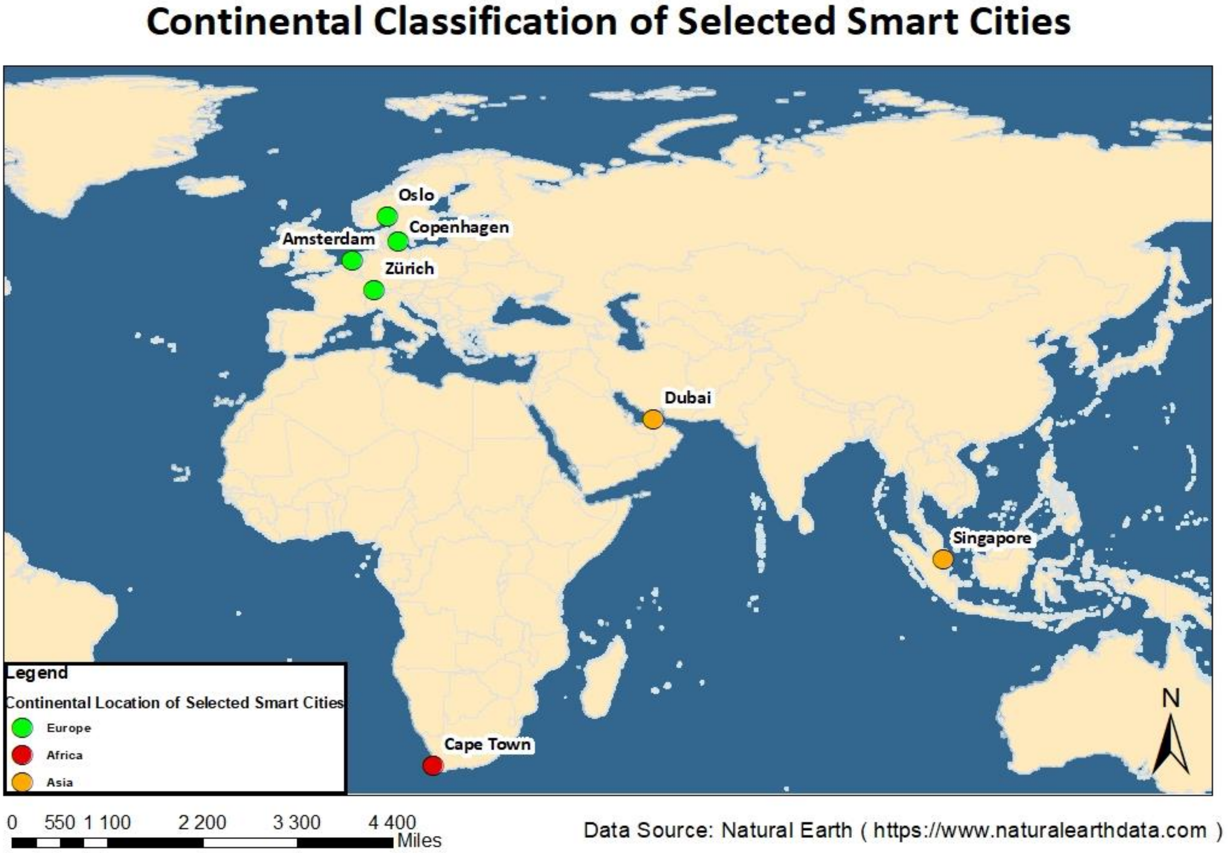
Together these trends suggest that Oslo’s climate success was not the outcome of isolated policies but of a comprehensive and coordinated digital strategy. By embedding ICT into the core functions of transport mobility and resource management the city achieved systemic and measurable improvements.

From my perspective as a researcher, Oslo shows a strong example of how using ICT in city management can bring real environmental benefits in different sectors:

- **Transport:** With real-time systems that track vehicles and full electrification of public transport, Oslo is moving clearly toward a future of zero-emission mobility.
- **Energy and Infrastructure:** The combination of digital support, government incentives, and automated systems has made it easier for people to switch to electric vehicles, placing Oslo among the world’s leading cities in clean transportation.
- **Waste and Recycling:** Smart waste management that uses real-time data and involves citizens has helped increase recycling rates above 60%, while deposit return systems further support recycling efforts.

This approach, guided by Oslo’s Zero Emission 2028 plan and supported by climate budgeting proves that digital tools, when fully used across all areas of city management, can help cities achieve real and fast progress toward environmental sustainability. This experience also offers valuable lessons to other cities planning similar transitions.

Appendix B. Continental Location of the Selected Smart Cities Used in The Thesis



Data Source: Natural Earth (https://www.naturalearthdata.com)

Figure 15 Continental Location of the Selected Smart Cities Used in the Thesis

Source: Author's Creation by using ArcMap

Appendix C. Selected Smart City Dashboards

All figures presented in this appendix are sourced from:

IMD Business School. (2025, April 8). *Smart City Index Results*. Available at: https://www.imd.org/smart-city-observatory/home/rankings/

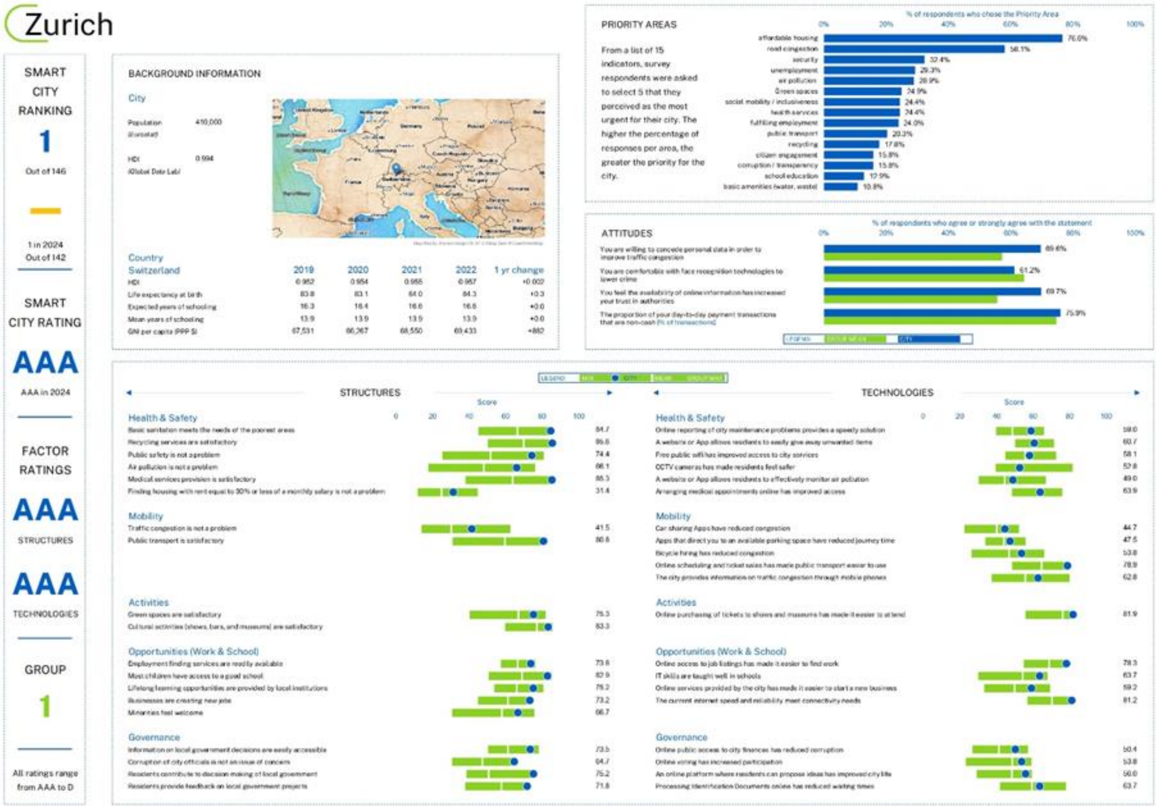
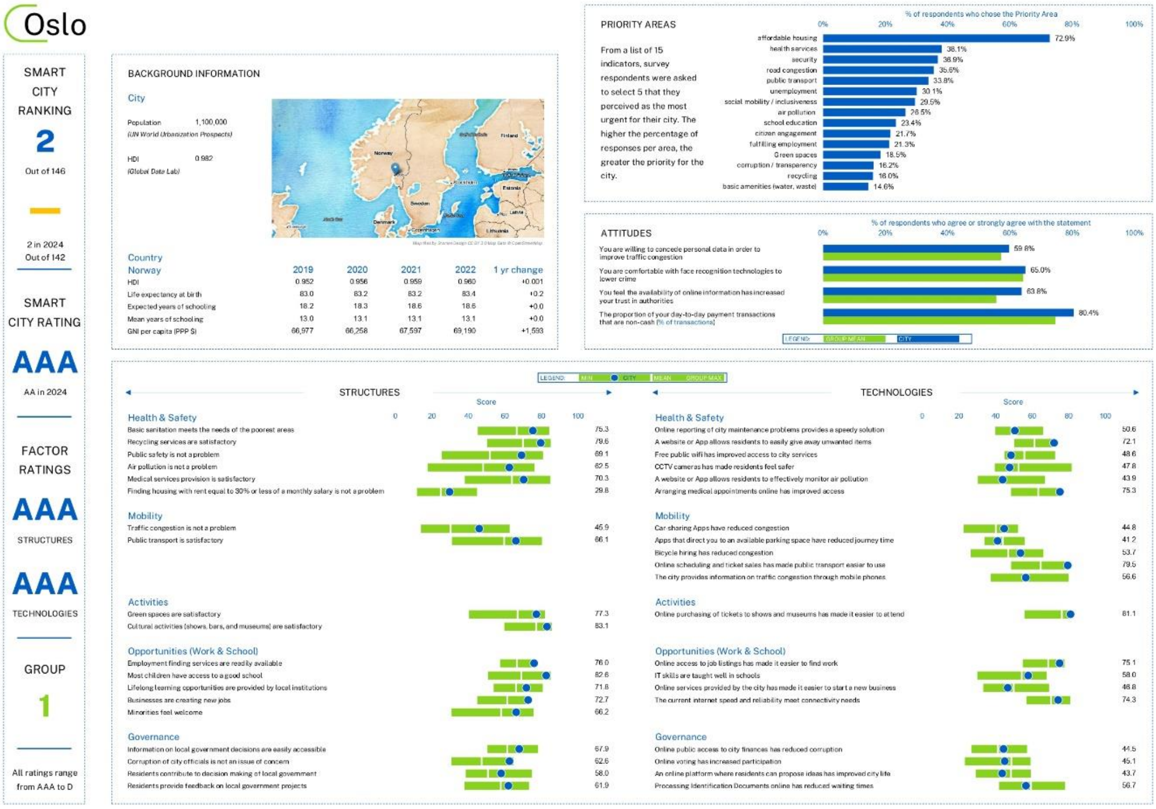


Figure 16 Zurich Index Dashboard



Oslo

SMART CITY RANKING
2
Out of 146

2 in 2024
Out of 142

SMART CITY RATING
AAA
AA in 2024

FACTOR RATINGS
AAA
STRUCTURES
AAA
TECHNOLOGIES

GROUP
1

All ratings range from AAA to D

BACKGROUND INFORMATION

City

Population (UN World Urbanization Prospects)	1,100,000
HDI (Global Data Lab)	0.982

Country

Norway	2019	2020	2021	2022	1 yr change
HDI	0.952	0.956	0.959	0.960	+0.001
Life expectancy at birth	83.0	83.2	83.2	83.4	+0.2
Expected years of schooling	18.2	18.3	18.6	18.6	+0.0
Mean years of schooling	13.0	13.1	13.1	13.1	+0.0
GNI per capita (PPP $)	66,977	66,258	67,597	69,190	+1,593

PRIORITY AREAS

From a list of 15 indicators, survey respondents were asked to select 5 that they perceived as the most urgent for their city. The higher the percentage of responses per area, the greater the priority for the city.

	% of respondents who chose the Priority Area
affordable housing	72.9%
health services	38.1%
security	36.9%
road congestion	35.6%
public transport	33.8%
unemployment	30.1%
social mobility / inclusiveness	29.5%
air pollution	26.5%
school education	23.4%
citizen engagement	21.7%
fulfilling employment	21.3%
Green spaces	18.5%
corruption / transparency	16.2%
recycling	16.0%
basic amenities (water, waste)	14.6%

ATTITUDES

	% of respondents who agree or strongly agree with the statement
You are willing to concede personal data in order to improve traffic congestion	59.8%
You are comfortable with face recognition technologies to lower crime	65.0%
You feel the availability of online information has increased your trust in authorities	63.8%
The proportion of your day-to-day payment transactions that are non-cash (% of transactions)	80.4%

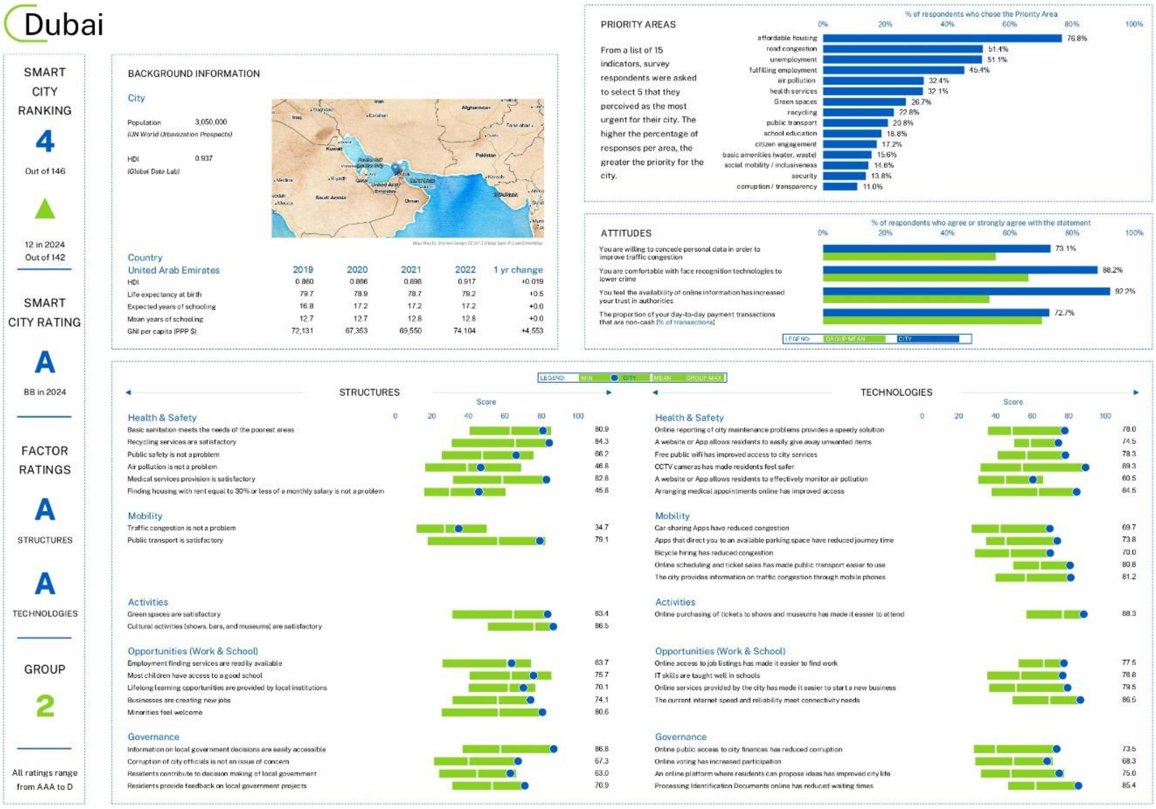
STRUCTURES

	Score
Health & Safety	
Basic sanitation meets the needs of the poorest areas	75.3
Recycling services are satisfactory	79.6
Public safety is not a problem	69.1
Air pollution is not a problem	62.5
Medical services provision is satisfactory	70.3
Finding housing with rent equal to 30% or less of a monthly salary is not a problem	29.8
Mobility	
Traffic congestion is not a problem	45.9
Public transport is satisfactory	66.1
Activities	
Green spaces are satisfactory	77.3
Cultural activities (shows, bars, and museums) are satisfactory	83.1
Opportunities (Work & School)	
Employment finding services are readily available	76.0
Most children have access to a good school	82.6
Lifelong learning opportunities are provided by local institutions	71.8
Businesses are creating new jobs	72.7
Minorities feel welcome	66.2
Governance	
Information on local government decisions are easily accessible	67.9
Corruption of city officials is not an issue of concern	62.6
Residents contribute to decision making of local government	58.0
Residents provide feedback on local government projects	61.9

TECHNOLOGIES

	Score
Health & Safety	
Online reporting of city maintenance problems provides a speedy solution	50.6
A website or App allows residents to easily give away unwanted items	72.1
Free public wifi has improved access to city services	48.6
CCTV cameras has made residents feel safer	47.8
A website or App allows residents to effectively monitor air pollution	43.9
Arranging medical appointments online has improved access	75.3
Mobility	
Car sharing Apps have reduced congestion	44.8
Apps that direct you to an available parking space have reduced journey time	41.2
Bicycle hiring has reduced congestion	53.7
Online scheduling and ticket sales has made public transport easier to use	79.5
The city provides information on traffic congestion through mobile phones	56.6
Activities	
Online purchasing of tickets to shows and museums has made it easier to attend	81.1
Opportunities (Work & School)	
Online access to job listings has made it easier to find work	75.1
IT skills are taught well in schools	58.0
Online services provided by the city has made it easier to start a new business	46.8
The current internet speed and reliability meet connectivity needs	74.3
Governance	
Online public access to city finances has reduced corruption	44.5
Online voting has increased participation	45.1
An online platform where residents can propose ideas has improved city life	43.7
Processing Identification Documents online has reduced waiting times	56.7

Figure 17 Oslo Index Dashboard



Dubai

SMART CITY RANKING
4
Out of 146

12 in 2024
Out of 142

SMART CITY RATING
A
BB in 2024

FACTOR RATINGS
A
STRUCTURES
A
TECHNOLOGIES

GROUP
2

All ratings range from AAA to D

BACKGROUND INFORMATION

City

Population (UN World Urbanization Prospects)	3,050,000
HDI (Global Data Lab)	0.937

Country

United Arab Emirates	2019	2020	2021	2022	1 yr change
HDI	0.860	0.886	0.898	0.917	+0.019
Life expectancy at birth	79.7	78.9	78.7	79.2	+0.5
Expected years of schooling	16.8	17.2	17.2	17.2	+0.0
Mean years of schooling	12.7	12.7	12.8	12.8	+0.0
GNI per capita (PPP $)	72,131	67,353	69,550	74,104	+4,553

PRIORITY AREAS

From a list of 15 indicators, survey respondents were asked to select 5 that they perceived as the most urgent for their city. The higher the percentage of responses per area, the greater the priority for the city.

	% of respondents who chose the Priority Area
affordable housing	76.8%
road congestion	51.4%
unemployment	51.1%
fulfilling employment	45.4%
air pollution	32.4%
health services	32.1%
Green spaces	26.7%
recycling	22.8%
public transport	20.8%
school education	18.8%
citizen engagement	17.2%
basic amenities (water, waste)	15.6%
social mobility / inclusiveness	14.6%
security	13.8%
corruption / transparency	11.0%

ATTITUDES

	% of respondents who agree or strongly agree with the statement
You are willing to concede personal data in order to improve traffic congestion	73.1%
You are comfortable with face recognition technologies to lower crime	88.2%
You feel the availability of online information has increased your trust in authorities	92.2%
The proportion of your day-to-day payment transactions that are non-cash (% of transactions)	72.7%

STRUCTURES

	Score
Health & Safety	
Basic sanitation meets the needs of the poorest areas	80.9
Recycling services are satisfactory	84.3
Public safety is not a problem	66.2
Air pollution is not a problem	46.8
Medical services provision is satisfactory	82.8
Finding housing with rent equal to 30% or less of a monthly salary is not a problem	45.8
Mobility	
Traffic congestion is not a problem	34.7
Public transport is satisfactory	79.1
Activities	
Green spaces are satisfactory	83.4
Cultural activities (shows, bars, and museums) are satisfactory	86.5
Opportunities (Work & School)	
Employment finding services are readily available	63.7
Most children have access to a good school	75.7
Lifelong learning opportunities are provided by local institutions	70.1
Businesses are creating new jobs	74.1
Minorities feel welcome	80.6
Governance	
Information on local government decisions are easily accessible	86.8
Corruption of city officials is not an issue of concern	67.3
Residents contribute to decision making of local government	63.0
Residents provide feedback on local government projects	70.9

TECHNOLOGIES

	Score
Health & Safety	
Online reporting of city maintenance problems provides a speedy solution	78.0
A website or App allows residents to easily give away unwanted items	74.5
Free public wifi has improved access to city services	78.3
CCTV cameras has made residents feel safer	89.3
A website or App allows residents to effectively monitor air pollution	60.5
Arranging medical appointments online has improved access	84.5
Mobility	
Car sharing Apps have reduced congestion	69.7
Apps that direct you to an available parking space have reduced journey time	73.8
Bicycle hiring has reduced congestion	70.0
Online scheduling and ticket sales has made public transport easier to use	80.8
The city provides information on traffic congestion through mobile phones	81.2
Activities	
Online purchasing of tickets to shows and museums has made it easier to attend	88.3
Opportunities (Work & School)	
Online access to job listings has made it easier to find work	77.5
IT skills are taught well in schools	76.8
Online services provided by the city has made it easier to start a new business	79.5
The current internet speed and reliability meet connectivity needs	86.5
Governance	
Online public access to city finances has reduced corruption	73.5
Online voting has increased participation	68.3
An online platform where residents can propose ideas has improved city life	75.0
Processing Identification Documents online has reduced waiting times	85.4

Figure 18 Dubai Index Dashboard

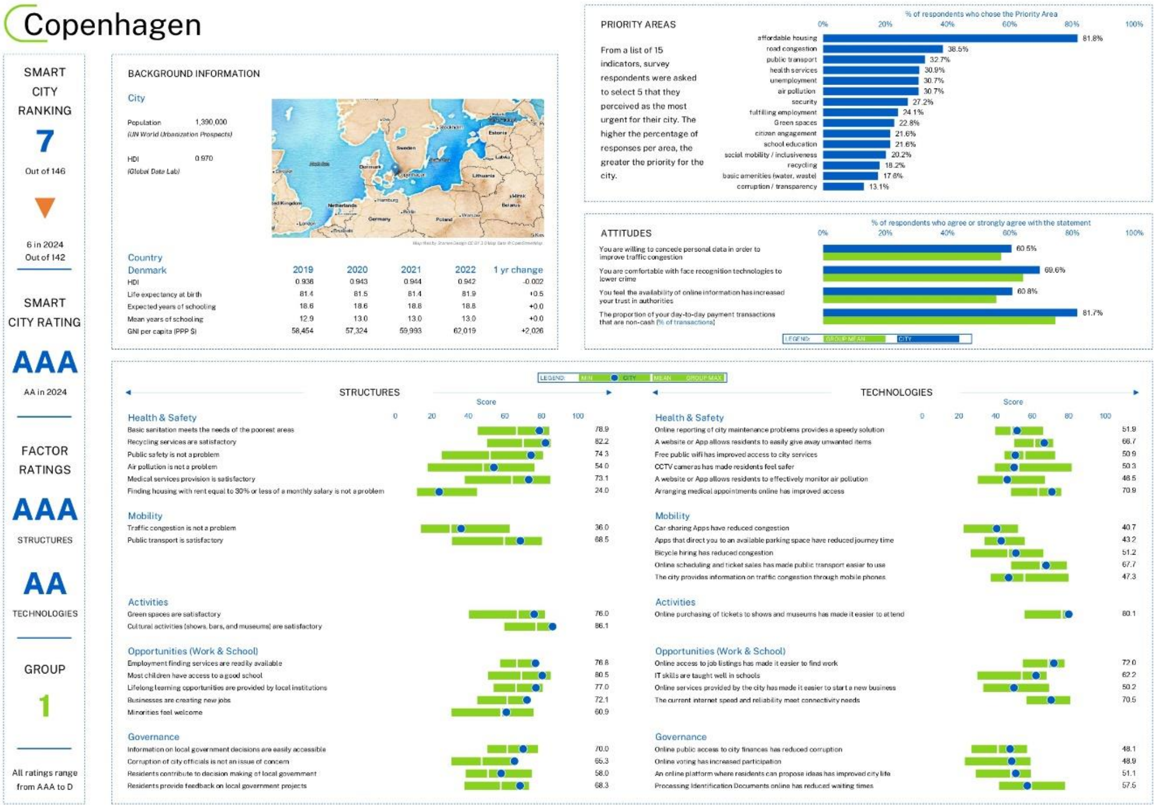


Figure 19 Copenhagen Index Dashboard

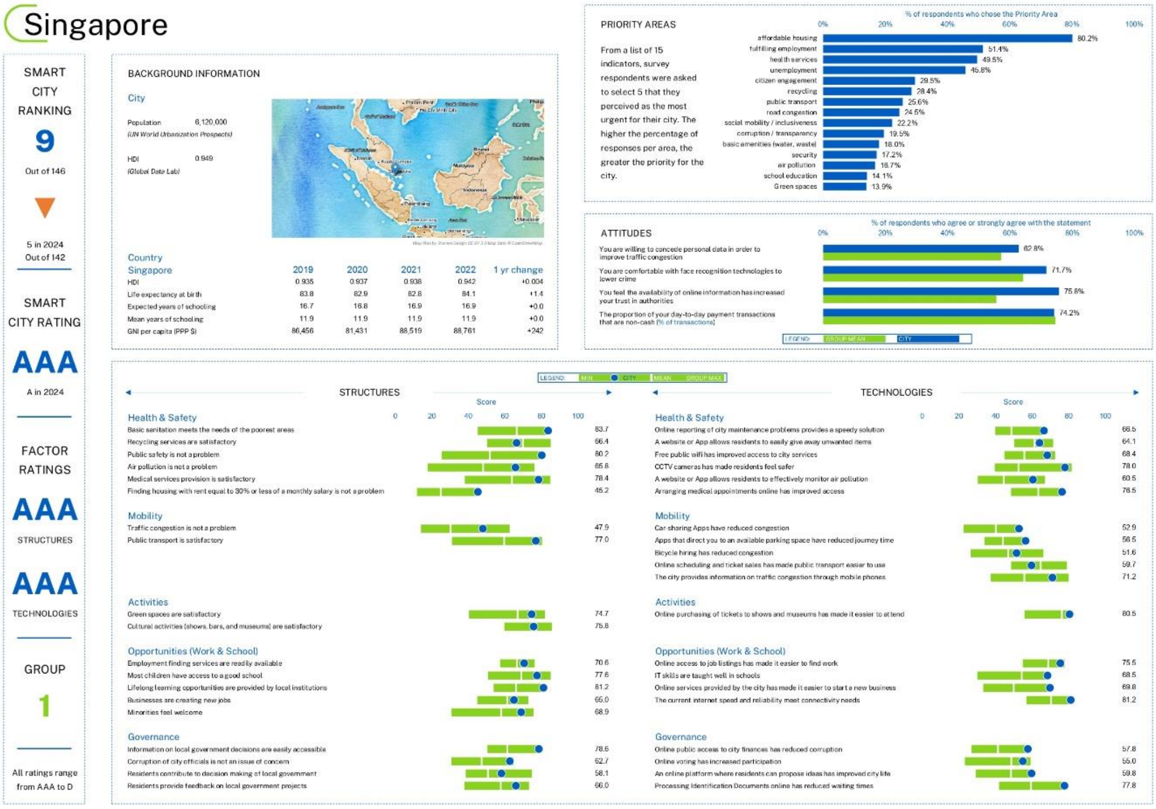
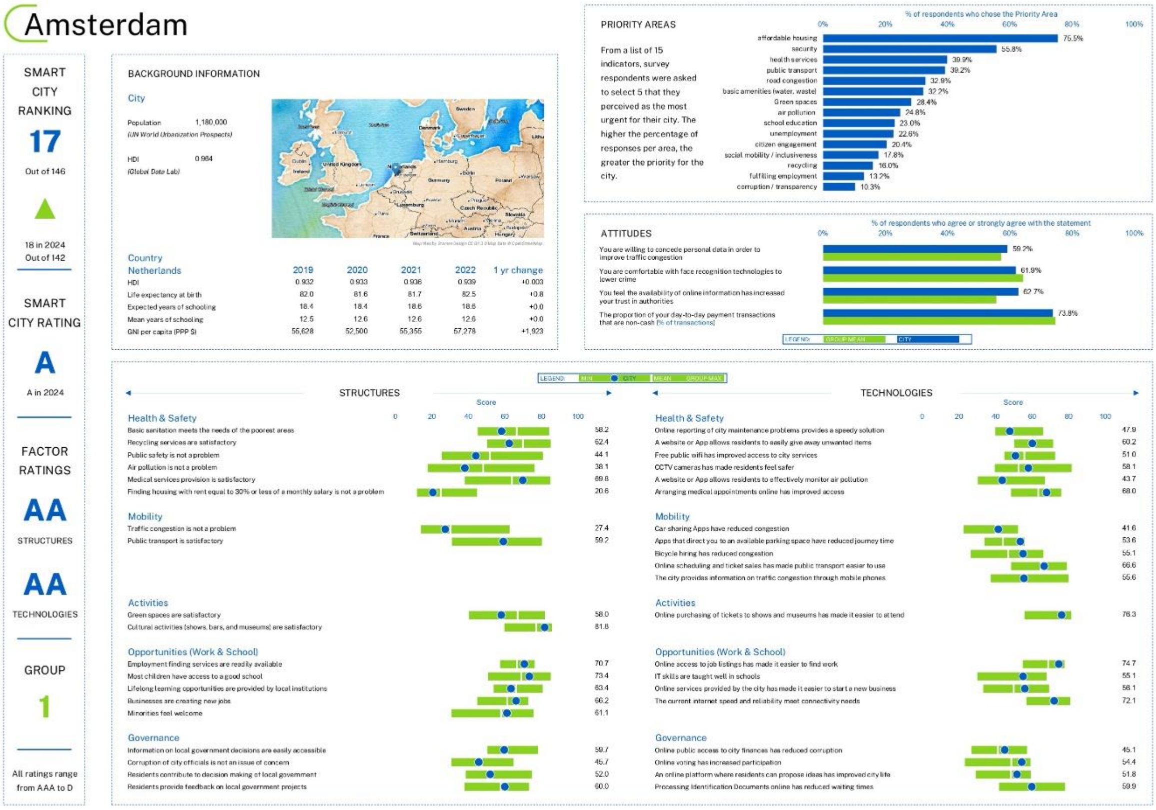


Figure 20 Singapore Index Dashboard



City

Population 1,180,000
(UN World Urbanization Prospects)

HDI 0.984
(Global Data Lab)

Country Netherlands	2019	2020	2021	2022	1 yr change
HDI	0.932	0.933	0.936	0.939	+0.003
Life expectancy at birth	82.0	81.6	81.7	82.5	+0.8
Expected years of schooling	18.4	18.4	18.6	18.6	+0.0
Mean years of schooling	12.5	12.6	12.6	12.6	+0.0
GNI per capita (PPP $)	55,628	52,500	55,355	57,278	+1,923

PRIORITY AREAS

From a list of 15 indicators, survey respondents were asked to select 5 that they perceived as the most urgent for their city. The higher the percentage of responses per area, the greater the priority for the city.

	% of respondents who chose the Priority Area
affordable housing	75.5%
security	55.8%
health services	39.9%
public transport	39.2%
road congestion	32.9%
basic amenities (water, waste)	32.2%
Green spaces	28.4%
air pollution	24.8%
school education	23.0%
unemployment	22.6%
citizen engagement	20.4%
social mobility / inclusiveness	17.8%
recycling	16.0%
fulfilling employment	13.2%
corruption / transparency	10.3%

ATTITUDES

	% of respondents who agree or strongly agree with the statement
You are willing to concede personal data in order to improve traffic congestion	59.2%
You are comfortable with face recognition technologies to lower crime	61.9%
You feel the availability of online information has increased your trust in authorities	62.7%
The proportion of your day-to-day payment transactions that are non-cash (% of transactions)	73.8%

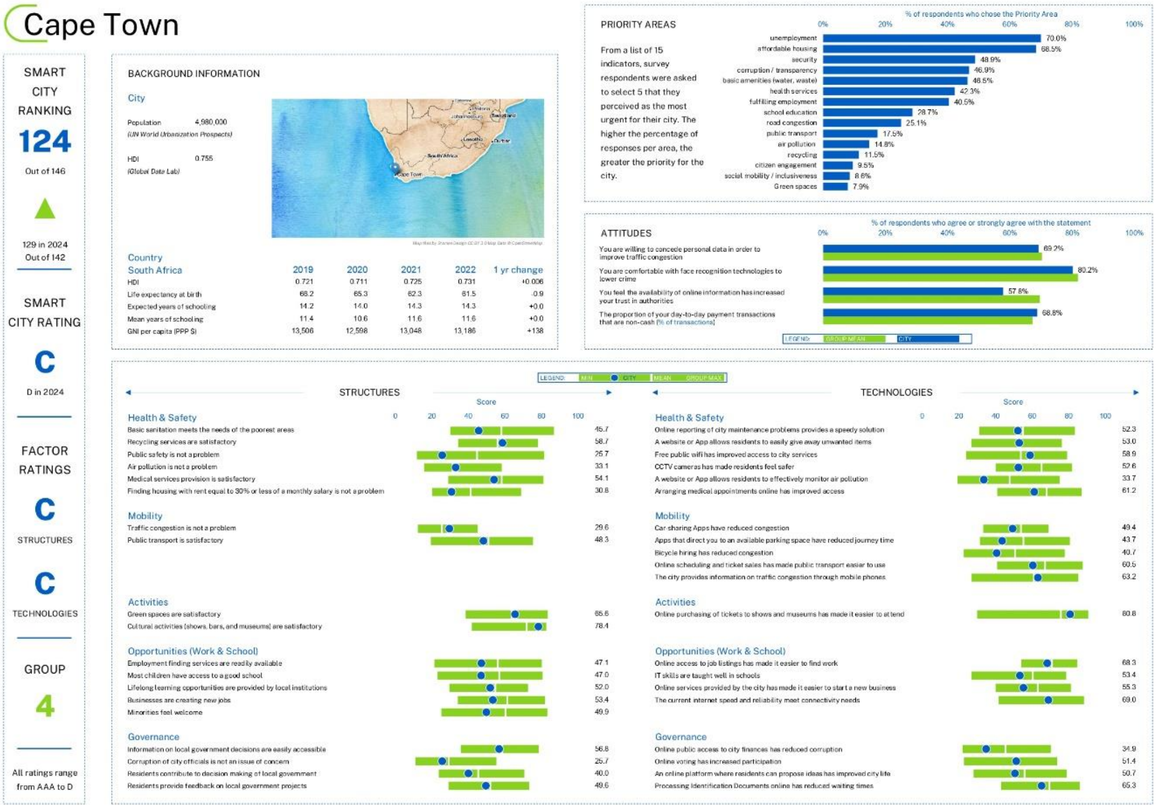
STRUCTURES

	Score
Health & Safety	
Basic sanitation meets the needs of the poorest areas	58.2
Recycling services are satisfactory	62.4
Public safety is not a problem	44.1
Air pollution is not a problem	38.1
Medical services provision is satisfactory	69.8
Finding housing with rent equal to 30% or less of a monthly salary is not a problem	20.6
Mobility	
Traffic congestion is not a problem	27.4
Public transport is satisfactory	59.2
Activities	
Green spaces are satisfactory	58.0
Cultural activities (shows, bars, and museums) are satisfactory	81.8
Opportunities (Work & School)	
Employment finding services are readily available	70.7
Most children have access to a good school	73.4
Lifelong learning opportunities are provided by local institutions	63.4
Businesses are creating new jobs	66.2
Minorities feel welcome	61.1
Governance	
Information on local government decisions are easily accessible	59.7
Corruption of city officials is not an issue of concern	45.7
Residents contribute to decision making of local government	52.0
Residents provide feedback on local government projects	60.0

TECHNOLOGIES

	Score
Health & Safety	
Online reporting of city maintenance problems provides a speedy solution	47.9
A website or App allows residents to easily give away unwanted items	60.2
Free public wifi has improved access to city services	51.0
CCTV cameras has made residents feel safer	58.1
A website or App allows residents to effectively monitor air pollution	43.7
Arranging medical appointments online has improved access	68.0
Mobility	
Car-sharing Apps have reduced congestion	41.6
Apps that direct you to an available parking space have reduced journey time	53.6
Bicycle hiring has reduced congestion	55.1
Online scheduling and ticket sales has made public transport easier to use	66.6
The city provides information on traffic congestion through mobile phones	55.6
Activities	
Online purchasing of tickets to shows and museums has made it easier to attend	76.3
Opportunities (Work & School)	
Online access to job listings has made it easier to find work	74.7
IT skills are taught well in schools	55.1
Online services provided by the city has made it easier to start a new business	58.1
The current internet speed and reliability meet connectivity needs	72.1
Governance	
Online public access to city finances has reduced corruption	45.1
Online voting has increased participation	54.4
An online platform where residents can propose ideas has improved city life	51.8
Processing Identification Documents online has reduced waiting times	59.9

Figure 21 Amsterdam Index Dashboard



City

Population 4,980,000
(UN World Urbanization Prospects)

HDI 0.755
(Global Data Lab)

Country South Africa	2019	2020	2021	2022	1 yr change
HDI	0.721	0.711	0.725	0.731	+0.006
Life expectancy at birth	68.2	65.3	62.3	61.5	-0.9
Expected years of schooling	14.2	14.0	14.3	14.3	+0.0
Mean years of schooling	11.4	10.6	11.6	11.6	+0.0
GNI per capita (PPP $)	13,506	12,598	13,048	13,186	+138

PRIORITY AREAS

From a list of 15 indicators, survey respondents were asked to select 5 that they perceived as the most urgent for their city. The higher the percentage of responses per area, the greater the priority for the city.

	% of respondents who chose the Priority Area
unemployment	70.0%
affordable housing	68.5%
security	48.9%
corruption / transparency	46.9%
basic amenities (water, waste)	46.5%
health services	42.3%
fulfilling employment	40.5%
school education	28.7%
road congestion	25.1%
public transport	17.5%
air pollution	14.8%
recycling	11.5%
citizen engagement	9.5%
social mobility / inclusiveness	8.6%
Green spaces	7.9%

ATTITUDES

	% of respondents who agree or strongly agree with the statement
You are willing to concede personal data in order to improve traffic congestion	69.2%
You are comfortable with face recognition technologies to lower crime	80.2%
You feel the availability of online information has increased your trust in authorities	57.8%
The proportion of your day-to-day payment transactions that are non-cash (% of transactions)	68.8%

STRUCTURES

	Score
Health & Safety	
Basic sanitation meets the needs of the poorest areas	45.7
Recycling services are satisfactory	58.7
Public safety is not a problem	25.7
Air pollution is not a problem	33.1
Medical services provision is satisfactory	54.1
Finding housing with rent equal to 30% or less of a monthly salary is not a problem	30.8
Mobility	
Traffic congestion is not a problem	29.6
Public transport is satisfactory	48.3
Activities	
Green spaces are satisfactory	65.6
Cultural activities (shows, bars, and museums) are satisfactory	78.4
Opportunities (Work & School)	
Employment finding services are readily available	47.1
Most children have access to a good school	47.0
Lifelong learning opportunities are provided by local institutions	52.0
Businesses are creating new jobs	53.4
Minorities feel welcome	49.9
Governance	
Information on local government decisions are easily accessible	56.8
Corruption of city officials is not an issue of concern	25.7
Residents contribute to decision making of local government	40.0
Residents provide feedback on local government projects	49.6

TECHNOLOGIES

	Score
Health & Safety	
Online reporting of city maintenance problems provides a speedy solution	52.3
A website or App allows residents to easily give away unwanted items	53.0
Free public wifi has improved access to city services	58.9
CCTV cameras has made residents feel safer	52.6
A website or App allows residents to effectively monitor air pollution	33.7
Arranging medical appointments online has improved access	61.2
Mobility	
Car-sharing Apps have reduced congestion	49.4
Apps that direct you to an available parking space have reduced journey time	43.7
Bicycle hiring has reduced congestion	40.7
Online scheduling and ticket sales has made public transport easier to use	60.5
The city provides information on traffic congestion through mobile phones	63.2
Activities	
Online purchasing of tickets to shows and museums has made it easier to attend	80.8
Opportunities (Work & School)	
Online access to job listings has made it easier to find work	68.3
IT skills are taught well in schools	53.4
Online services provided by the city has made it easier to start a new business	55.3
The current internet speed and reliability meet connectivity needs	69.0
Governance	
Online public access to city finances has reduced corruption	34.9
Online voting has increased participation	51.4
An online platform where residents can propose ideas has improved city life	50.7
Processing Identification Documents online has reduced waiting times	65.3

Figure 22 Cape Town Index Dashboard