



# **UNIVERSITÀ DEGLI STUDI DI PADOVA**

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**Dipartimento di Tecnica e Gestione dei Sistemi Industriali**  
**Corso di laurea magistrale in Management Engineering**

**Tesi di Laurea**

**Smart cities as interconnected systems: the role of smart  
infrastructures and energy network**

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**Anno Accademico 2024-2025**



## **Abstract**

Nowadays cities are evolving towards increasingly interdependent systems, where energy, mobility, digital networks, buildings and urban services must operate in a coordinated manner. The growing electrification, the diffusion of renewable sources and the extensive use of digital technologies are turning the energy infrastructure into an enabling element for the correct functioning of most elements within the city.

The thesis analyses this scenario adopting a systemic perspective, tracing the role of smart grids, flexible technologies and mechanisms for integration between sectors. Through this critical review and a technical analysis of some of the main models, the results highlight the opportunities and tensions that arise when heterogeneous infrastructures must cooperate.

A case study is used as empirical evidence to confirm that digitalisation, governance and long-term investments can converge into successful outcomes. The analysis shows good practices and positive results, which, however, are not universally transferable as they depend on technical, institutional and socio-cultural conditions specific to each urban context.

Overall, the study highlights that a “smart” city is not synonymous with increased technology, but rather with the ability to integrate information, infrastructure and different actors into an adaptive, resilient and sustainability-oriented urban ecosystem.



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## **Introduction**

Modern cities are undergoing profound transformation driven by growing urbanization, environmental pressures, digitalization and continuous changes in socio-economic models. In this scenario the concept of smart city emerges as an attempt to integrate smart infrastructure, digital technologies, energy networks and new governance models to systematically face these rising challenges. A smart city is not just the adoption of innovative technologies, it is a complex ecosystem where all its components interact dynamically through flows of data, interconnected infrastructures and multi-level coordination mechanisms.

Within this picture, the energy infrastructure bears an enabling role. The evolution towards more flexible, digitalised and integrated networks has drastically enhanced the impact of the smart grid on many smart city functionalities. From flexibility management to integration of renewables, electric mobility, bidirectional energy exchange and the synchronisation between different subsystems. This complexity also requires new analytical approaches that must consider the interdependencies and interpret them from a system-of-systems perspective.

Based on these premises, the thesis pursues four main objectives:

- Critically analyse the concept of smart city, highlighting definitions, characteristics and limitations, with particular focus on the systemic nature of urban infrastructure
- Explore the role of the energy infrastructure as the cornerstone of smart cities, illustrating how smart grids enable integration and flexibility processes
- Examine the interdependencies between urban infrastructures through a system thinking approach to interpret how heterogeneous networks can cooperate and generate collective benefits.
- Analyse an advanced real case, identifying good practices, constraints and enabling conditions for the implementation of smart infrastructures

These goals reflect the nature of the study, an interdisciplinary, conceptual and applied analysis, based on an extensive critical review of the literature, not on original experiments or modelling.

The methodological approach adopted for the thesis, in fact, has a qualitative, analytical and reconstructive nature. The research develops from a critical and selective review of academic, institutional and technical literature, used to reconstruct recurring concepts, models and dynamics in smart cities and their underlying infrastructures. The analysis of interdependencies relies on system-of-systems and system thinking principles, aiming to identify relationships, feedback mechanisms and emerging behaviours across urban subsystems.

The technical aspects presented and discussed throughout the work, which include power flow models, demand response, flexibility management and more, derive from existing literature and are employed exclusively for illustrative purposes, not as experimental or validation tools.

Similarly, the case study is based on secondary sources and does not try to test or verify the theoretical framework. Instead, it provides a reference to observe how policies, technologies and infrastructures converge in an advanced real-world situation, which allows identifying enabling conditions, critical issues and contingent factors.

# **Chapter 1 - Architecture and Dynamics of Smart Cities**

This chapter provides the conceptual foundation of the thesis by examining how smart cities have emerged in response to environmental, technological and socio-economic transformations. It reviews definitions, historical developments and the core elements that characterise smart urban systems. Particular attention is given to the role of infrastructures (energy, mobility, ICT, buildings and services) and to the systemic interdependencies that shape their functioning.

## **1.1. Definition of Smart City**

Smart cities are a developing trend aiming to solve some existing and growing difficulties faced by contemporary urban environments. One of the main challenges is urban growth. More than half of the human population currently lives in cities, and the UN forecasts that this percentage is destined to increase up to 70% within 2050, because of growing urban population and migration from rural areas ([1] Abdulrahman Alkandari et al., 2012). Consequently, cities infrastructure is under immense pressure, due to the supply outpacing the demand for essential needs such as water, healthcare, energy, transportation, education and safety ([2] M. R. Naphade et al., 2011). The concept of smart cities emerged as an integrated response to these complex obstacles, along with climate change and the goal of improving the quality of life. Central to the idea is a strategic exploitation of information and communication technologies (ICT), which allow to optimize urban services, while actively involving citizens, firms and institutions ([3] Michael Batty et al., 2012).

Although the term is globally widespread, it lacks an agreed-upon universal definition. Different organizations provide different definitions that focus on different aspects of smart cities, with some recurrent characteristics such as the use of ICT, the attention for environmental sustainability, the optimization of urban services and more:

- European commission: “A smart city is a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business.” ([4] European Commission, 2025)

The definition, going more into detail, also states that a smart city goes beyond the use of digital technologies, for better resource use and less emissions. Consequently, there are smarter urban transport networks, improved water supply and waste disposal facilities as well as more efficient heating and lighting systems. It also entails a more interactive and responsive city administration, safer public spaces, and better support for the needs of an ageing population.

- British Standards Institute: “Effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens”. ([5] British Standards Institution, 2025)

This definition is more complete if integrated with the one previously given in the same article about the concept of smart, which is explained as the application of technology systems to exploit the use of resources, reducing their consumption in order to improve the quality of life.

- Institute of Electrical and Electronics Engineers: “The new intelligence of cities resides in the increasingly effective combination of digital telecommunication networks (the nerves), ubiquitously embedded intelligence (the brains), sensors and tags (the sensory organs), and software (the knowledge and cognitive competence).” ([6] Hamed Chourabi et al., 2012)

This definition is focused on the similarity between the operation of smart cities and a human brain. Following this definition, during the rest of the conference, the authors also talked about the importance of ICT in smart cities and how a core concept of a smart city is the use of technology to increase sustainability and better manage its resources.

- Department of Industrial Engineering, University of Arkansas: “Smart cities use digital technologies, communication technologies, and data analytics, to create an efficient and effective service environment that improves urban quality of life and promotes sustainability”. ([7] José Sánchez Gracias et al., 2023) This definition is particularly interesting because it’s not just the definition decided by a restricted group of people, but it’s the result of an analysis of other smart city definitions that can be found in different contexts.

These and other definitions, although different in various aspects, all converge on a shared understanding. A smart city is not seen merely as a more technological city, but rather as an environment where digital tools are strategically integrated to support social, environmental and economic goals. It is important to address this misconception that a smart city is simply a high-tech city. The term “smart” involves also the rethinking of how cities operate and evolve thanks to the use of technology.

Therefore, the smart city is increasingly conceptualized as a systemic and multidimensional framework, where digital technologies play an enabling but not exclusive role, and hence they facilitate and not dictate urban development. This reflects the complexity of modern cities, where many aspects have to be taken into consideration, from the social factors to the economic and institutional ones as well as much more. What is generally recognized is that smart cities exploit digital technologies and smart infrastructures to enhance the city’s well-being.

From now on, during this and the following chapters, a smart city will be considered as a dynamic and adaptive urban ecosystem that leverages technological innovation

and data-driven approaches to enhance sustainability, improve quality of life and promote efficient governance.

## **1.2 Brief history and objectives**

After defining the concept of smart city, it's useful to analyze briefly the historic evolution and the ultimate objectives that smart cities pursue.

The concept of smart city wasn't forged instantly, but has instead evolved throughout time, and its roots can be identified in the first experiments of "digital city" developed in the 90s ([8] Renata Dameri et al., 2013). In this initial phase the focus was mainly directed towards the integration of ICT in the urban infrastructures, with the objective of improving operational efficiency and systems management. The reasons behind the failure of this first stage in the development of what we now call smart city, is rooted mainly in the lack of continuous effort and involvement of the community. The case that perfectly exemplifies it, is the Amsterdam Digital City model (DDS), where the term was also invented. The project failed due to a lack of stable funding, declining innovation and low user participation in governance. Born as a non-profit project to promote digital democracy, it turned into a commercial enterprise that did not withstand market competition and lost its value as a virtual public space. The focus was merely on the technical features, and not on the urban environment ([9] Peter van den Besselaar, 2001).

What emerges from this attempt is that technological innovation alone is rarely sufficient to generate lasting urban transformation. A recurring pattern that can be observed in the literature is that projects don't fail for a lack of technical capability but because social, institutional and governance dimensions are treated as secondary. This suggests that the "smartness" of a city is less a property of its devices and more a product of the ecosystem that adopts them.

During the following decade, despite this stumble, the concept began to spread on a global scale. Governments, institutions and private companies launched the first

pilot projects and other initiatives to test digital solutions for the emerging urban challenges, such as sustainable mobility, efficient energy management and security. Some programs, like the CUD (connected urban development) program promoted by Cisco in 2006, already showcased awareness of climate related challenges ([10] Cisco Systems, 2008). However, in most cases, the model of smart city was still highly technocentric, with an emphasis on digitization and operational efficiency rather than on the social or systemic dimensions of urban development.

Starting from 2010, there has been a further shift in the concept that started to be considered in a wider and multidimensional way. The emergence of new global priorities, such as climate change, social disparities and a growing complexity of urban systems, carried with them wider perspectives: a city is not considered smart when just efficient thanks to the exploitation of ICT and new technologies, but when it's also sustainable, resilient, inclusive and well-governed. In this new situation, different regulatory frameworks and indicator systems were elaborated, with the scope of providing new shared criteria for the evaluation and organization of smart cities. Some examples are the norm ISO 37120 ([11] International Organization for Standardization, 2018) and the guidelines for sustainable cities by ITU ([12] International Telecommunication Union, 2025).

In the latter years the concept has been further developed with other elements, that include civic participation, open government, digital ethics and conscious use of data. The city, as previously said, is not perceived as a complex system where technology is just a tool and where digital innovation is serving the collectivity and the urban wellbeing, respecting principles of equity, transparency and sustainability. To do so, the European Commission has also developed a guidance package, a document that “aims to help fast-tracking financially viable smart climate-neutral urban projects in an integrated and inclusive way”. ([13] J. Borsboom-van Beurden et al., 2021)

This gradual shift of its definition towards a more people-oriented end also reflects those that are the goals of building smart cities around the world. The final objective has also been changing constantly, and as of today we can outline a series of different valuable points in many different fields. What all these objectives have in

common is their contribution to the development of an advanced and sustainable urban future.

o *Environmental sustainability*

Smart cities promote sustainability through technology to enhance citizens' experience and reduce the environmental impact. Smart metering and digitalization allow the collection and analysis of data to optimize urban services and efficiently address growing environmental challenges. One of the main advantages of sustainable smart cities lies in the optimization of energy consumption, especially through the implementation of intelligent LED lighting systems. These systems reduce significantly the use of energy, whilst maintaining safety and efficient visibility. Air pollution is also mitigated thanks to the development of efficient public transportation networks and the deployment of smart environmental sensors that monitor air quality in real time.

Moreover, smart sensors play an important role in preventing infrastructure damage by enabling predictive maintenance and enhancing urban security through advanced surveillance systems. Furthermore, smart mobility solutions reduce traffic congestion, lower the amount of CO<sub>2</sub> emissions, and improve overall urban mobility, making travel within the city more efficient and less stressful for its inhabitants. ([14] Smart City Blog, 2021)

o *Boosting the local economy*

One of the objectives of smart cities is also an improvement of the local economy. Smart cities bring multiple advantages across different fields, and one of them is on the economic side. A study conducted by Abutabenjeh in 2021 ([15] Sawsan Abutabenjeh et al., 2024) shows how the strategic use of technology and ICTs stimulates the economic development through three main mechanisms:

- 1) Political and institutional commitment: When local governments prove to be committed towards smart technologies (e.g. through budget allocations and political leadership), also the importance of local economic development is perceived differently.

Commitment to digital innovation fosters decisions geared towards economic growth and community resilience.

- 2) Active technological engagement: Cities that actively use smart technologies in areas such as energy, transport, waste, health and civic participation create new economic opportunities (such as ICT jobs, more efficient services, business incubators).
- 3) Response to constraints: Also, the perception of obstacles (lack of resources, competences or infrastructures) motivates public managers to see economic development to overcome these barriers. In other words, challenges push towards economic growth policies to face local issues and limitations

Smart technologies don't only improve the efficiency and quality of public services, but they also foster the local economy as key instruments to create new job opportunities, attracting investors and enhancing the overall productivity of the city.

- o Community engagement and social inclusion

Smart cities also aim to improve the social situation, that is why social sustainability is one of the objectives that smart city projects seek to pursue. However, this is not at all a simple goal.

Even though social sustainability has proven to be a crucial objective for a smart city, it often receives less attention compared to other fields like economy and environmental sustainability. Nonetheless, in order to build a truly smart city, it is essential to consider social equity, quality of life, participatory governance and active citizen involvement.

The introduction of digital tools generates new interesting opportunities, but it can also be responsible for concerning issues like social exclusion. This phenomenon can affect especially vulnerable groups, whose people may face difficulties in accepting, assessing and leveraging smart city solutions. For this reason, it is

essential that every smart initiative takes the social impact of its actions into account at an early stage.

To do so, a study ([16] Tzuhao Chen et al., 2022) shows that it is crucial to combine top-down and bottom-up approaches and adopt solutions involving public bodies, enterprises and local communities. Hence, to prioritize this goal, it is important to reorient the concepts of smart city towards more human-centric and inclusive models. By doing so, smart cities will truly improve quality of life, reduce inequalities and reinforce social cohesion.

- o Guarantee control and security

Physical and Digital security are key responsibilities that a smart city must face to ensure a secure environment for its citizens. Their well-being also relies on these important factors, hence it is crucial to build a cohesive and safe ecosystem. To properly exemplify this goal, the S4AllCities project ([17] S4AllCities Consortium, 2022) represents an important initiative. This project focuses on building resilient infrastructures, services, ICT systems and IoT networks, while promoting the collection and sharing of data between the main stakeholders involved.

To achieve this, the system will integrate advanced technological and organizational solutions into a unified cyber-physical security management framework. As the European commission platform CORDIS reports ([18] CORDIS, 2023), the goal is to make cities safer by combining Internet of Things (IoT), artificial intelligence (AI) and urban monitoring and analysis systems to anticipate threats and support decision-making by authorities.

Therefore, security in this context cannot be interpreted as just surveillance, but rather as a smart and integrated ecosystem capable of addressing emergencies and protecting citizens' privacy, promoting a feeling of trust and well-being in the urban lifestyle.

- o Resilience and adaptation

Last but not least are resilience and adaptation. During the last decades, the increase of catastrophic natural and anthropic events highlighted the urgency to develop cities able not just to resist the shock these events might cause, but also to quickly recover and adapt to the situation. Here comes the smart city, proving to be a viable solution able to integrate advanced technologies to improve the resilience of the community.

A study conducted by the Politecnico di Torino and UC Berkeley ([19] G. P. Cimellaro, 2017) has built a “virtual city” modelled on Turin, in which it is possible to simulate the impact of earthquakes on thousands of buildings belonging to strategic sectors. Thanks to the integration between MATLAB and SAP2000, it performed non-linear analyses from which it quickly and realistically assessed potential damage, providing those who will have to take the decisions with support tools for emergency planning and reconstruction. This and other simulations facilitate the identification of the most vulnerable areas and develop targeted strategies to contain damage and optimize resources.

This approach is a concrete example of how urban digitization, and the use of predictive tools can transform cities into smart organisms, capable of learning from risk and improving their adaptive capacity. Indeed, smart cities are not just connected and technological cities, but ecosystems designed to resist, react and regenerate, reducing losses in case of a disaster.

### **1.3 Characterizing elements of a smart city**

Based on these objectives and the given definition, as said, smart cities are not limited to the adoption of advanced technologies. The concept of a smart city should provide a holistic view of urban development, integrating together multiple interdependent dimensions. A widely recognized framework to understand and evaluate smart city development is the one proposed by Giffinger ([20] Rudolf Giffinger and Hui Lü, 2015), who identified six key pillars: smart economy, smart environment, smart governance, smart living, smart mobility and smart people

[Figure 1.1]. These pillars are the core characterizing elements of a smart city, shaping the ecosystem that aims to fulfill the goals discussed in the previous chapter. Each of them plays a vital role in shaping the structure and identity of a smart city. A thorough understanding of these elements is essential, both to comprehend how and why smart cities operate and evolve, and to understand and analyze which are the infrastructural systems that sustain them.

From the analysis of these frameworks, it became clear that these dimensions do not operate in isolation, each of them is sustained by specific infrastructures whose integration determines whether a city can truly function as a coherent system. This observation has guided the structure of the following sections, which shift from the conceptual to the infrastructural perspective.



Figure 1.1: Smart city's Griffinger model (169] Khashoggi, A. N., & Mohammed, M. F., 2025)

### Smart economy

The first of these pillars is the smart economy, which acts as a driving force for the development and innovation of the whole urban ecosystem. Recent studies highlight the direct positive impact that smart economy generates on the other characterizing elements of the smart city listed previously, making it a key element to build urban ecosystems that are sustainable and innovative. Interestingly, a study

by Popova and Popovs ([21] Y. Popova and S. Popovs, 2022) underlines how the impact of smart economy on the other areas is significantly more decisive than the opposite, hence the countries that lack truly strong national economies still have opportunities for the development of smart areas.

The smart economy is an economic system based on digitalisation processes, which enable the adoption of technologies such as the Internet of Things, artificial intelligence and big data to improve the efficiency and quality of urban services. Moreover, it's driven by greening processes, which are the integration of environmental sustainability into production and consumption, and social inclusion, aiming to ensure equal opportunities and benefits for all citizens. ([22] I. Kalenyuk, 2021)

In addition, smart economy incorporates aspects of institutionalisation and urbanisation, recognizing the fact that smart economic development is strictly related to urban politics, to the institutional structures and social context of the city. This multidimensional approach allows to build a more resilient urban environment, capable of adapting quickly to the growing challenges, especially following the arrival of industry 4.0, that simultaneously affect economic, social and environmental aspects. ([23] T. Vasile and I. Popescu, 2022)

Therefore, it's clear how a smart economy doesn't operate as an isolated compartment, but rather as a network of integrated processes and relationships engaging citizens and involving companies, institutions and technology. The system itself allows to generate revenue, but also social and environmental value, improving competitiveness within the city and the quality of life of its inhabitants. It wouldn't be wrong to identify the smart economy as the beating heart of the smart city, as it's the engine connecting and enforcing all the other elements of the complex ecosystem that is a smart city.

### 1.3.2 Smart environment

To define a smart environment in the context of a smart city, it is crucial to first have a clear definition of one of its key technologies, the Internet of Things (IoT). Referred to a smart environment, IoT, according to Jayavardhana Gubbi et al. ([24] J. Gubbi et al, 2013) is the “interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. This is achieved by seamless ubiquitous sensing, data analytics and information representation with Cloud computing as the unifying framework.” A smart environment, “able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment” ([25] D. J. Cook, S. K. Das, 2007) is based on a network of IoT sensors that monitor parameters such as air quality, energy consumption, noise level, humidity, temperature and much more. These sensors communicate with central or distributed systems via wireless networks (LoRaWAN, NB-IoT, 5G), transmitting data that is then analysed using machine learning techniques.

One of the benefits of smart environmental management is the green urban planning that integrates green spaces, ecological corridors and natural water management, promoting biodiversity and improving the air quality. Urban design is based on geospatial analysis and environmental simulations to reduce the heat island effect and optimize the urban microclimate. ([26] A. Townsend and M. P. Rice, 2016)

Smart environment includes the adoption of renewable energies integrated into the urban context supported by microgrids to efficiently manage the energy distribution and consumption. Moreover, green buildings are equipped with automation systems that regulate air conditioning, lighting and ventilation based on environmental conditions and the presence of people within the building, creating a pleasing environment for the occupants and optimizing the energy consumption. Another useful element is waste management, which exploits bins with sensors and sometimes computer vision or AI to optimize the waste collection and improve sorting operations. ([27] I. Sosunova and J. Porras, 2022)

### 1.3.3 Smart governance

Another important factor that defines a smart city is its governance. With the term “smart governance”, we identify an administrative model that exploits digital technologies and processes to enhance efficient, transparent and inclusive decision-making. As noted by AlAwadhi and Scholl ([28] S. AlAwadhi and J. Scholl, 2016), it also involves a rethinking of institutional roles, decision-making dynamics, and the relationship between public and private actors, while placing greater emphasis on citizen participation. Smart governance combines ICTs, open data, adaptive policies, and flexible governance structures tailored to the city and its political and administrative context.

At the heart of any smart city project, often underestimated, lies its human-centric approach. Mathew and Bangwal in their analysis about the Gulf Cooperation Council (GCC) region ([29] B. Parappallil Mathew and D. Bangwal, 2024), highlight the failure of high-tech projects that aimed to improve the quality of life, but failed due to the lack of a people-centric strategy. Their proposal is based on an inclusive model in which citizens are not merely end-users of services, but co-creators of urban policy, actively shaping public decisions and contributing to the development of the city of the future. Hence, for the authors, smart governance must facilitate access to information, data transparency and active participation through digital instruments, physical spaces and inclusive institutional processes.

The digital transformation of a smart city, generates vast amounts of data, from IoT sensors to the behaviour of the citizens on the platforms and more. However, Bozkurt, Rossmann, Pervez and Ramzan ([30] Yusuf Bozkurt et al., 2025) argue that data alone doesn't generate value. To do so it requires an institutional framework capable of managing data lifecycle (data collection, analysis, sharing and protection), guaranteeing the reliability of the data, its accessibility and security. According to the study, many governance models are still derived from the private sector and are poorly suited to the public context, which requires more accountability, participation and regulatory adaptability. A major challenge is coordination between sectors and institutional levels, especially in fragmented or resource-constrained settings.

The article *Smart governance for smart cities and nations* by Kaiser ([31] Z.R.M. Abdullah Kaiser, 2024) highlights fourteen key challenges that smart governance has to face to transform a country into a smart nation and create smart cities, many of which are not related to a technological project. A structural and cultural transformation of public administration, oriented toward innovation, sustainability and participation, is required.

Therefore, there is not a unique model that can fit all environments, but rather a dynamic approach, adaptable to different urban and institutional contexts.

#### 1.3.4 Smart living

Smart living represents the set of innovations and technological solutions aiming to improve the citizens' well-being within smart cities. It offers livable, safe, and accessible environments, as well as efficient public services, a rich cultural and educational offering, and a high standard of sustainable living.

Therefore, to provide a more comfortable, safe and inclusive lifestyle, the focus of smart living is on the following branches:

- Digital healthcare services

The European commission states that it's "working to provide citizens with access to safe and top-quality digital services in health and care". These actions empower citizens to build a healthier society, with in mind three main priorities: access to health data, also across borders, personalised medicine through shared data infrastructure and empowerment of the citizens with digital tools for user feedback and person-centered care. Health data and advanced data analytics drive scientific research, enable an anticipated diagnosis of diseases and allow tailored treatments of the patients. ([32] European Commission, 2025)

- Smart safety systems

Smart safety systems in smart living are the result of the integration of different urban technologies. The combination of intelligent surveillance (AI-powered CCTV networks, video analytics platform ecc.) with adaptive infrastructure (like smart street lighting, IoT sensors or flood-responsive infrastructure) improves the security within a smart city, consequently improving the quality of life of its citizens. Smart safety systems are designed to proactively detect risks, ensure reliability on an operational level and enable automatic preventive actions to improve safety and security while supporting sustainable city management. ([33]I. Gonçalves et al., 2021)([34] M. Vogiatzaki et al. 2024)

- Smart housing

Smart housing assumes a key role in the improvement of safety, comfort and health at home. It exploits technologies such as sensors and IoT to monitor daily activities in the house, detecting possible risks and acting to prevent them, as well as optimizing energy consumptions in the house and assisting those in need to be as independent as possible. These features improve the quality of life of the inhabitants offering benefits not only in terms of safety and commodities but also allowing spare thanks to a more efficient energy consumption. ([35] Adeola Anifowose et al., 2013)

- Access to culture and education

Smart living includes the access to culture and education as a cornerstone of smart cities. The term “learning environment” is not strictly related to schools or universities, but all those interconnected formal, informal and social learning environments, easily accessible to all citizens (such as families, museums, workplace...). ([36] E. Aguaded-Ramírez, 2017) This structure promotes cultural participation, educational inclusion and intellectual preparation for life in urban communities. Simultaneously, urban digital infrastructures can incorporate specific contents based on the local target, enforcing the identity of the city and enhancing the participation. ([37] B. Bucher et al., 2021) Libraries and related cultural

spaces can promote social interaction, disseminate knowledge and offer educational opportunities even to marginalised groups, strengthening urban community networks.

- Connected public spaces

Connected public spaces in smart cities integrate digital infrastructures, such as public wi-fi, interactive kiosks and sensor-equipped smart furniture, to improve accessibility, security and cultural participation. By integrating the physical environment with IoT networks, public spaces foster social interaction, providing real-time information and supporting inclusive urban experiences. ([38] P. Neirotti et al., 2014)

### 1.3.5 Smart mobility

For a functioning smart city, the integration of advanced technologies in urban mobility, allows to reduce the environmental impact and improve the everyday experience for the citizens. Following the study conducted by Brčić et al. ([39] D. Brčić et al., 2018), smart mobility is a key component in a smart city, focusing on a smart adoption of ICT, on smart public transport and on smart parking technologies. Crucial is the management of transport demand, especially in densely populated areas, to reduce traffic congestion and the excessive use of private cars. The implementation of smart solutions such as efficient public transport and dynamic traffic management, is therefore essential to address these challenges.

It's also important to highlight the importance of enabling technologies to support smart cities. In particular IoT, AI and Big Data allow the development of services like Mobility-as-a-service (MaaS), traffic flow optimization, smart logistics and autonomous vehicles, core principles for the transformation of cities into smart ecosystems.

The study ([39] D. Brčić et al., 2018) also underlines the connection between smart mobility, environmental sustainability and quality of life, emphasising how the adoption of smart solutions might reduce pollution, boost energetic efficiency and foster a sustainable urban development.

To this picture, it is worth also adding the perspective drawn by “The Fourth Wave of Digitalization” ([40] P. Davidsson et al., 2016), which gives smart mobility a crucial dimension: advanced digitalisation, and in particular the use of IoT, enables real-time data collection and automated management of public transport systems. This generates tangible benefits also for tourists, thanks to precise scheduling and reactive services, helping also urban operators and planners, who have access to an updated and solid base to plan in a strategic way.

### 1.3.6 Smart people

The last of these six dimensions of the smart city model are smart people, who are citizens with digital skills (e-skills), incorporated into ICT-enabled contexts, with access to education, training and human resource management. Smart people live in inclusive societies, open to creativity and innovation, and with the ability to access, manage and personalize data through adequate analytical tools. Besides technical abilities, smart people are recognisable for their open mentality, entrepreneurial inclination, creativity, involvement in public affairs and the propension towards continuous learning. ([41] S. Gupta et al., 2017) Empirical studies show that in smart people the most recurrent traits are those that encourage and foster collaboration, resiliency and the adoption of innovative practices in urban environments. ([42] Choo Mun Chye et al., 2022)

From a sociological perspective emerges an important distinction that should be kept in mind ([43] S. Piazza, 2017):

- on one side there's the ideal type of smart person promoted by the institutions, companies and academic world (top-down approach)
- on the other side, the smart city users, those citizens that throughout their daily actions embody authentic smart behaviours

However, for the sake of this study, the two concepts will be merged into an ideal scenario, only referring to these groups as smart people.

These people are critical for the success of a smart city, as they represent its human engine: they turn tech into socially useful solutions, co-design urban services, making them more inclusive and responsive to real needs, adopt sustainable practices and shape the city following their consumer choices, lifestyles and political participation. Thus, without them, a smart city would just be a collection of infrastructures and technologies with no real impact; with them, it becomes a living, innovative, inclusive and sustainable ecosystem.

#### **1.4. Existing examples of smart city**

After outlining the definition, objectives and characteristics of a smart city, it's worth analysing some practical cases that display how the theoretical principles are applied into real case scenarios. The following cities provide a diverse picture, featuring different development strategies, priorities and governance models. Usually the adoption of the principles analysed above is just partial, focusing on different areas based on the city itself.

BARCELONA - Barcelona is considered as a smart city oriented towards an enhancement of civic participation and ensuring social inclusion, which is one of their main focuses. The implementation of IoT infrastructures, urban sensors and digital platforms such as *Decidim Barcelona*, aim to improve public services, transparency and inclusion, confirming the citizen-centric approach. ([44] M. Almela et al., 2017) These platforms are quite peculiar, as they allow the citizens to actively propose, discuss and co-design public policies in a transparent manner. Particularly advanced in Barcelona are the management of waste, lighting and mobility.

This Bottom-up approach, based on open data and collaborative governance between institutions, communities and businesses, is responsible for longer times and higher costs compared to a top-down approach, but ensures social acceptance and legitimacy. Therefore, this is the main reason why as of today Barcelona is

internationally recognised as an example of a well balanced solution between technological and social dimensions. ([45] Á.Veloso et al., 2024)

SINGAPORE - Singapore is considered to be one of the most advanced smart cities in the world, thanks to centralized planning and the widespread integration of IoT, Big Data and AI in urban management. The strategy “Smart Nation”, launched in 2014, combines advanced technological infrastructures and real time monitoring systems to face challenges related to mobility, energy, environment, healthcare and security. ([46] J. A. Correa Giraldo et al., 2018) Among the most relevant initiatives are the “Smart Nation Platform” ([47] Smart Nation Singapore, 2025), analysing information about traffic, air quality and energy consumption, and “Virtual Singapore”, a digital twin about the city, used for urban planning and to manage emergencies. ([48] OECD-OPSI, 2015)

The model adopted by Singapore is based on lean and proactive management, promoting continuous adoption of ICT solutions. However, the extensive use of surveillance raises doubts in terms of privacy and data management. Moreover, comparative studies show lower performance than other cities in terms of public participation and social inclusion [45], reporting the need for policies that promote civic engagement. Even in domestic energy efficiency, the success of smart technologies depends on citizen involvement and behavioural change. ([49] A. Bhati et al., 2017)

AMSTERDAM - Amsterdam represents probably the most emblematic example of a European smart city based on a model of collaborative innovation and open governance, fostering business development and environmental sustainability. At the heart of this strategy is the platform “Amsterdam Smart City” (ACS), a network connecting public bodies, private entities, universities, social organizations and citizens, creating an ecosystem capable of co-designing and testing sustainable urban solutions. The driving principle of ASC is open innovation: through an open digital platform, different stakeholders can propose ideas, share data and knowledge and develop transparently new projects, encouraging continuous local and international collaboration ([50] Z. D. W. Putra and W. G. M. van der Knaap, 2018).

A study by Hogeschool van Amsterdam, highlights how ASC acts as a catalyst for partnerships in the fields of energy, mobility, circular economy and waste management ([51] W. van Winden et al., 2016). The model is mainly business-driven and perceives private actors as central, leveraging open-data and collaborative platforms to develop digital services and new business models. Decentralized and adaptive governance promotes co-decision-making among stakeholders and aims to integrate sustainability, technological innovation and social inclusion. These projects are generally conceived in living labs, and afterwards scaled to an urban level, rocketing their effectiveness and public acceptance.

**SPECIALISED AND EXPERIMENTAL CITIES** - Besides big cities as the ones discussed so far, there are multiple smaller cities that undertake a different path, often specializing on targeted sectors. This strategy allows them to become sort of experimental laboratories, developing agile solutions that can eventually be upscaled to bigger cities.

- *Masdar City*: Masdar city (UAE) is an eco-friendly city designed to eliminate air pollution and minimize waste of resources. The city uses renewable energies, especially solar and wind power, for all its urban planning activities and to power the city. Moreover, buildings were built with materials with low impact (close to none) and they exploit smart technologies to reduce hydric and energetic consumption. The result is an environment built to be completely self-sufficient, eco-friendly and regenerative. ([52] F. Guadalupi, 2013)
- *Santander*: Santander can be considered one of the first true smart cities worldwide. Located in the north of Spain, the city developed a wide network of sensors aiming to optimize services like parking, irrigation, waste management and more. This experimental and practical model was designed to reduce waste, improve operational efficiency, and enhance the quality of urban life. ([53] OBS Italia, 2023)
- *Songdo*: located near Seoul, South Korea, this city was projected ex novo to become a cutting edge smart city, with the goal of becoming an international

benchmark for innovative urban planning. The city itself is characterized by the absence of private cars and a strong focus on public and soft mobility. The model focuses on green urban planning, eco-friendly buildings, and integrated technological systems for waste and resource management. ([54] F. Calò, 2020)

To compare the differences between these cities is useful to build a table [Table 1.1] that compares what characterizes each of them.

Table 1.1: Comparison existing smart cities

<b>City</b>	<b>Approach</b>	<b>Main technologies</b>	<b>Strenghts</b>	<b>Weaknesses</b>
Singapore	Centralized, integrated and data-driven	Extensive IoT, Big Data, AI, Digital twin	Efficient planning, strong government support, advanced infrastructure	Privacy concerns and mass surveillance risks
Barcelona	Citizen-centric, open-source	Participatory platforms, smart lighting, open data	Social inclusion, transparency, participatory governance	Difficulties integrating into historic infrastructures
Amsterdam	Collaborative and sustainable	Open data portal, electric mobility and smart logistics	Open innovation ecosystem, strong environmental focus	Need for coordination to ensure project continuity
Masdar City	Ex novo, carbon-neutral city	Renewable energy, microgrid, sustainable mobility	Reduced emissions, model of energy sustainability	High costs, difficulties attracting permanent residents
Santander	Experimental urban laboratory	Sensor network	Advanced IoT testing, experimental flexibility	Limited scalability to more complex contexts
Songdo	Ex novo, with integrated smart infrastructure	Distributed sensors, advanced energy management and waste collection	Full technological integration from the design phase	Lack of urban vibrancy and social identity

In sum, the comparison shows that smart city models vary widely. Some prioritize centralized technology; others focus on citizen participation or sustainability. Their final success depends on balancing innovation with governance and social inclusion.

### **1.5. Current criticalities**

As analysed so far, smart cities are a rapidly growing trend that goes hand in hand with technological development and other key factors. The model has a huge potential if exported and adapted properly based on the area, it could help solve many problems of different nature, bringing multiple benefits to the population living in that area. However, not all that glitters is gold. As of today, smart cities are not yet what they aspire to be and there are still some criticalities that should be solved.

#### ❖ Cybersecurity

The infrastructure that currently supports smart cities, such as sensor networks, IoT platforms, energy management, etc., constitutes a highly interdependent ecosystem. As a result, various IT vulnerabilities arise and can compromise the stability of the entire city.

The possible risks are of various kinds. The first of these is the theft and manipulation of data by third parties. Another significant risk is the hijacking of IoT devices, with insufficiently protected devices that might be compromised and become a dangerous access point for the manipulation of urban services. More cybersecurity risks are DDoS (Distributed Denial of Service) attacks, which saturate the network by blocking essential services, or the compromise of critical networks, where, given the interconnection, an attack on a single node can cascade and disable entire urban infrastructures. ([55] K. Trapenberg Frick et al., 2021)([56]R. José and H. Rodrigues, 2024)

These risks stem from the technological heterogeneity of devices and platforms, which often lack security-by-design principles and regular updates. ([55] K. Trapenberg Frick et al., 2021). This fragility is further amplified by the interconnection of critical sectors such as energy, transport and healthcare, which means that in the event of an attack, there is a risk of a domino effect with serious consequences ([56]R. José and H. Rodrigues, 2024). The absence of shared standards for data and infrastructure protection makes it even more difficult to guarantee total security. The possible consequences are therefore not limited to technical aspects. Attacks could cause power blackouts, traffic jams, emergency system failures or other issues, thereby significantly impacting citizens' lives ([57] Q. Gu et al., 2025). Such events can undermine citizens' trust in institutions or even turn urban infrastructure into potential targets for cyber warfare, and this explains why so many investments are focused on avoiding it.

#### ❖ Privacy and surveillance

The growing diffusion of sensors, cameras and digital platforms in the cities entails a continuous and massive collection of data, arising significant doubts in matters of privacy and surveillance. That information can include highly sensitive personal data, like movements, consumption habits and also healthcare information, and are often used for ends that are not always transparent or fully agreed by the citizens. ([58] E. Ismagilova et al., 2022)

Consequently, this paves the way for both commercial exploitation practices, like profiling and targeted advertising, and systematic surveillance from public authorities or private entities, compromising fundamental rights such as personal freedom. The absence of structured mechanisms for consent and shared rules for data management worsens these issues, highlighting the danger that smart cities might turn into panoptic spaces rather than ecosystems geared towards the well-being of citizens. ([59] L. Xia et al., 2023)

#### ❖ Data governance

Another critical and delicate theme to be faced is that of data governance in smart cities, as the collection and elaboration of copious amounts of data requires to determine precise rules, use the appropriate resources and follow a coherent strategy. Although very important, as of today the management of data is still often fragmented. There is a lack of common standards and shared policies to regulate the collection, storage and sharing of information, creating risks in terms of security, reliability and ethical use of urban technologies ([60] O. Kolotouchkina et al., 2024). In addition, limited financial resources and technical competencies represent obstacles for local administrations in the adoption of solid data governance systems and address further difficulties in ensuring an adequate level of protection.

According to the OECD, the rapid growth of digital ecosystems in cities often exceeds the institutional capacity to govern them, creating gaps between the innovative potential of technologies and their actual application. ([61] OECD, 2020) The consequence is dual: the risk that the data collected is not exploited to its full potential, as it might be incomplete or fragmented, limiting the impact of smart initiatives, and the possibility that in the absence of solid governance rules inappropriate usage of the information, ethic violations or other digital inequalities may emerge. ([57] Q. Gu et al., 2025)

#### ❖ Social inclusivity

Social inclusivity represents a vital challenge for smart cities, as the adoption of urban technology risks accentuating social inequalities if not followed by inclusive strategies. Differences in access to the internet, digital devices, and technological skills may exclude vulnerable groups such as the elderly or individuals with low levels of digital literacy, thereby generating new forms of marginalization.

Recent analysis underline how “digital divide” should be considered at three distinct levels: access to infrastructures, development of competences and capacity to obtain socio-economic benefits. This way, a strategy that only

aims to the expansion of connectivity won't be enough. Integrated approaches that combine investments in infrastructures, digital literacy programs and governance models promoting active involvement within the citizens are needed. ([62]V, Kruhlov and J. Dvorak, 2025) Only through this synergy can smart cities avoid becoming elitist ecosystems and become inclusive spaces, capable of reducing instead of amplifying social inequalities.

#### ❖ Economic feasibility

A concern around the smart cities is also their economic feasibility, especially thinking about the long term run. In fact, to realize this model several investments in ICT infrastructure, digital systems and ongoing maintenance are needed, without the certainty of recouping the investment in the short term. ([63]S. Jangjoo, 2025) Added to this is the difficulty for local administrations to bear the operational and organisational costs, especially in contexts with limited resources.

An article published in 2022 ([64] G. Puron-Cid and J. R. Gil-Garcia, 2022) studies the impact of ICT infrastructures in municipal financial sustainability as an indicator, showing that well-calibrated investments can have a positive impact on various balance sheet indicators, including liquidity, short- and long-term solvency, and the ability to maintain service levels. All this is conditional on spending decisions being supported by long-term analysis and robust financial strategies. The result highlights the importance of well-built investment to guarantee that administration won't have to face costs that in the future wouldn't be sustainable.

What emerges from the literature is that many of the limitations of smart city initiatives derive not from technical barriers but from institutional and social dynamics. Lock-in effects, uneven access to digital infrastructures, fragmented governance and the failure of several early projects show that technological progress does not automatically translate into effective or inclusive urban transformation. These structural tensions delineate the boundaries of current smart

city models and suggest the need for caution when generalising successful experiences across different urban contexts.

In conclusion, smart cities provide interesting opportunities for urban innovation and improvement of the quality of life for the citizens, nevertheless the implementation is obstructed by the criticalities listed above. These dimensions, strictly interconnected, require an interdisciplinary approach, crucial for a proper development of smart cities towards a resilient, sustainable and citizen-centric future.

## **1.6. Overview of smart infrastructures**

Within the scope of smart cities there is no single official classification of infrastructures. The literature proposes various interpretative models. The one presented by Fakhimi et al. ([65] A. H. Fakhimi et al., 2021) for example distinguishes between physical, digital and social infrastructures, while Birbi & Krogstie ([66] S. E. Bibri and J. Krogstie, 2017) adopt a similar tripartition, enriching the framework with a different articulation.

Other authors propose functional diagrams, where the three previous groups are intertwined. Anthopoulos ([67] Leonidas G. Anthopoulos, 2015) for example identified seven main domains in smart cities: resources, transportation, urban infrastructure, living, government, economy and coherency. Perboli et al. ([68] G. Perboli et al., 2014) present a taxonomy that considers areas of application such as construction, energy, the environment, mobility, health, education and governance. Another complementary perspective is the one offered by the International Telecommunication Union (ITU) ([69] Roberto Ortiz et al., 2015), which distinguished ICT-based infrastructures (telecommunication, cloud, IoT...) and non-ICT based (energy, transport, buildings, water...).

Starting from these contributions, in this work a revised functional classification will be adopted, with the objective of highlighting the most involved sectors, further detailed later. Therefore, the main domains selected are:

- *Energy and smart grids*, which enable efficiency, sustainability, and integration of renewables
- *Transport and mobility infrastructures*, including intelligent public transport, electric mobility, and real-time traffic management
- *ICT and telecommunication networks*, providing the digital backbone through IoT, 5G/6G, cloud services, AI and data platforms
- *Buildings and urban infrastructure*, with smart buildings and sustainable construction practices
- *Environmental and resource management infrastructures*, concerning water, waste, and air quality monitoring
- *Public services and governance platforms*, leveraging digital technologies for citizen participation and efficient city management

It's important though to stress that this distinction doesn't imply independence between these categories, on the contrary the different infrastructures interact and reinforce each other. The classification should therefore be understood as a conceptual tool useful for schematisation, keeping in mind that the interrelationships between the various levels are fundamental to ensure the overall functioning of the urban system. Each of these domains will be analyzed in detail in the following sections, highlighting their internal components and their interconnections with other infrastructures, which are crucial for the integrated functioning of a smart city.

### 1.6.1 Energy and Smart grids

The energy sector is the beating heart of smart cities, and smart grids, based on advanced control and communication technologies, are a backbone to guarantee efficiency, sustainability and urban resiliency . In general, however, the transition to smart cities requires more sustainable, resilient and efficient energy systems that can integrate renewable sources, reduce emissions and ensure reliable distribution ([70] D. Szpilko et al., 2024). This theme of the energy sector will be further addressed in the latter chapters of this thesis, only providing here an initial overview.

Smart cities aim for a diversified energy mix with growing shares in renewable energies (especially solar, wind and hydro power). The decentralized production of energy and the diffusion of prosumers (users that produce and consume their own energy) significantly impact the structure of the urban energy system. The traditional centralized electric grid is gradually being overtaken by the smart grid, which integrates distributed production and advanced energy flow management.

Smart grids are based on real-time monitoring through sensors, smart meters and SCADA systems, on the integration of storage systems to balance the unevenness of renewable power and on the use of digital technologies like IoT or AI. ([94] C. Zilio, 2024) These infrastructures do not merely distribute energy, but also enable new functions. They guarantee operational efficiency through demand-response mechanisms and dynamic balancing, increase resilience against failures and blackouts, promote sustainability by allowing greater penetration of renewables, and encourage active user participation.

In spite of the huge potential, as of today there are still some criticalities that raise important engineering challenges. ([71] K. Ota et al., 2017) The main ones are:

- ❖ Interoperability among heterogeneous systems
- ❖ Cybersecurity and data protection
- ❖ Governance and regulation to coordinate utilities, institutions and citizens
- ❖ High costs for infrastructures' modernization

### 1.6.2 Transport and Mobility Infrastructure

An important infrastructure in constant evolution is transportation and mobility, complex cyber-physical systems in which the integrated management of mobility, energy and data ensures operative efficiency, reliability and sustainability. In these systems, that include everything and everyone involved in moving people and goods, the spreading of IoT sensor networks and different communication platforms are key. These technologies facilitate continuous monitoring of traffic conditions,

safety measures, transportation demand and availability of parking spaces, thus creating an adaptive transport ecosystem based on empirical evidence. ([72] D. Oladimeji et al., 2023)

Within this paradigm, the theme of electric mobility became a strategic priority. The planning of the charging network for electric vehicles (EV), besides the geolocalization of the stations, also has to consider the impact of the load on the electric grid, the variability of the demand and the integration with renewable sources. Advanced approaches, such as Machine Learning combined with multivariate analysis and optimization models with multiple goals, are crucial to sustain resilient and sustainable decision-making in this field. ([73] J. A. Guerrero-Silva et al., 2025)

Simultaneously the management of traffic flow is shifting towards the adoption of reinforcement learning algorithms for adaptive traffic light control, overcoming the limitations of fixed cycles or rule-based logics. These solutions allow to reduce significantly traffic congestion, average travel times and CO<sub>2</sub> emissions, reacting in real-time to the changing dynamic scenarios of urban environments. ([74] P. Michailidis et al., 2025) Another piece is those services based on Real-Time Transit Information (RTI), allowing public transport users to be updated on arrival times, the availability of vehicles and the state of the network. The implementation of RTI through GPS and advanced communication platforms, improves the quality of the service, encourages a shift from private to public transport, and supports dynamic network planning. ([75] Y. Chen and Y. Liu, 2023)

Finally, the implementation of these instruments with approaches to AI applied to logistics and multimodal transport systems, open the possibility for an even better optimized combination of means of transport, improving proactive response for raising demand and approaching decarbonization goals.

### 1.6.3 ICT and Telecommunication Networks

Smart cities evolution lays heavily on the development of telecommunication network and ICT technologies, which grant the connection and the coordination

between complex urban infrastructures. The availability of advanced networks is not just a technical requirement, but a condition to enable innovative digital services, efficient urban systems and a continuous interaction between citizens, institutions and businesses.

Most recent mobile networks, 5G and soon 6G, are distinguishable for the ability of supporting mass communications between IoT devices that require extremely low latency and high reliability, like autonomous mobility or emergency management. From an engineering perspective this can be translated into the need to build heterogeneous and distributed architectures capable of endorsing growing and diversified traffic volumes. ([76] I. Yaqoob et al., 2017) Simultaneously, the use of cloud services allows for decentralized processing, reducing response times and supporting data-intensive applications.

These infrastructures aren't confined to data transmission, they also introduce new functions for urban management. They allow the integration of sensors and actuators spread throughout the city, enable data-driven governance models and encourage the scalability of digital services. However, some criticalities remain, generating engineering and managerial challenges. Among them, the main ones are interoperability, cybersecurity, the need for shared governance rules to coordinate different stakeholders, and the high costs associated with upgrading and modernising infrastructure. ([77] A. R. Javed et al., 2022)

#### 1.6.4 Buildings and Urban Infrastructure

Smart building and urban infrastructures are central in the transition towards smart cities, contributing to make them more sustainable, resilient and efficient. Smart buildings differ from the so called "connected buildings" because they don't just integrate digital technologies, instead they exploit IoT, sensors and AI to monitor and manage in real-time parameters like lighting, ventilation, thermo-climatic comfort and air quality. The objective of doing so is to improve the well-being of those occupying the building. An actual example is "The Edge" in Amsterdam, which with around 28000 sensors connected to a centralized platform allow to automatically regulate different parameters, reducing energy consumption up to

70% compared to conventional buildings. ([78] University of the Built Environment, 2025)

Technically speaking, smart buildings are analyzed through established KPIs that include Smart readiness Indicator, energy labels, systems' reliability and users' involvement. Tools like Building Energy Management Systems (BEMS) integrate sensors, devices, and analytical software to monitor things such as consumption, but they also manage the demand and activate demand-response mechanisms, improving resiliency and efficiency. However, these systems also provide some challenges, especially in terms of interoperability, safety and privacy. ([79] J. Al Dakheel et al., 2020)

In terms of infrastructure, sustainability requires a systemic approach that considers the entire lifecycle of the building. The sector is responsible for about 50% of global CO<sub>2</sub> emissions and 40% of materials' consumption, highlighting the urgency for low-carbon practices, eco-refurbishment strategies and innovative approaches for lifecycle-based planning. ([80] B. Sodagar and R. Fieldson, 2008) To foster this transformation, innovative financial approaches are needed, as the economic dimension is not neglectable. Green bonds, incentives and publi-private partnerships are gaining ground, although some significant barriers remain. The main ones are those linked to high initial costs, the lack of data standards or legislative gaps that hinder the full implementation of resilient and low-carbon models. ([81] Ming Shan et al, 2017)

#### 1.6.5 Environmental and Resource Management Infrastructure

This infrastructure is a paramount one for the realization of a smart sustainable city. It includes the management of different systems, like water, waste, air quality and natural resources. To do so, critical is the adoption of tools for monitoring and mitigation of environmental risks. The main objective is to guarantee sustainability, urban resiliency and improve citizens' quality of life. ([82] M. Yilmaz Salman and H. Hasar, 2023)

Enabling technologies also in this case include IoT sensors for continuous monitoring of air quality, water pollution level, urban noise and more. Smart water management systems for example allow to detect losses, monitor water consumption and optimize its distribution, providing a complete overview of the water network. The implementation of IoT here guarantees a higher quality level for drinking water as well as a more efficient flow for agricultural purposes and more. Also for waste management it combines data from smart bins, planning optimized collection routes and promoting recycling practices. The use of predictive models and AI algorithms allows to foresee critical events such as heat waves, floods or pollution peaks and react to improve urban resiliency. ([83] M. Bacco et al., 2022)

Practically speaking these technologies allow not only to reduce waste and optimize the use of resources, but they also provide useful information for sustainable urban planning and enhance the active participation of the citizens. Some instruments, platforms and models assess ecosystem services, supporting public decision-makers in implementing resilience strategies and green infrastructure through useful KPIs.

Therefore, the main benefits of this infrastructure include the reduction of environmental impact, improved public health, efficient resource management, and greater resilience to climate change. However, some challenges remain, in particular the interoperability between different platforms and sensors, as well as data security, institutional barriers and the costs of implementation and maintenance. Moreover, another obstacle is represented by the difficulties in intersecting this infrastructure with the other ones, to guarantee a synergic operation of the city. ([82] M. Yilmaz Salman and H. Hasar, 2023)

#### 1.6.6 Public Services and Governance Platforms

In smart cities another important infrastructure is built around digital governance platforms, which play a vital role in dispensing and innovating public services, as they allow to combine advanced technologies with participative decisional processes. As Ryu, Kim and Hong highlight ([84] Seung Eui Ryu, 2022), the model “Smart Governance-Decision Support System” (SG-DSS) is an explicative

example of how the exploitation of Big Data and AI can amplify the capabilities of administrations to collect, analyze and transfer people’s preferences into tailored public policies.

In this perspective, citizens are no longer a passive final end of a service, instead they become a major actor in the co-production process of public services. A wider vision ([85] I. Abdulaziz et al., 2025) proposes a multidimensional framework of smart governance, based on efficiency, transparency and collaboration, where the adoption of IoT allows real-time monitoring of urban conditions and a wider range of services (in healthcare, education ecc.) improving the responsiveness of the city to the needs of its inhabitants. Nevertheless, these platforms also pose certain challenges. System interoperability, infrastructure constraints, and the lack of digital skills in public administrations are factors that can limit the effectiveness of citizen-oriented innovations. ([86] D.Landsbergen et al., 2022)

Anyhow, all in all, the evidence provided in the studies just mentioned show how governance platforms are not just technological systems, but true socio-technic ecosystems that, if implemented correctly, have the potential of improving the quality, the level of customization and the legitimacy of public services in smart cities.

A useful summary to understand the main infrastructure of a smart city is presented in the following table [Table 1.2].

Table 1.2: Smart city main infrastructures

<b>Infrastructure</b>	<b>Definition</b>	<b>Physical components</b>	<b>Smart components</b>
Energy and Smart grids	Energy infrastructure based on smart grids that integrate renewables, digital technologies, and user participation to ensure efficiency, sustainability, and resilience	<ul style="list-style-type: none"> <li>- Power distribution networks</li> <li>- Primary and secondary substations</li> <li>- Renewable energy plants (PV, wind, biomass)</li> <li>- Physical energy storage systems</li> </ul>	<ul style="list-style-type: none"> <li>- Smart meters, sensors, SCADA systems</li> <li>- IoT &amp; AI for monitoring and demand-response</li> <li>- Energy management systems &amp; renewable integration</li> </ul>
Transport and mobility	Transport and mobility infrastructure using IoT, AI, and data integration	<ul style="list-style-type: none"> <li>- Roads, bike lanes, parking facilities</li> <li>- Rail, tram, and bus</li> </ul>	<ul style="list-style-type: none"> <li>- IoT sensor networks &amp; communication platforms</li> </ul>

	to optimize traffic, support electric mobility, and enable sustainable, efficient, and adaptive urban transport systems	networks - Stations, stops, intermodal hubs - EV charging stations (physical side)	- AI & Machine Learning-based traffic prediction - Real-Time Transit Information (RTI) via GPS
ICT and Telecommunication	ICT and telecommunication networks infrastructure connects all other urban infrastructures, enabling digital services, IoT communication, and data-driven governance in smart cities	- 5G/6G towers and antennas - Fiber-optic networks - Data centers - Edge computing hardware	- 5G / 6G software networks - Cloud & Edge computing services - IoT connectivity for urban systems - Network management systems
Urban and Smart buildings	Infrastructure of smart buildings and urban systems that use IoT, sensors, and AI to improve comfort, efficiency, and sustainability while reducing environmental impact	- Buildings and HVAC systems - Low-carbon construction materials - Electrical and hydraulic systems	- IoT sensors & AI for real-time monitoring - Building Energy Management Systems (BEMS) - Lifecycle-based low-carbon technologies
Environmental and resource management	An infrastructure for sustainable management of resources and environment, using smart technologies to monitor, optimize, and reduce urban impact	- Water supply and sewage networks - Treatment plants - Waste collection and sorting facilities - Physical waste containers	- IoT sensors - Smart water & waste management systems - AI predictive models for environmental risks
Public services and governance	A digital infrastructure that integrates technologies and participation to deliver and innovate public services	- Administrative buildings - Public service centers - Physical service desks - Emergency infrastructure	- Big Data & AI decision-support systems (SG-DSS) - IoT for real-time monitoring of services - Digital platforms for citizen participation

This classification should not be interpreted as rigid, since the infrastructures rarely function as self-contained units. One recurring insight across the literature is that the effectiveness of each system depends on its capacity to interact with the others. This interdependence is not a corollary of the model but its defining trait, and it is precisely what makes the smart city both promising and inherently complex.

## **1.7. Overview of interrelationships between different infrastructures**

In order to have a smart city that properly works in all its functionalities, it's fundamental to have a strong interconnection within and between the different infrastructures. Doing so is not an easy task, as the components and technologies of the city itself usually work with different configurations and providers. In order to enable this collaboration and obtain a working complex ecosystem that is a smart city, interoperability is a crucial feature.

Interoperability can be defined, in the broadest sense, as the ability of products and services to work together and to exchange information during all lifecycle stages. ([94] C. Zilio, 2024) It may seem obvious, but it's worth remarking on the fact that interoperability is an essential condition for the correct functioning of a smart city, as the various infrastructures don't operate separately, rather as an integrated and interdependent system. It emerged from literature that it is not just a technical requirement, but a true systematic challenge. As analyzed by Koo and Kim ([87] J. Koo and Y-G Kim, 2021), the main challenges don't lay only in the integration between the different components, rather, as said, in guaranteeing an efficient communication between heterogeneous platforms, managed by different suppliers and based on not always uniform standards.

This issue reveals an even deeper challenge. The more interconnected the infrastructures become, the more the city behaves as a coupled system in which failures can propagate and optimizations in one domain affect the functioning of others. Recognising this systemic behaviour is essential for understanding why the smart city cannot be reduced to a technological upgrade of existing services.

Interoperability as just defined is composed of 3 levels:

- Technical, about the compatibility of protocols and interfaces
- Systematic, to ensure that the data shared is eventually read with the same meaning in spite of its source
- Managerial and organizational, which concerns the coordination between institutions, businesses and citizens involved

Only by ensuring this multidimensionality of interoperability is it possible to truly develop an integrated urban ecosystem, where infrastructures don't remain isolated compartments but they support each other, enabling innovative and synergic systems.

In literature, ICT is often recognised as the enabling infrastructure that allows interoperability and the integration of different urban domains. Nikolay Tcholtchev and Ina Schieferdecker in their publication ([88] Nikolay Tcholtchev, Ina Schieferdecker, 2021) define it as the glue of the smart urban ecosystem, as it ensures communication and the exchange of data among different sectors (energy, transport, healthcare, environment ecc.) through 'Open Urban Platforms'. Similarly, other studies (like "The Impact of ICTS in the Development of Smart City: Opportunities and Challenges" ([89] S. Al-Maqashi et al., 2024)) suggest a layered view of smart systems, where network and platform technology layers (which are based on ICT) enable applications in vertical domains, stressing on how the digital infrastructure is the cornerstone for every advanced urban system.

Next to ICT, governance is seen as the other key enabling infrastructure. Smart governance has the capacity to orchestrate transactions between different actors and domains via digital tools. Smart governance, however, does so by exploiting ICT to facilitate collaborative decision-making processes and coordinate diverse sectors.

The other infrastructures, of those previously analyzed, can be considered as operative infrastructures, which interact with each other in an increasingly coordinated way thanks to ICT and governance infrastructures. This multi-layered approach is well exemplified by the Vitoria-Gasteiz case ([90] F. Larrinaga et al., 2021), pilot city for the European SmartEnCity project. Here energy, buildings, mobility, and environmental and resource management, were integrated by a digital urban platform (CIOP), which monitors and analyzes their performance efficiently managing the urban assets.

Practically speaking, how do these four operative infrastructures interact? As said they are strictly interdependent. *Energy and smart grids* support electric mobility and smart buildings, as well as it impacts environmental management, while

*Transport and mobility* impact energetic distribution and urban planning. *Buildings and other urban components* (which include the likes of aqueducts and public lighting) can be defined as prosumers, as they produce and consume energy flexibly, impacting the electric grid and requiring coordination with transportation systems. Simultaneously, *environmental and resource management* provide essential data for air quality monitoring, urban greenery, and water availability, which affect operative decision-making in transport and buildings. The confirmation comes from a study from Brunner and others ([91] L.G. Brunner et al., 2024), who studied the links and cascading effects between critical urban infrastructures in the city of Christchurch.

Fundamental is to underline the fact that also the infrastructures related to ICT and governance, although transversal and coordinating infrastructures, are themselves dependent on the correct functioning of the operative infrastructures. Without electric energy, digital platforms and communication systems wouldn't work, as every other characterizing element of a smart city. Without resilient urban and environmental networks, the data collected and managed by ICT would be neither complete nor reliable. Moreover, without efficient transport decision-making processes coordinated by governance would probably remain unfeasible in practice. In a broader sense all these infrastructure can be seen as enabling, yet for the sake of a better schematisation it's worth separating those two that also coordinate the others. Therefore, the intelligent urban ecosystem is an integrated and circular ecosystem, where top-down (from ICT and governance) and bottom-up (from operative infrastructures) approaches mutually reinforce each other, ensuring the resiliency and efficiency of the smart city. [Figure 1.2]

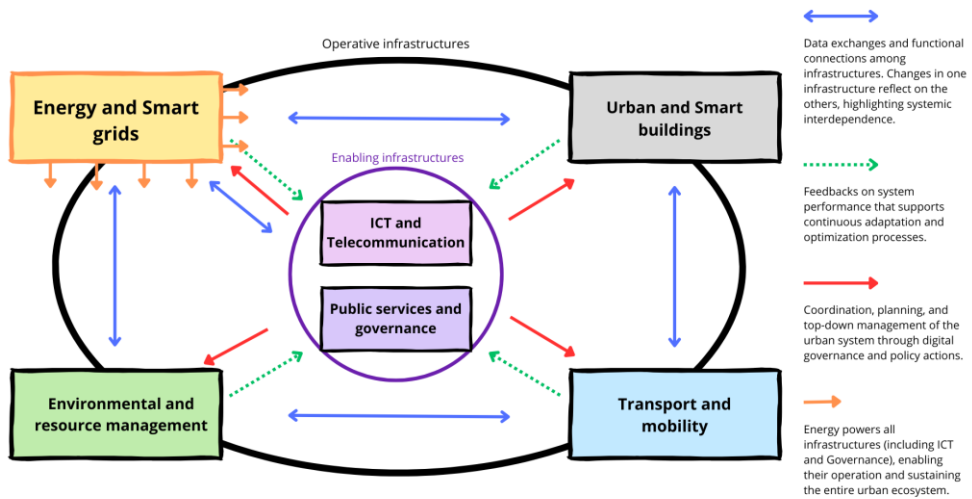


Figure 1.2: Schematisation of the main relationships between the infrastructures of a smart city

## **Chapter 2 - Advanced Energy Systems in Smart Cities**

This chapter focuses on the infrastructures that underpin smart cities, with a specific emphasis on energy systems as an enabling component. It analyses how smart grids, electrification, storage and sector coupling support the operation of urban services. The chapter also outlines modelling elements from the literature, such as power flow, flexibility and demand response, to clarify technical mechanisms without aiming at numerical validation. Overall, it builds the analytical framework linking energy, digitalisation and urban operations.

### **2.1 Energy as the heart of a smart city**

Energy can be seen as one of the most relevant elements in the development of a smart city and is hence worth investigating it further in detail. It is, in fact, an area that covers technical and managerial aspects, having also an impact on social matters related to the involvement of citizens and accessibility to services, making it particularly significant to comprehend the evolving urban transformations.

As previously discussed, energy and smart grids can be classified as an operative infrastructure, as it guarantees the daily operation of smart cities. Unlike ‘ICT and communication networks’ and ‘public services and governance’ infrastructures, the energetic one doesn’t impose a direct management system functions over other systems, instead it becomes their enabling factor: without electric energy the city couldn’t live, as proven by the blackout in the Iberian Peninsula in April 2025.

As studied by Pimentel, Balázs and Drotár ([92] J. Pimentel et al., 2023), smart cities are complex urban systems where subsystems like water management, mobility ecc. require integrated energy management, capable of coordination, distribution and storage. From this perspective, the energy network assumes a key operative role. It's not just a support role for other infrastructures, but rather the core mechanism that sustains the entire urban system running.

Furthermore, the smart grid, the key element of the energy infrastructure, over time is turning into a paramount element for adaptive urban energy management, able to integrate renewable energy sources and guarantee operative efficiency simultaneously, as depicted in figure [2.1]. Although not directly managing other systems, this infrastructure enables their use thanks to a smart, resilient and stable supply. ([93] D. Szpilko et al., 2024)

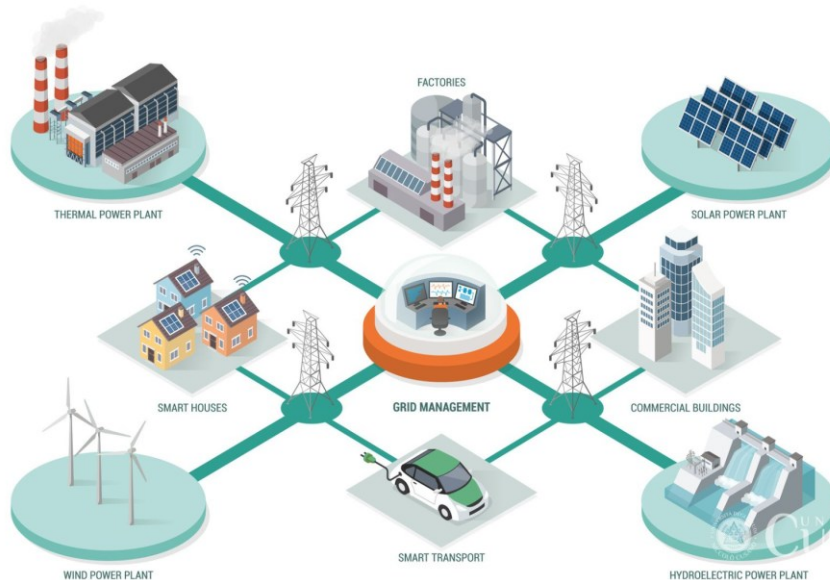


Figure 2.1: Overview of the smart grid's structure ([93] D. Szpilko et al., 2024)

A useful and intuitive parallel for understanding the role of energy in smart cities is that of the human body. Just as the circulatory system distributes blood and oxygen to all organs, ensuring the functioning of the body, the energy network and smart grids convey electricity efficiently, safely and economically to all urban subsystems. In both cases, this is vital infrastructure: invisible in everyday life, but essential to ensure the continuity and balance of the entire system.

## 2.2 From centralized to distributed model

The traditional power grid [Figure 2.2] is a centralized control and management system that uses supervisory control and data acquisition (SCADA). It is based on a centralized approach, where energy generation happens in large plants (thermoelectric, hydroelectric and nuclear power stations) and the flow of electricity in the grid is from top (high-voltage network) to bottom (low-voltage network) where it reaches the final consumer. In this scheme the final user has a passive role, only being the consumer, while communication and information exchange between producer and consumer are basically non-existing. Therefore, the system appears to be rigid, and this lack of flexibility makes it unsuitable for embracing new innovative solutions that include renewable energy sources and the widespread use of electric vehicles. ([94] C. Zilio, 2024).

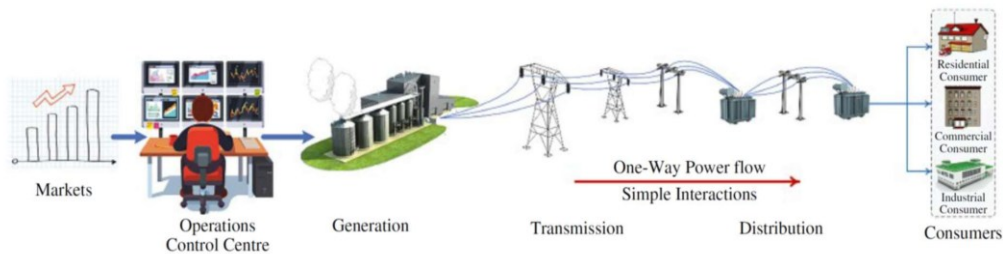


Figure 2.2: schematic representation of a traditional grid's flow ([94] C. Zilio, 2024)

Compared to this model, the smart grid (SG) embodies a fundamental evolution. In fact, the SG is designed to tackle the challenges and limitations of the traditional grid by integrating and smartly utilizing the electricity, information, and communication infrastructures through digital technologies. The Department of Energy (DOE) defines it as “the electricity delivery system, from point of generation to point of consumption, integrated with communications and information technology for enhanced grid operations, customer services, and environmental benefits” ([95] Electricity Advisory Committee, 2008), while The European Technology Platform underlines its capacity to “intelligently integrate the actions of all users” to guarantee an efficient, sustainable and secure energy supply. ([94] C. Zilio, 2024)

From a structural point of view, SG is distinguishable for the presence of the two-way exchange of power and information within the grid, which allows a more flexible and resilient system. To better understand its characteristics and how it works, we can group the SG's composing elements into seven key technology areas: ([94] C. Zilio, 2024)

- *Distributed generation*: it includes the microgrid and have the capability to work both connected to the main network or isolated
- *Electric storage system*: which enable to balance and manage the intermittent energy production of renewable sources
- *Smart meters and advanced control*: smart meters and AMI (advanced metering infrastructure) that includes them, constitute the communication network of the smart grid that allows to have a constant dialogue between utilities and users
- *Integrated communications*: this is a smaller multilevel infrastructure that allows real-time data exchange, it's purely about data transfer. It connects all the elements of the smart grid, organised in three levels: HAN (home area network), NAN (neighborhood area network) and WAN (wide area network)
- *Sensing and measurement*: phasor measurement units (PMUs) for instantaneous monitoring and distributed control, providing detailed information about the network and its state of art
- *Customer engagement*
- *Demand response*: allows the consumers to adapt their energy consumption based on the energetic availability, hence inverting the traditional paradigm where demand pulls the demand

In scientific literature, it's been highlighted that the smart grid is based on the convergence between electric and communication networks, enhancing the key role of ICT in order to enable advanced services. ([96] J. Zheng et al., 2013) Other studies insist on the importance of active participation from the prosumers (those that with the traditional grid were just consumers, now also produce and sell energy in this relatively new model) and on the integration of renewable energy as crucial

steps for energetic sustainability. ([97] R. Bayındır et al., 2016) These characteristics show how this transition towards smart grids is not limited to a technical aspect, but also has socio-economic retrospectives. It radically modifies the relationship between producers, distributors and consumers by removing the centralization of the system and handing more power to the user that now has more power as well. ([98] B. Schäfer et al., 2015)

As the table in figure 2.3 shows, there are easily noticeable differences between the two models. The main one is the fact that there's a shift from a centralized production, with one-directional flow and passive users to a solution where the distributed generation of energy and the two-way flow allow the user to become a prosumer, hence an active participant of this system. Furthermore, it's worth also mentioning that while the management of the traditional grid is reactive and based on SCADA systems, smart grid management is predictive, supported by distributed intelligence algorithms and real-time analysis. ([94] C. Zilio, 2024)

Characteristics	Traditional grid	Smart Grid
<b>Technology</b>	<ul style="list-style-type: none"> <li>• Electromechanical</li> <li>• Mechanical devices electricity operated</li> <li>• No communication between devices</li> <li>• Little internal regulation</li> </ul>	<ul style="list-style-type: none"> <li>• Digital</li> <li>• Digital devices</li> <li>• Increased communication between devices</li> <li>• Remote control and self-regulation</li> </ul>
<b>Flow of power and communication</b>	<ul style="list-style-type: none"> <li>• One way</li> <li>• Power flow starts from the main plant using traditional energy structure to the customer</li> </ul>	<ul style="list-style-type: none"> <li>• Two way</li> <li>• Power flow goes to and from various grid users</li> </ul>
<b>Generation</b>	Centralized	Distributed
<b>Fault location</b>	Difficult to determine	Can be determined remotely as well as predicted
<b>Monitoring</b>	Manual	Self- monitoring
<b>Equipment failure</b>	System responds to deal with post failure and blackout incidents	Adaptive and can be isolated and automatically reconnected.
<b>Control</b>	Limited control system	Pervasive control system
<b>Operation and maintenance</b>	Manually equipment checks	Remotely monitor equipment

*Energy management and digitalization – prof. Claudio Zilio*

Figure 2.3: Main differences between traditional and smart grid ([94] C. Zilio, 2024)

Consequently, the SG carries multiple advantages compared to the traditional approach: greater energy efficiency, reduced losses along the network, better integration of renewable sources, increased resilience against failures or extreme events and, last but not least, consumer empowerment, allowing consumers to produce, consume and share energy in a participatory manner. In synthesis, SG doesn't just represent a technological evolution of the electric network, it is a real paradigm shift, where communication infrastructures and smart meters act as the nervous tissue of the new energy architecture, controlled by the public services and governance infrastructure.

### 2.3 Smart grid's energy management models

Following the qualitative analysis of the differences between the traditional approach and the smart grid, it's important to also analyze those differences from a quantitative and technical point of view. The goal of this paragraph is to illustrate, in a simplified and conceptual way, how mathematical models describe the main mechanisms of energy management in a smart city, dynamically and on different levels, by reducing energy losses, implementing more renewable sources and involving the citizens who become prosumers, hence active actors in this scheme. The following models are not intended as computational tools for the present work, but as simplified representations used in the literature to clarify the key mechanisms that characterize smart grids.

#### ➤ *Energy Balance Equations*

In the *traditional model* we can analyze the macroscopic instantaneous energy balance by simply balancing the active power.

$$\sum_g P_g(t) = \sum_d P_d(t) + P_{loss}(t)$$

where  $P_g(t)$  is the total generated power in the power stations at the instant t,  $P_d(t)$  is the total demand of the consumers at the same instant t, while  $P_{loss}(t)$  are the

total power losses, including both transmission and distribution.

These equations are presented for explanatory purposes, to clarify the physical constraints governing smart grids, without aiming at their numerical implementation.

This equation specifically exemplifies, in an extremely simple way, the philosophy of the centralized system, where power generation is programmed to follow the demand and the end user has a passive role, being just the receiver of these unidirectional flow.

Maintaining a simple approach without expliciting many of the existing variables the following equation is set to give an idea of the differences from a macro perspective. For the *smart grid* we consider the constraints related to distributed generation, import/export with the higher network, and charging/discharging flows of the storage systems as follows:

$$\begin{aligned} \sum_{i \in G_{conv}} P_i(t) + \sum_{j \in DG} P_j(t) + P_{import}(t) + \sum_{s \in S} P_s^{dis}(t) \\ = \sum_{k \in D} P_k(t) + \sum_{s \in S} P_s^{ch}(t) + P_{loss}(t) \end{aligned}$$

- $G_{conv}$ : conventional and controllable power stations
- $DG$ : distributed generators (PV, wind, local combined generation...)
- $P_{import}$ : power withdrawal (positive) or transfer (if negative) from the external network
- $S$ : total storage, with  $P^{dis}$  discharge and  $P^{ch}$  charge
- $D$ : loads/utilities (including prosumers), therefore the demand

In this equation the component that is probably less obvious to predict is that of power losses, which are determined by the difference between the energy that enters the distribution system and the one that arrives to the end user. These losses can be divided into two categories, technical and non-technical losses. ([99] D. F. Niste et al., 2025) Technical losses are defined as losses of electrical energy due to the physical properties of transmission and distribution system components (mainly lines and transformers). They naturally manifest themselves as thermal effects,

magnetic fields, eddy currents or phenomena such as the corona effect, and are generally quantifiable. Extending the concept to smart grids, losses introduced by power electronics and storage systems, such as AC/DC and DC/AC conversions, storage inefficiencies ( $\eta < 1$ ) and power factor losses can also be included.

Non-technical losses, on the other hand, do not depend on the physical characteristics of the grid but on external and management factors, such as energy theft, meter tampering, measurement or billing errors, and non-payment of bills. The latter are not easily quantifiable and represent a significant challenge to the economic and operational reliability of the electricity system. ([99] D. F. Niste et al., 2025)

Therefore, while in the traditional model the energy balance can be simply reduced to centralized power generation, demand and power losses, all with a monodirectional power flow, with the smart grid things change. The equation highlights the presence of distributed power sources, bidirectional flow with the external network and storage systems. Moreover, the power losses management becomes more articulated and the losses are not just technical related to transmission lines and distribution, but they also include conversion inefficiencies and managerial aspects.

➤ *Network constraints and power flow*

Energy balance only provides a macro-view of what's involved, however, in order to comprehend how this balance is achieved in practice, it's necessary to also consider the electrical constraints governing the network. Indeed, power distribution doesn't only depend on the comparison between generation and demand, but also on the flows that go through the network, which are a function of voltages, currents and line impedances. Hence, from these derives the necessity of introducing power flow equations, which describe the relationship between active and reactive power (which determine the complex power  $S=VI=P+jQ$ ) and the network status variables, therefore showing the local distribution features as a function of the network's characteristics.

Starting from the basics, active power is the result of the energy that actually becomes useful work (then used for things such as illumination, heating etc.):

$$P = VI\cos\varphi$$

Reactive power, on the other hand, is the power that is needed to maintain electric and magnetic fields (hence necessary for transformers, motors, lines etc.):  $Q = VI\sin\varphi$

Where: V = voltage, I = current,  $\varphi$  = phase shift between voltage and current

Reactive power is therefore essential for voltage control, while active power reflects actual energy consumption. Both must be managed together to maintain stability and reduce losses (which increase with increased currents and resistances,  $RI^2$ ).

In general, the network is described by power flow equations. ([100] J. D. McCalley, 2011)

$$P_i^{inj} = \sum_{j=1}^N |V_i| |V_j| (G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j))$$

$$Q_i^{inj} = \sum_{j=1}^N |V_i| |V_j| (G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos(\theta_i - \theta_j))$$

where:

- $|V_i|, |V_j|$  are the voltage modules at the nodes
- $(\theta_i - \theta_j)$  is the phasorial difference between the nodes
- $G_{ij}$  and  $B_{ij}$  are respectively the conductance and susceptance of the line connecting nodes i and j, parameters that describe the resistive and reactive effect of the network

These equations show that power flows are not dependent solely on generation and total load, but also on: local voltages values, phasorial angles and the physical characteristics of the lines, which determine resistances and reactances.

Therefore, from what has just been analyzed, it's possible to express three main implications:

- The power factor ( $\cos\varphi$ ) directly affects the line current and therefore losses.
- Reactive power management is essential for maintaining stable voltages at nodes
- Flows and losses are dynamic quantities, varying with changes in voltage, angle and impedance

Given this information, a direct consequence is the fact that smart grids have to face more complex constraints compared to the traditional grid. The variability of decentralized generation reduces the forecasting ability to predict energy flows ([101] H. Sun et al., 2019), storages introduce efficiency and power limits ([102] S. Massucco et al., 2020), prosumers generate bidirectional energy exchanges and inverters have limits on current, voltage and the capacity to provide reactive power. ([103] T. Morstyn, 2017)

In order to guarantee stability and reliability in this context, control cannot be centralized, it instead requires advanced monitoring systems such as AMI (advanced metering infrastructure) or PMU (phasor measurement units), allowing real-time measurement of voltages, currents and angles in order to apply distributed control strategies. ([94] C. Zilio, 2024)[104] S. S. Yu et al., 2025)

➤ *Demand response and consumption optimization models*

While power flows describe the physical aspects of the network, smart managing the demand allows it to impact the behaviour of the users, actively including them in the infrastructure.

According to IEA: “Demand response (DR) refers to balancing the demand on power grids by encouraging customers to shift electricity demand to times when electricity is more plentiful or other demand is lower, typically through prices or monetary incentives. Along with smart grids and energy storage, demand response

is an important source of flexibility for managing the impact of variable renewables and growing electricity demand on the stability and reliability of electricity grids.” ([105] International Energy Agency, 2023)

Therefore, DR is a strategy used to improve the distribution of energy over time based on availability, seeking to make the most of renewables and using fossil fuels as little as possible. In doing so it’s important to keep an eye on the market, reducing the costs and minimizing losses, which also involves a reduction of load peaks.

As presented in the paper ([106] L.-G. Hua et al., 2025), that will be used as reference, this strategy can be stipulated as a multi-objective problem where the goal is the minimization of a function, here presented with three main terms (user-side only):

$$\min_X F(X) = \gamma_1 C_A(X) + \gamma_2 RP_A(X) + \gamma_3 d_A(X)$$

where:

- X represents the set of all the decisional variables of the optimization problem, which include storage, network and loads scheduling variables
- A represents the set of the controllable appliances/utilities, so  $a$  is a single appliance
- $C_A$  is the cost of the utility bill

$$C_A = \sum_{a \in A} \sum_{t=1}^T p_r^a X_t^a \rho_{f,t} \quad \text{where } p_r^a \text{ is the utility's nominal power, } X_t^a \text{ it's a binary variable stating whether the utility is on or off at the instant } t, \rho_{f,t} \text{ is the electricity price at the time } t, \text{ which follows the dynamics of the market.}$$

- $RP_A$  is the peak-to-average demand ratio, which corresponds to the minimization of peaks, hence obtain a demand as distributed as possible throughout the day

$RP_A = \frac{T \max(\sum_a E_t^a)}{\sum_{t=1}^T \sum_a E_t^a}$  where T is the number of intervals considered,  $E_t^a$  is the energy consumption of the utility a in the interval t, so  $\max(\sum_a E_t^a)$  is the highest load in the building in the period considered, hence the peak demand,  $\sum_{t=1}^T \sum_a E_t^a$  is the total energy consumption in that period

→  $d_A$  is the cost of discomfort, related to delays or power faults  $d_A = d_{A^T} + d_{A^P}$

*time-flexible loads:*  $d_{A^T} = \sum_a \lambda_a (F_t^a - \alpha_a)^n$  where  $\lambda_a$  is a weight coefficient to measure how flexible the user is to a displacement,  $F_t^a$  is the chosen moment to start the utility, while  $\alpha_a$  is the favourite moment of the user to start it

*power-flexible loads:*  $d_{A^P} = \sum_t \sum_{a \in A^P} \omega_t^a (E_t^a - \hat{E}_t^a)^2$  where  $a \in A^P$  is a utility whose power can be modulated,  $\hat{E}_t^a$  is the desired energy consumption of the utility a in the interval t and  $\omega_t^a$  is a coefficient that considers the importance of the deviation in each interval

So  $d_{A^T}$  penalizes time displacements compared to the desired time, while  $d_{A^P}$  penalizes the deviations between effective and ideal power, the higher the distance from the ideal condition, the higher the cost

The three components ( $C_A, RP_A, d_A$ ) have different units of measurement, hence the coefficients  $\gamma_1, \gamma_2, \gamma_3$  enter the frame with a dual end: normalize the terms, allowing to sum them together, and act as weights to balance which component of the equation is more relevant between economic saving, comfort and reduction of peaks.

In order to represent the complexity of a smart grid, the model must be extended to include also the distributed power generation, storage systems and network losses, bringing the final function to:

$$\min_X \gamma_1 [C_A(X) + C_{loss}(X)] + \gamma_2 RP_A(X) + \gamma_3 d_A(X)$$

subject to the power balance constraint:

$$\begin{aligned} \sum_{i \in G_{conv}} P_i(t) + \sum_{j \in DG} P_j(t) + P_{import}(t) + \sum_{s \in S} P_s^{dis}(t) \\ = \sum_{k \in D} P_k(t) + \sum_{s \in S} P_s^{ch}(t) + P_{loss}(t) \end{aligned}$$

where  $C_{loss} = c_{loss} \sum_t P_{loss}(t)$  penalizes line losses computed from AC power flow equations.

For this function to be valid, some operative networks and users' constraints must be respected: power and load usage time limits, storage system capacity and efficiency, availability of renewable sources, and exchange capacity with the external grid.

According to this model, the formulation enables to optimize simultaneously cost, network stability and the comfort of the consumer, integrating in the decisional process all the peculiarities of the smart grid, which include distributed generation, storage and bidirectional power flows.

➤ *Battery storage and management of energy*

The implementation of storage systems is a pivotal passage in the evolution of the smart grid. DR strategies modulate load profiles in real-time and energy storage allows to overcome the traditional instant balance between production and consumption, transforming it into a dynamic constraint where time becomes a decisional variable. The opportunity to store excess energy and use it when needed is what maximizes the use of renewable sources, as they are sometimes unpredictable, reduce congestion and enhance self-consumption. ([107] Free Electrons, 2025) In this context, the State of Charge (SOC), which is the ratio between available energy and nominal capacity of the battery, is the key parameter to optimize charge/discharge cycles, preserve the battery's life and guarantee the reliability of the system.

A simplified SOC evolution model is often used in the literature to clarify the role of storage dynamics and here it is presented as a conceptual reference.

In fact, SOC management is crucial in the smart grid, as it grants a higher level of efficiency and a longer life for the storage system. It indicates the energy that is effectively stored in relation to the nominal capacity of the battery, varying throughout time as a function of charging and discharging flows.

A widely adopted model to describe the evolution of SOC, based on the law of energy conservation, is the following: ([108] S. H. Kim, Y.-J. Shin, 2023)

$$SOC(t + \Delta t) = SOC(t) + \eta_{ch} \frac{P^{ch}(t)\Delta t}{E_B} - \frac{1}{\eta_{dis}} \frac{P^{dis}(t)\Delta t}{E_B}$$

where:

- $P^{ch}$  and  $P^{dis}$  are respectively charging and discharging power at time  $t$
- $E_B$  is the nominal capacity of the battery
- $\eta_{ch}$  and  $\eta_{dis}$  are the charging and discharging efficiencies ( $0 < \eta_{ch}, \eta_{dis} < 1$ )
- $\Delta t$  is the timeframe considered

This equation, broadly used in literature on microgrids and energy management, empowers to estimate the SOC considering the losses due to power electronics and the inefficiencies of the charging/discharging cycles.

Moreover, with the distinction of the two cycles a more precise estimation of real losses is achieved, and policies that restrict the Depth of Discharge (DoD) can be included. As the study ([108] S. H. Kim, Y.-J. Shin, 2023) shows, SOC management within delimited intervals (for example maintaining it between 20% and 80%) allows deep cycles to be reduced, thereby extending the battery's useful life without significantly compromising the system's ability to provide support to the grid.

Energy management in smart grids is therefore not just an evolution of the traditional model, but a real paradigm shift: distributed generation, bidirectional flows, storage and prosumer users require optimisation models capable of integrating costs, network stability, loss reduction and comfort. Advanced

monitoring technologies and predictive algorithms enable more flexible and efficient management, thus also promoting the use of renewables.

This approach, which is responsible for greater efficiency, not only brings economic and managerial benefits, but also forms the basis for improving environmental prospects, with a significant reduction in CO<sub>2</sub> emissions.

#### **2.4 Smart grid as an essential tool for decarbonization**

The growing trend of incorporation of renewable energy sources (RES which include solar, wind, hydro and biomass) into smart grid infrastructure is proving to be an important lever to meet the goal of reducing greenhouse gas (GHG) emissions. As previously discussed, smart grids enable bidirectional flows of electricity and information, DR management and make the most of energy storage systems, therefore helping to meet the variability and intermittency of renewables while minimizing reliance on fossil-fuel-based generation. ([109] T. Kataray et al., 2023) For instance, smart grid technologies are responsible for a reduction of power losses thanks to the improved efficiency in transmission and distribution operations, thus allowing a dynamic matching between supply and demand (through DR) and reduce energy peaks in generation (that often to be fulfilled require fossil-fuel-based energy) as a result of forecasting and automation. Consequently, it's possible to rely more on renewables so that coal, oil or gas plants operate less often, thereby lowering CO<sub>2</sub> and other GHG emissions. ([109] T. Kataray et al., 2023) Moreover, a big contribution towards zero emissions is also provided by regulatory and market structures (like renewable portfolio standards, feed-in tariffs, net metering), which together with innovations such as microgrids, distributed energy resources (DERs), and hybrid systems (renewables + storage), support this transition toward cleaner, low-carbon power systems. ([110] O. K. Oladele, 2024)

In quantitative terms, a paper published in 2017 ([111] M. Moretti et al., 2017) analyzed a wide variety of studies about economic and environmental impacts derived by the application of SG. The study reports that the implementation of smart grid systems can lead to a reduction in greenhouse gas emissions of between 10 and

180 gCO<sub>2</sub>/kWh, with a median value of around 89 gCO<sub>2</sub>/kWh (figure [2.4]), depending on the national energy mix, the level of penetration of renewable sources and the boundaries of the system analysed. Consequently, it's clear how the reduction of losses, whose credit goes to the smart grid, has a lower impact in the reduction of GHG emissions compared to the implementation of renewable energies in the grid, but it is still a valuable saving. Thus, this confirms that the most decisive variable for reducing emissions is the increase in the share of renewable energy, which is also related to the implementation of the smart grid, as it allows its exploitation on a larger scale.

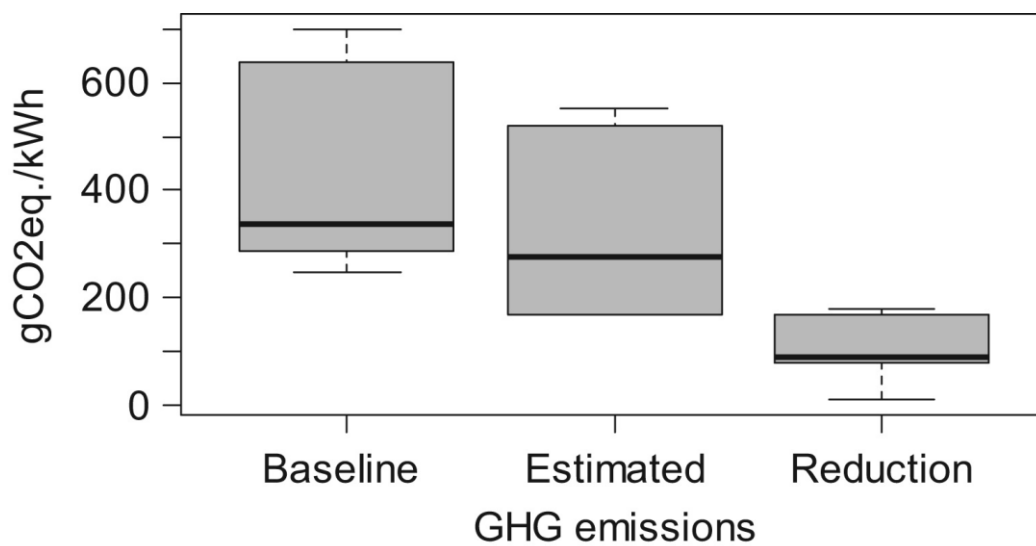


Figure 2.4: GHG emissions with implementation of smart grid systems ([111] M. Moretti et al., 2017)

Besides CO<sub>2</sub>, other advantages in terms of pollution are SO<sub>2</sub> emissions (responsible for acidification), reduced between 2 and 21 gSO<sub>2</sub>/kWh, and NO<sub>x</sub> (related to eutrophication) which vary between 0,41 and 12 gNO<sub>x</sub>/kWh saved.

It should be noted, however, that these figures are only updated until 2017. In recent years, given the continuous technological advancements (for example the growing use of AI for the management and optimization of the network, the evolution of storage systems and the upgrade of smart grid infrastructures) it is very likely that these performance, related to the reduction of GHG emissions and improved energy savings, has progressed even further.

Beyond reducing emissions, smart grids also contribute to a more diversified and resilient urban energy mix, facilitating the integration of distributed generation, storage, and renewable resources at the city level. ([112] M. G. M. Almihat and J. L. Munda, 2025) This enhanced flexibility not only strengthens the reliability of urban power supply but also lays the foundation for stronger interconnections with other key urban subsystems, an aspect that will be further discussed in the next section.

## **2.5 The connections with other urban subsystems**

As previously mentioned, in smart cities the energy infrastructure doesn't operate as an isolated body, instead it is deeply interconnected and interdependent with other urban subsystems. As stated, at its heart lays the smart grid, which, thanks to the management of bidirectional flows and integrated ICT, coordinates electric mobility, smart buildings, local microgrids and public services, while adapting its management based on data and the behaviour of these systems, such as dynamic loads, distributed generation and demand signals. ([113] B. N. Alhasnawi et al., 2025)

This interdependency grants real-time monitoring, predictive maintenance and decentralised control, improving overall efficiency, resiliency and sustainability of the smart city. ([114] R. Castro et al., 2025)

In this framework, the diffusion of digital twin technologies, that create a virtual counterpart of complex fiscal systems, is helping the integration between the different infrastructures. Through real-time simulation and monitoring, digital twins support the analysis and interaction between energy networks, mobility, buildings and urban systems, improving coordinated and resilient resource management. As a result, they represent a key enabler for holistic and sustainable urban planning.

Therefore, this section explores how energy and the other urban subsystems mutually influence each other, analyzing the main linkages that create synergies and interactions that empower an integrated and sustainable resource management in smart cities.

❖ Electric mobility and vehicle-to-grid (V2G)

Electric mobility assumes an important role towards the clean energy transition, as it reduces GHG emissions in the transportation sector. However, its diffusion on a larger scale raises some relevant challenges for the electric system, mainly for their additional effect as a variable and potentially reprogrammable load. In this context emerges the idea of Vehicle-to-grid (V2G), a concept where an electric vehicle is no longer a mere consumer, but it can also store energy in low load times and return it to the grid at peak times, acting as a flexible resource for the network. ([115] A. Pellino, 2024)

In other words, as figure [2.5] illustrates, V2G uses the electric batteries of the vehicles as distributed energy storages that participate in balancing services, frequency regulation, or peak demand management. ([116] M. İnci et al., 2024) Hence in smart grids, electric vehicles (EV) that enable V2G can be managed in a coordinated manner, for instance through aggregators, to properly balance supply and demand. By doing so the network's stability and efficiency improve, promoting also the integration of renewable sources. This interaction is indeed highlighting the interdependency between energy and mobility infrastructures, as the expansion of the EV fleet impacts energy's generation, distribution and storage. Simultaneously the characteristics of the network (flow management capacity, penetration of renewables and control systems) influence charging methods, costs and reliability of mobility itself. In this picture V2G is a key element for the synergistic evolution of the smart grid and sustainable transport. ([117] P. Biswas et al., 2025)

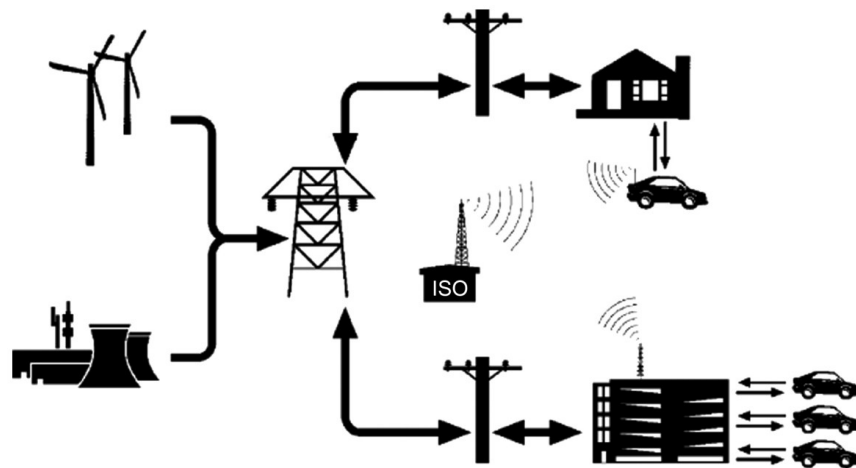


Figure 2.5: V2G scheme ([117] P. Biswas et al., 2025)

❖ Smart buildings and demand-side management

Another crucial innovation for the energetic transition that is quickly gaining ground, is the one of smart buildings, which are becoming nodes in the energy infrastructure. Not just as consumers but also as resources capable of modulating and, in some cases, feeding energy into the grid. This integration building-network is required to face the growing diffusion of renewable energy sources, which are variable and unpredictable, hence, through demand-side management (DSM) strategies, smart buildings are becoming flexible means that interact dynamically with the smart grid. The latter exploits advanced monitoring technologies, distributed control systems, and reduces peaks, facilitating the alignment between supply and demand.

While the smart grid provides price signals and response commands, Building Energy management systems (BEMS) use predictive and control functions to adapt their energy consumption balancing efficiency and comfort for the occupants of the building. ([118] S. Pless et al., 2016)

The interdependency between the two infrastructures manifests on different levels.

Operatively speaking smart buildings can reduce or shift non-essential loads in response to dynamic tariffs, limiting the need to generate additional power. Moreover, they can act as distributed resources thanks to thermal or electric storage, attenuating renewables' fluctuations and improving reliability. Strategies based on advanced control systems, such as *model predictive control*, allow to predict outcomes and improve setpoints without compromising comfort and air quality level, albeit these benchmarks reduce the actual flexibility. ([118] S. Pless et al., 2016) This integration must also be observed from a multi-scale perspective: from smart devices to individual buildings, to local microgrids and the national grid, where flexibility depends on load aggregation and effective coordination mechanisms.

In a nutshell, the smart grid offers signals and tools while smart buildings modulate the demand, becoming prosumers. The results are improved resiliency and decarbonization levels. Of course in order to do so these two structures alone are not sufficient as an important part is also played by ICT and governance, which pull the strings to convert this technical potential into tangible benefits.

#### ❖ Microgrid and energetic resiliency

An element that is gaining relevance in the evolution of smart energy infrastructures is the microgrid, a local system that combines distributed energy , storage and loads in a limited perimeter, such as commercial buildings, districts, university campuses and more. Their distinctive characteristic is the ability to operate either interconnected with a wider network, the smart grid, or in islanded mode, therefore isolated, guaranteeing continuity of supply also in the event of failures or extended interruptions. ([119] M. A. H. Chowdhury et al., 2014)

From a systemic perspective, microgrids enforce the integration of distributed energy resources (DER) and, through the technological support of smart grids, they offer flexibility and balancing services that improve

stability and efficiency of the network. Their diffusion is hence a key passage to reach a decentralized and dynamic energy model able to bear the growing diffusion of renewables. ([120] M. R. Islam et al., 2018)

Another vital aspect is related to energy resiliency: microgrids reduce the system's vulnerability from unforeseen events thanks to the diversification of sources, the local independency and the possibility to work on islanded mode. The immediate consequence is a more reliable supply for critical infrastructures and essential services, ensuring operative continuity also in emergency situations. ([121] G. Kostenko and A. Zaporozhets, 2023)

Last but not least, seen from an environmental and resource management perspective, microgrids, besides optimizing the local use of energy, create synergies with other urban subsystems that include waste and management, promoting a more circular and sustainable approach. Thereby, they act as strategic nodes that strengthen the interconnection between smart grid and resource management, supporting resilience, efficiency and energy transition in smart cities. ([122] Y. Yoldaş et al., 2017)

To sum up, these interactions between the energy infrastructures and the other urban subsystems, highlight strong interdependencies that shape the evolution of smart cities. Smart grids do not only enable these domains, but they also depend on their behaviours, data flows and flexibility to maintain stability, efficiency and sustainability.

A similar dynamic might as well be observed with ICT and governance infrastructures. On one end, ICTs are the digital backbone for monitoring, distributed control and communication, while governance provides regulations, incentives and coordinating mechanisms that allow energy integration. On the other end, both these infrastructures are intrinsically dependent on the energy one, as most of the technologies they use require constant and reliable electricity to operate. Simultaneously, the needs of the energy system, such as secure data transmission, low-latency response for grid balancing, or regulatory frameworks for demand response, directly influence the development of ICT solutions and governance models. ([123] Arif I. Sarwat et al., 2018)

It's necessary though to note that energy has a dual role within urban subsystems. On one side it is the driving force for physical mechanisms, such as mobility, thermal comfort or lighting, on the other it sustains the operation of information and communication systems, enabling signal transmission, data processing and control functions. Therefore, the quantity, continuity and quality of energy, as well as its origin, local or transported, are connected to the specific function it's going to serve in that specific subsystem.

Under this light it appears clear how the energy network is not just an enabler , it's instead part of a coevolving ecosystem of infrastructures, where they sustain each other and jointly determine the resiliency and sustainability of smart cities.

## **2.6 Engineering challenges and criticalities**

As said, the energy infrastructure is a central figure to develop a smart city, as it is responsible for its operative efficiency, environmental sustainability and overall resiliency. However, its planning and management are accountable for some serious engineering challenges, as a result of both the internal complexity of smart energy systems and their interdependencies with other urban infrastructures, such as mobility and communication. Hence, it becomes important to analyse the engineering challenges and criticalities outlining the main issues that concern techniques, operations and resiliency.

### *Core engineering challenges in urban smart energy systems*

The evolution of urban energy systems towards smart integrated models set some challenges that reflect the complex and multidimensional nature of smart cities. Following the ideas presented by Zheng et al. ([124] Z. Zheng, 2024), urban energy should be seen as a cyber-physical-social system (CPSS), where there's an interaction between physical processes (generation, transmission, storage and consumption), cyber ones (monitoring, forecast, control and optimization) and social components related to users' behaviour and managerial policies. This hybrid

structure generally causes numerous critical issues in the planning, management and interoperability of energy infrastructures.

From a technical and physical perspective, one of the biggest challenges is the integration of distributed energy resources (DERs), such as solar and wind, into urban electric grids that were initially thought for monodirectional power flows. The variability and intermittency of these sources complicate maintaining the balance between demand and supply, requiring advanced forecasting, load balancing and voltage/frequency control techniques. From an engineering point of view, the consequence is the necessity of implementation of automated regulation systems (like droop and inverter-based control) and distributed optimization algorithms able to operate in real-time. ([124] Z. Zheng, 2024)

Furthermore, the growing spread of multi-carrier energy networks, in which different energy carriers (electricity, heat, gas, cooling) are interconnected, is adding modelling and control complexity. In fact, every carrier has its own features (different constants, capacity limitations, thermodynamic constraints...) that must be harmonised through multi-domain coupling and co-optimisation strategies. Consequently, the stability of the integrated systems assumes a multidimensional connotation, where sudden changes in the electric or thermic load might proliferate through different subsystems, generating a cascading effect if not correctly compensated.

Another technical/physical issue derives from the spatial constraints typical of urban environments: the installation of solar panels and electrochemical storage systems for example is often limited by the lack of space, or the excessive shade or architectural constraints. Ergo, the possibility of implementing decentralised storages is reduced, moving on to the use of shared storage systems and local energy communities, which pose new challenges in terms of flow management and network protection. ([124] Z. Zheng, 2024)

The cyber and operative sides also highlight the difficulty in ensuring an efficient control of energy systems where uncertainty and fragmentation reign. The lack of shared communication standards, the poor interoperability between devices and management platforms, and the low scalability of experimental solutions hinder the

diffusion of energy management systems (EMS). Another key engineering concern is cybersecurity. Smart grids rely heavily on interconnected ICT networks and distributed IoT devices, which means that they're significantly exposed to cyberattacks, data breaches and malicious control manipulation. Therefore, ensuring data integrity, privacy protection and secure communication protocols are becoming a critical priority already in the design phase. ([125] J. Chen et al., 2025)

The social dimension as well, which includes the behaviour of prosumers, the consumption habits and demand-supply response mechanisms, creates further uncertainty, adding variables that impact the reliability of the system. ([124] Z. Zheng, 2024)

The simultaneous integration of physical, cyber and social dimensions, combined with the need to adapt to existing infrastructure and organisational models, accentuates the difficulties in implementing the CPSS model. This coexistence of heterogeneous technologies and established operational structures makes the implementation of truly integrated systems a gradual and technically burdensome process.

Beyond these internal challenges, energy systems must also coexist and interact with other urban infrastructures, introducing an additional layer of complexity.

#### *Interdependent infrastructure challenges*

Besides the intricate complexity of urban energy systems themselves, another serious challenge emerges from the interconnection between the energy infrastructure with the other infrastructures. Lu et al. ([126] X. Lu et al., 2019) propose a multi-layer modelling framework that highlights the strictly interdependent nature of some of these systems, in particular analyzing here energy, mobility and communication. As it is stated in the study, a breakdown in any of them might spread quickly, generating cascading failures and reducing the overall resiliency of the smart city.

From an engineering perspective, to manage these phenomena the identification of physical interfaces among the infrastructures is not sufficient, it's also needed the

modelling of functional coupling mechanisms linking different domains. For example, the dependency of electrified transport on the grid supply, or that of energy control systems on ICT networks.

These bidirectional relationships generate dependency chains that enhance the system's vulnerability, while making it more difficult to anticipate the behaviour of the urban system under stress or disturbance conditions. For this reason the study underlines the importance of developing coupled models and co-simulations able to represent the dynamics between heterogeneous infrastructures, each characterized by their own time scales, granularity levels, and communication protocols.

This technical and systemic complexity adds a dimension of infrastructure governance, which plays a big role in the energy infrastructure. The lack of coherence between institutional, contractual and regulatory frameworks became one of the main engineering and organisational critical issues, as it hinders data integration, risk management and goals alignment between public and private stakeholders. ([127] T. Sainati et al., 2023)

The resulting main challenge becomes the complexity in conciliating the technical modelling of interdependencies with the institutional and decision-making design that regulates their functioning.

Among these interdependencies, the coupling between energy and communication networks is particularly critical, as it directly affects monitoring, control and recovery capabilities.

#### *Resilience and vulnerabilities in coupled energy-communication networks*

To better understand how these infrastructures are linked, the relationship between energy and communication networks is particularly helpful. Nowadays power grid infrastructures are heavily coupled with communication networks because of a dual dependency: communication networks need power supply in order to work, while the energy network depends on their control functionalities, such as sensors, data and more. A study conducted in 2020 ([128] X. Liu et al., 2020) shows that this

relationship is risky, as failures or disruptions in one network can quickly spread to the other, reducing overall resilience.

Technically speaking, the main challenge is the maintenance of operative stability during communication or power interruptions. These phenomena can also propagate across other interdependent infrastructures and are amplified in contexts with high connection density and load concentration, as they carry a bigger chance of spreading the failure.

The authors, with the goal of limiting these issues, set two types of approaches, the analytical ones, useful to identify vulnerable configurations, and simulations, which provide a realistic representation of the interdependencies but require significant computational resources and accurate synchronisation between electrical and communication domains. The resiliency metrics identified include structural robustness, service reliability, restorability, speed of recovery. Some quantitative approaches used to assess reliance and reliability in the context of power systems are KPIs such as SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index), which measure the average duration and frequency of service interruptions per user. ([129] G. Adinolfi, 2021)

$$SAIFI = \frac{\textit{Total Number of Service Interruptions per Year}}{\textit{Total Number of Users Served}} [\textit{year}^{-1}]$$

$$SAIDI = \frac{\sum \textit{Duration of the Interruption to Users}}{\textit{Total Number of Users Served}} \left[ \frac{\textit{hours}}{\textit{year}} \right]$$

These indicators are increasingly integrated into smart grid monitoring frameworks to evaluate how cyber-physical interdependencies affect service continuity under stress conditions, with a proper communicative strategy crucial to minimize any loss.

The mitigation strategies adopted are based on redundancy, segmentation and energy backup for critical nodes, as well as coordinated recovery procedures between the two domains. However, these approaches are limited by the complexity of accurately shaping bidirectional interactions and the shortage of real-world data. Eventually, to ensure the resiliency of the urban network effectively, the best way

is a joint design of energy and communication systems, which can prevent failure cascading and support integrated recovery strategies.

To summarize, the analysis of engineering challenges and criticalities concerning the energy infrastructure in a smart city highlights how the complexity is not just restricted to the technical design of the systems, instead it's mainly about the integration with the other urban components (as figure [2.6], although just an example and simplified representation, shows). The transition towards smart and decentralized energy models requires deeply rethinking management, control and planning paradigms, to harmonise physical, digital and organisational aspects.

As seen, the main challenges are related to the need to guarantee stability, interoperability and resiliency in a context characterized by increasingly strong interdependencies between energy, mobility and communication. In this scenario, as said, the design of real smart systems cannot be restricted to technological efficiency, instead has to include governance, safety and sustainability (both social and environmental).

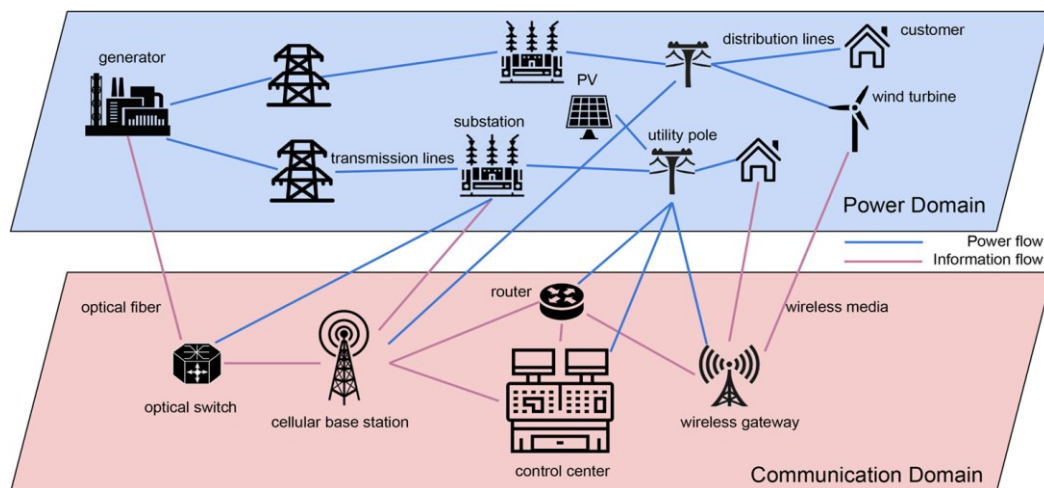


Figure 2.6: Illustration of the interdependent relationship between power and communication domains ([129] G. Adinolfi, 2021)

To achieve these results, the studies cited in this paragraph exhibit how urban resiliency depends on the capability to develop flexible, modular and co-designed infrastructures capable of adapting to technical and organisational disruptions. Therefore, in the future, smart city's engineering will have to evolve towards a more integrated and systemic approach where energy, digital and social technologies are

designed and managed synergistically, to ensure operative efficiency, environmental sustainability and structural soundness for the entire urban ecosystem. However, it's important to consider also that this transition entails significant economic investment challenges. The modernization of legacy grids, the deployment of smart communication systems, and the integration of distributed resources require long-term financial commitments that often exceed the capacity of local authorities. Consequently, economic feasibility and funding mechanisms become decisive elements in determining the pace and equity of smart city development. ([130] T. Woolf et al., 2021)

## **2.7 Real-world applications**

In the context of smart cities, the European Union is promoting multiple projects oriented towards urban energy transition, such as *Horizon Europe*, *NetZeroCities* and *Smart Cities Marketplace*, which encourage the experimentation of digital solutions, distributed infrastructures and integrated energy governance models. Two cities that stand out, although different from one another, are Barcelona and Vienna, which apply in practice smart principles to the energy infrastructure. Barcelona does so mainly through digitalisation and local production from renewable sources, while Vienna exploits an advanced integration of urban energy systems and modelling through digital twins. ([131] B. Tundys and T. Wiśniewski, 2024)

### *Barcelona: digitalisation and local renewable production*

Barcelona is one of the most active cities in the field of urban sustainable energy, with the goal of reaching climate neutrality by 2050. The 'Observatorio de la Energía de Barcelona' reported that in 2022 the overall energy consumption of the city was 14413 GWh, 1037 of which originated from local renewable sources, which is about 7% of the overall consumption. ([132] Ayuntamiento de Barcelona, 2022) The city, to further improve these numbers, has a public and private energy monitoring network, also managed through the open-source Sentilo platform ([133]

Ajuntament de Barcelona, 2025), which collects real-time data on consumption, public lighting, traffic and air conditioning.

The municipal initiative ‘Barcelona Energia’, launched in 2018, is now the main public operator for renewable energy distribution towards both public administration and private users. According to municipal data, the utility already provides 100% renewable electricity to more than 4700 domestic buildings and more than 100 public ones, and is in continuous expansion. ([134] Barcelona Energia, 2025)

Besides the technologies, the city also adopted self-consumption and distributed micro-generation strategies, with a significantly increased PV installed capacity in public buildings. The ‘Pla Clima’ and ‘Pla d’Energia i Clima’ 2030 guidelines set emission reduction targets of 45% compared to the 2005 levels and plan to increase considerably the share of renewable energy in the citizen’s energy mix.

The Barcelona model highlights how the urban energy infrastructure might evolve towards a data-driven system, capable of exploiting efficiency and real-time planning. However, the growing digitalization of the society requires careful evaluations regarding ICT systems’ energy consumption, as their incidence tends to increase proportionally to the density of sensors and data managed. ([131] B. Tundys and T. Wiśniewski, 2024)

#### *Vienna: integrated planning and urban digital twin*

Vienna, instead, represents one of the most advanced examples of integration between energy infrastructure, urban planning and digital governance, as they coordinate for a common final purpose.

Vienna’s strategy for sustainable development ([135] City of Vienna, 2022), set the goal of diminishing emissions per capita by 50% within 2030, aiming to reach climate neutrality by 2040, with particular focus on energetic efficiency and on urban heat recovery.

‘DecarbCityPipes2050’, for example, is a project that documented the final energy consumption in the Austrian Capital, providing for 2021 a value of 37005 GWh/year, with an yearly average consumption per capita of 19502 kWh, significantly lower compared to the national average of 35564 kWh. ([136] H/C

plan of Vienna, 2022) This outcome reflects the city's high overall energy efficiency, which stems from a mix of district heating, electricity generation, and sustainable mobility systems. Vienna's approach combines centralized heat supply with decentralized renewable sources and efficient public transportation, resulting in an integrated urban energy ecosystem that minimizes per-capita energy demand while maintaining a high standard of living.

About half of this consumption is intended solely for the thermal sector (heating, hot water, related processes), which obviously takes a serious slice of the overall energetic needs. The city disposes of a district heating network about 1200 km long, serving about 430000 apartments and more than 7700 business customers, confirming the fact that the thermal sector accounts for a significant portion of the urban energy demand.

To support the management and optimisation of this complex urban energy infrastructure, Vienna has developed a Digital Twin of the city as part of the 'URBEM' project at the Technische Universität Wien. This is a three-dimensional virtual replica of the city, based on real data from buildings, networks and energy infrastructure, allowing to simulate urban scenarios and assess the effects of decisions on energy demand and supply.

The digital twin serves as an interdisciplinary decision-making tool, allowing for the consistent analysis of the interaction between district heating, electricity distribution and other urban infrastructure, with the aim of optimising resource management and improving the overall efficiency of the city's energy system. ([137] T. Bednar et al., 2022)

These cases demonstrate how urban energy infrastructure can evolve through both the deployment of local renewable resources and the integration of advanced digital tools, such as energy monitoring networks and city-scale digital twins. By combining data-driven management, interdisciplinary planning, and optimized coordination of heating, electricity, and mobility systems, cities like Barcelona and Vienna can enhance energy efficiency, reduce emissions, and increase the resilience of their urban energy systems, offering practical examples of how smart city principles can be applied to achieve long-term sustainability goals.

## **Chapter 3 - Methodologies and frameworks for managing interconnected smart infrastructures**

This chapter applies a system-of-systems perspective to understand how urban infrastructures interact, co-evolve and influence each other. Through system thinking principles, it highlights feedback loops, delays, emergent behaviours and coordination challenges. The analysis shows why silo-based approaches are insufficient and why integrated planning and governance are essential.

### **3.1 System Thinking**

The growing interdependency between urban infrastructures - transport networks, energy systems, water management, security services etc. - requires a change in their planning and management paradigms. Traditional approaches, based on sector analysis and local optimisations, can't provide a complete representation of the interconnected systems, and neither can they control their behaviour. In this context system thinking can be used as a reference methodology to understand and manage the integrated smart infrastructures.

Donella H. Meadows ([138] Meadows, 2008) wrote in her book that "A system isn't just any old collection of things. A system is an interconnected set of elements that is coherently organized in a way that achieves something." This apparently simple definition, implies an important epistemological revolution: the attention shouldn't be directed towards single components, rather towards the relationships,

flows and feedback mechanisms that determine the overall dynamics. In the context of smart cities, this approach permits the interpretation of complex urban phenomena, such as traffic congestion, energy peak demand, water inefficiencies or digital divide, not as isolated obstacles, but as the result of underlying systemic structures.

Smart cities can also be described as Systems-of-Systems (SoS) ([139] Cavalcante et al., 2016), which are aggregations of autonomous, heterogeneous and dynamically coupled systems that cooperate to generate emergent behaviours. Each subsystem (energy, transportation, ICT and more) maintains its managerial and operative independence, but interacting with the others generates collective effects that couldn't be predicted by analysing it individually. From an engineering perspective, this configuration implies that urban behaviour is the result of dynamic coupling circumstances, like delays, feedbacks and cross-flows of energy, materials and information.

The discussed interpretation is also shared by other experts ([140] Ammara et al., 2022), emphasising that urban intelligence doesn't lay in the mere digitisation of infrastructures, instead it's mostly about the ability of coordinating adaptively physical and cybernetic systems through coherent information flows. Technological integration by itself might even enhance the vulnerability of the system if it is not properly partnered with a systemic design of interfaces and control mechanisms.

Therefore, systems thinking sets out the conceptual and methodological basis for managing interconnected infrastructure. It encourages a shift from a local optimization approach to a global coordination mechanism, where performances are evaluated in terms of stability, resiliency and complexive adaptability of the urban system. As underlined by Meadows ([138] Meadows, 2008), the ability of a system to maintain its own balance does not depend on the perfection of its parts, but on the effectiveness of the relationships that connect them, and this will be the standpoint that will drive all the coming considerations in this chapter, where system thinking will be the conceptual matrix at the base of every consideration regarding smart infrastructures.

## **Systemic principles and dynamics of smart infrastructure**

To apply system thinking to smart cities' infrastructures means to translate its pillars into the language of physical and digital networks that comprise the backbone of the smart city. These concepts are not just theoretical abstractions but represent measurable and controllable dynamic parameters on which the stability, efficiency and resilience of urban systems depend.

- *Stocks and flows: capacity and dynamic demand*

'Stocks' are all those resources stored in the system (energy, water, data, vehicles etc.), while 'flows' describe the velocity at which these resources are consumed, restored or transferred. In urban systems, stability depends on the dynamic balance between infrastructural capacity and rate of use. Often, however, urban policies miss the mark, as they treat congestion and blackouts as static events, solvable by just increasing the physical capacity. Meadows ([138] Meadows, 2008) instead shows that these systemic problems derive more frequently from poorly managed flows and missing feedbacks, rather than stock shortages.

Moreover, in interconnected infrastructures, the balance between stocks and flows is further complicated by the different time horizons of the subsystems. The electricity network reacts in minutes, the transport one in hours and the buildings one in years. If these timings are not properly coordinated fluctuations and inefficiencies will manifest ([139] Cavalcante et al., 2016). From this comes the need for smart infrastructure managers to develop predictive models and simulation tools able to align the dynamics between domains operating on different time scales. ([140] Ammara et al., 2022)

- *Feedback loops: interdependencies and instability*

Feedback loops are the circular connections through which infrastructures impact each other, and thanks to digitalization the amount of feedback in the different fields is skyrocketing. The access to real-time data often triggers self-reinforcing cycles, where more data collected guarantees more

efficient services, which attract more users and a more frequent use of the platform, hence more data is collected. ([140] Ammara et al., 2022) However, without balancing mechanisms, these cycles can generate systemic vulnerabilities like network saturation, dependence on algorithms, loss of redundancy.

A common mistake is to consider all positive feedback as desirable. Instead, an excess of feedback loops leads to instability and collapse as the system isn't able to sustain them. For an engineer, to design resilient systems means introducing multi-scale damping and control mechanisms capable of stabilising interactions between independent infrastructures. ([138] Meadows, 2008)

- *Delays and time misalignments*

Every infrastructure has its own inertia. Construction, response, data collection and decision-making times vary enormously, and these delays, if ignored, are a major source of inefficiency.

The delays are often responsible for fluctuations and overshoots, and in smart cities the problems don't disappear, but change scale. Urban SoS witness both technical and institutional delays, where each business operates with their own decisional timings, causing intertemporal misalignments. The result is a loss of synchronization between physical and information systems. The response to this issue is not to bring the delays to zero, which is unrealistic, but to design compatibility, providing time coordination algorithms and communication protocols that can harmonise different decision-making cycles. ([139] Cavalcante et al., 2016)

- *Emergent behaviour and resilience*

The interconnection between different infrastructures brings out new behaviours, collective events non-explicable by observing a single branch. Urban resiliency, the capacity of the system of maintaining base functions also in stress conditions, is one of the main emerging behaviours. Cavalcante and his colleagues ([139] Cavalcante et al., 2016), describe

emergencies as the result of coordinating dynamically autonomous subsystems, whose outcome might correspond to innovation or systemic failure, depending on the quality of the linkages. The goal, however, is not to control emergencies, which are unpredictable, but to improve the system so that it can become capable of learning and adapting.

Consequently, the goal is moved from deterministic forecasting to adaptive robustness, building systems that can absorb disruptions and evolve without collapsing. ([140] Ammara et al., 2022)

Therefore, system thinking, applied to interconnected infrastructures, does not offer immediate solutions but rather a methodological framework for recognising patterns, delays and causal relationships that are often invisible. The managerial skills are required to maintain a dynamic coherence in the system. As all the sources used in this paragraph share, the main risk is the reduction of this complexity to a technological control issue. Systemic engineers, on the other hand, must learn to design infrastructures that communicate, learn and regulate each other, promoting stability without suppressing diversity and the adaptability of the urban system.

### **Associated modelling methods**

The management of interconnected infrastructures requires models capable of describing temporal dynamics, emerging behaviours and interdependency relationships between physical, digital and organizational systems. The system thinking, as discussed by Meadows ([138] Meadows, 2008), provides a conceptual frame, while the operative translation happens through quantitative and computational methods that grant to simulate and manage the complexity of the urban system. Among these, three methodological families stand out for their prevalence and complementarity:

- System Dynamics (SD)
- Agent-Based Modeling (ABM)
- System-of-Systems (SoS) / DEVS-based Modelling

### System Dynamics (SD)

System dynamics represent the most direct mathematical interpretation of Meadows' thought.

Originated from the work of Jay Forrester and developed by Sterman ([141] J. D. Sterman, 2000), it is based on the representation of state variables (stocks) and flow variables (flows) linked by differential or difference equations. Each SD model describes how the rate of change of a variable depends on the other variables of the system and on the feedbacks set throughout time.

The typical structure of an SD model is:

$$\frac{dS(t)}{dt} = F_{in}(t) - F_{out}(t)$$

where:

- $S(t)$  represents the stock (could be energy, or the number of circulating vehicles or more)
- $F_{in}(t)$  and  $F_{out}(t)$  are the incoming and outgoing flows, where the function  $F$  depends on control variables, delays, and feedback parameters

Sterman underlines that the strength of this approach is not about the numerical precision, rather about the ability of reproducing characteristic systemic behaviours (exponential growth, logistic saturation, fluctuations etc.)

SD in urban infrastructures is particularly efficient to:

- ❖ Analyze long-term scenarios (energy demand, network capacity, resource sustainability)
- ❖ Test regulation policies (dynamic pricing, traffic management, capacity planning)
- ❖ Evaluate the sensibility of the system to variations in structural parameters

A typical applicative example is the traffic congestion dynamic, that can be presented as:

$$\frac{dV}{dt} = \alpha \cdot (C - V) - \beta \cdot V$$

where  $V$  is the number of vehicles in the network,  $C$  the maximum capacity,  $\alpha$  the entry rate and  $\beta$  the runoff rate.

The oscillatory behaviour that emerges illustrates the unstable nature of systems subject to feedback delays, as written by Meadows.

However, from a critical perspective, Cavalcante and his colleagues ([139] Cavalcante et al., 2016) remind that classical System Dynamics tends to be monolithic: it represents the entire system as a single structure of equations, ignoring the autonomy of subsystems. In urban SoS, this might generate excessively aggregated models, unable to capture the spatial distribution and the distributed nature of the processes.

#### Agent-Based Modeling (ABM)

When emerging dynamics stem from heterogeneous behaviours of autonomous actors, SD is not enough.

In these cases, Agent-Based Modelling (ABM) is adopted. This model, formalized by Macal and North ([142] C.M. Macal and M.J. North, 2009), simulates the interaction of individual actors (people, vehicles, sensors...) in a shared environment.

An ABM model can be expressed as a triple (A,E,R), where:

- $A = \{a_1, a_2, \dots, a_n\}$  is the set of agents, each with its own status and behavioural rules
- $E$  is the environment where the agents operate and can evolve in time
- $R: A \times E \rightarrow A$  is the updating function that regulates the interactions

The local rules of each agent generate emerging phenomena at the macro level.

In the infrastructure sector, ABMs are used to study collective behaviours (mobility, energy consumption, response to incentives), analyze multi-agent interactions (for example the coordination between transport and energy network) and analyze policy effects in the presence of uncertainty or limited rationality.

ABM's models are recommended to explore the socio-technical aspect of smart cities, where human and automated decisions interact in a non-linear way. Their strength lays on the capability of representing heterogeneity and adaptation.

However, ABM is responsible for semantic interoperability challenges. Every agent or subsystem can adopt different languages or objectives, making it more difficult to validate collective behaviour.

Nonetheless, it is important also to treat ABM correctly, as a common mistake, as pointed out also by Meadows ([138] Meadows, 2008), is to treat them as realistic surrogates of the real world. Instead, every model has a useful yet partial interpretation and they should hence be integrated with structural models (for example SD) to ensure dynamic coherency.

#### System-of-Systems modelling: DEVS formalisms and hybrid models

In more complicated situations, where smart infrastructures operate as coordinated autonomous systems, a multi-level approach becomes needed. Cavalcante et al. ([139] Cavalcante et al., 2016) describe smart cities as SoS, where each subsystem is independent yet interconnected.

Zeigler, Kim and Praehofer ([143] B. P. Zeigler et al., 2019), in order to represent formally this structure, proposed a model called DEVS (Discrete Event System Specification), which defines a system as a pair of models:

$$M = (X, Y, S, \delta_{int}, \delta_{est}, \lambda, ta)$$

Where:

- $X$  = input events
- $Y$  = output events
- $S$  = internal states of the system
- $\delta_{int}, \delta_{est}$  = internal and external transition functions
- $\lambda$  = output function
- $ta$  = time spent in the current state

This formalism allows to simulate heterogeneous and asynchronous systems, such as those found in urban infrastructures. Every subsystem could be modelled as a standalone DEVS module, and consequently the city as a hierarchy of interconnected models.

SoS/DEVS approach is particularly useful for three ends. Model discrete processes and asynchronous events (failures, congestion, service priorities), guarantee interoperability between models developed in different domains, and integrate different levels of simulation (physical, cyber and decisional).

These techniques also constitute the conceptual base of urban digital twins, which combine real-time data and physical systems' simulations to support the governance of the infrastructure.

None of these modelling methods, taken by itself, is sufficient to represent the complexity of interconnected infrastructures. Smart cities, in fact, require hybrid approaches, where SD describe the aggregate evolution of resources, ABM represent the adaptive behaviour of the actors, and SoS/DEVS coordinate the interactions between autonomous domains.

In this picture, the value of the model lies in the learning ability that produces. As written by Cavalcante et al. ([139] Cavalcante et al., 2016), urban models should be designed as communicating systems, capable of updating and communicating in real time. The goal is not to simulate the reality in a deterministic way, but to create an iterative modelling environment that enhances coherency and adaptability between different decisional levels.

### **Practical applications and limitations of system thinking**

System thinking has a direct application in modelling and managing interconnected urban infrastructures, where the objective is not just to describe the complexity, but to govern it in a dynamic and predictive manner.

Models based on System Dynamics ([141] J. D. Sterman, 2000) are adopted to simulate the evolution of supply and demand in the likes of energy and mobility networks, evaluating the long-term effects of new policies or external contingencies.

Agent-Based Modelling approaches ([142] C.M. Macal and M.J. North, 2009), on their hand, integrate this perspective introducing the personal behaviour of individuals within the system, such as relocation decisions, adoption of technologies, or response to incentives. These simulations allow to study emerging phenomena like congestion, demand flexibility and the diffusion of the proposed innovative technology.

At a higher level, System-of-Systems modelling ([139] Cavalcante et al., 2016) and DEVS formalisms ([143] B. P. Zeigler et al., 2019) allow for the representation of autonomous yet coordinated infrastructures through discrete events and modular states. Some practical examples that exploit these approaches include energy, water and mobility networks.

These three modelling approaches, that today stand at the base of urban digital twins, enable the integration of real-time data and multi-scale simulations to sustain operative and strategic decisions ([140] Ammara et al., 2022). In such platforms the city becomes a system that is continuously modelled and learned, where policies can be virtually tested before being implemented.

To summarize, the applications of system thinking in smart infrastructures show a clear shift from static planning to dynamic simulation-based management, where models and data become a single cognitive infrastructure to support decision-making.

### **Critical issues and prospects for development of system thinking**

Despite the progress, the application of this method still has intrinsic limitations. Each model is indeed a simplification, and the trade-off between complexity and clarity is crucial to avoid a state of ‘illusory precision’. In urban SoS the non-linearity and feedback delays sometimes make the forecasts unreliable ([139] Cavalcante et al., 2016), while the institutional and semantic fragmentation is an

obstacle to the interoperability between the different domains ([143] B. P. Zeigler et al., 2019).

Without integration with governance and continuous data updating, models risk to remain isolated analytical tools. Experience shows the need to build adaptive modelling ecosystems, where simulation and reality feed back into each other, promoting an iterative and transparent decision-making process. ([140] Ammara et al., 2022)

With this perspective, system thinking evolves from an analytical instrument to an organisational learning methodology, able to embed data, models and decision-making processes. New technologies, in particular AI and machine learning, are playing a growing role as support instruments to this collective learning.

AI allows the extraction of patterns with relevant volumes of data produced from smart infrastructures, improving the predictive and adaptive capacity of the models. While not replacing the systemic approach, these technologies amplify its scope, bringing urban management closer to the integrated and dynamic vision that is the ideal goal of system thinking.

### **3.2 Tools for analysis and simulation**

System thinking provides the conceptual lens to interpret complexity, while analytical and simulation tools translate this vision into operational decision support. Through these tools, urban infrastructures can be modelled as dynamic, data-driven systems:

- a) System Dynamics tools: System Dynamics (SD) represent one of the most consolidated analytical frameworks to study the temporal evolution of complex systems through feedback mechanisms. SD models are based on stock-flow diagrams (as the example at figure 3.1), differential equations and feedback loops, which together describe how changes in one variable propagate across the system over time ([144] Pavlov et al., 2025). This approach allows for representing the structure of cause-effect relationships, which determine the dynamic behaviour of infrastructures, and for testing

the effects of different policies' scenarios in a controlled simulated environment.

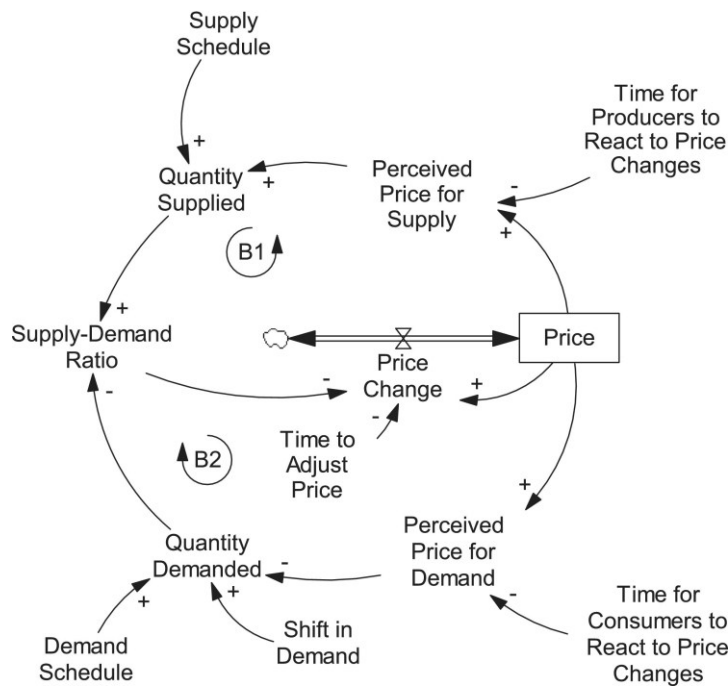


Figure 3.1: stock and flow diagram for a system dynamics model. (Lyneis, J. 2003)

From a practical perspective, multiple software have been developed to implement SD's models. Following a revision published on "Sustainability" ([145] Naeem et al., 2023), 'Venim' is currently the most widely used simulation software in SD modelling, with this predominance due to the availability of a free academic version and even more due to its advanced sensitivity analysis and optimization functionalities. ([146] V. B. Bureš, 2015) 'Stella' follows as the second most used software, particularly appreciated for its graphical layout and its graphical environment and educational focus, which make it suitable for collaborative modelling and participatory processes. Both these platforms provide intuitive interfaces to build stock-flow models and conduct continuous-time simulations, facilitating the use of SD in contexts of research and professional planning. Other common softwares include 'AnyLogic' (which has a module dedicated to SD) and 'Powersim Studio', frequently used in industrial applications and energy systems.

Overall, System Dynamics tools allow for exploring the long-term evolution

of urban infrastructures, such as supply-demand balance in energy systems, re-enacting typical system behaviours like exponential growth, saturation and fluctuation. Their strength, as said, is not the numerical accuracy, but rather the ability to highlight feedback structures and leverage points in public policy. However, it should be noted that classic SD models tend to aggregate variables at a high level, thus reducing their ability to represent spatial or behavioural heterogeneity. For this reason, they are increasingly being integrated with agent-based or discrete event approaches within hybrid simulation frameworks.

b) Agent-Based Modelling tools: ABM is a bottom-up simulation approach where the system's behaviour is the result of interactions between autonomous agents, people, vehicles, buildings and more, following the local regulations. As explained by Macal and North ([142] C.M. Macal and M.J. North, 2009), the strength of ABM lies in the capability of representing heterogeneity, adaptation and non-linearity, central characteristics of complex urban systems.

Compared to SD, which exploits aggregate variables, ABM allows the analysis of emerging behaviours like congestion, the diffusion of technologies or a collective response to incentives. In urban planning, it is widely used, as well as in decentralized energy management and in smart mobility.

The most used technologies/software are:

- NetLogo: Simple, with ready-made libraries and an intuitive interface, ideal for educational models and models of medium complexity
- Repast: Open source platform in Java, suitable for large-scale simulations
- AnyLogic: Enables multi-method modelling (SD, ABM, discrete events), useful in smart city contexts
- GAMA Platform: oriented towards high-resolution spatial and territorial simulation

As observed by Hamill ([147] L. Hamill, 2010), ABM's diffusion comes from the capacity to integrate empirical data and realistic decisional processes, however, there still are some issues in validation and semantic interoperability. The main value of these tools is not predictive, but explorative, allowing the understanding of local integrations generating systemic outcomes, laying the foundations for hybrid simulations and urban digital twins.

- c) System-of-Systemas and DEVS framework: Discrete Event System Specification (DEVS), provides a modular and hierarchical representation to model discrete and hybrid event systems. Thanks to its structure, it's particularly fitting for describing autonomous and asynchronous systems which must be coupled in complex networks, which is the typical configuration of urban interconnected infrastructures. That's the reason why it's suitable to represent urban SoS. ([143] B. P. Zeigler et al., 2019)

Among the main operative implementations there are 'DEVSJava', 'pyDEVS', 'Adevs' and 'Cadmium', which are made in order to build modular models and integrate them in bigger platforms. Interoperability with continuous simulation tools are essential for representing asynchronous and multi-scale interactions. ([148] B. P. Zeigler et al., 2025) In urban settings, DEVS models are used to describe traffic, distributed energy management, and modular digital twins. Their strength is their modularity and reusability, but the complexity level arises rapidly in multi-domain co-simulations, which require advanced engineering skills and careful management of time synchronisation.

Although, as previously mentioned, none of these techniques is enough if used by itself, it's their integration that brings the wanted results, with coherent, adaptive and multi-scale models.

The convergence of different data in real-time, IoT infrastructures and the exploitation of these methods are represented by the urban digital twin, a virtual replica of the urban environment that gets updated continuously. These digital twins are based on the integration of heterogeneous data, from sensors, administrative

databases and citizen contributions, aiming to support the prediction, optimisation and testing of different scenarios. ([149] V. V. Lehtola et al., 2022)

The Digital Twin Consortium ([150] A. Budiardjo and D. Migliori, 2021), while analyzing the interoperability framework, highlighted that the efficiency of digital twins depends on three levels of interoperability among systems: syntactic, semantic, and pragmatic. It defines a layered architecture that includes federated twins, digital threads, and system connectors, which ensures coordinated information flows across heterogeneous infrastructures. In this framework interoperability is not merely technical but also conceptual, hence systems must share a “common understanding of context and intent,” allowing decision support to extend across domains such as energy, transport, and environmental management.

Moreover, the FIWARE Foundation ([151] F.I. WARE Foundation, 2024) puts the principle of interoperability into practice through its open-source architecture based on NGSI-LD (Next Generation Service Interface – Linked Data), an open standard which enables real-time data exchange between urban platforms. Cities such as Porto and Vienna display how open standards turn system thinking into reality in the integrated management of mobility, energy and services.

Despite progress, digital twins still face critical issues related to data heterogeneity and governance fragmentation ([150] A. Budiardjo and D. Migliori, 2021). Unregulated interoperability can lead to inconsistencies and loss of context, so common ontologies and federated governance are proposed. Open ecosystems to ensure data sovereignty and technological neutrality, reducing the risk of lock-in, today are also a concrete proposal ([151] F.I. WARE Foundation, 2024). However, interoperability remains an ongoing socio-technical challenge rather than a definitive solution.

The evaluation of smart infrastructure is shifting from static efficiency parameters to dynamic metrics that measure the system's ability to adapt, integrate data and maintain consistency.

Indicators such as interoperability, information latency, update frequency and model consistency allow the evaluation not only of individual performance, but also

of the quality of the relationships between different subsystems, in line with the principle of system thinking.

### **3.3 Evaluation metrics**

Metrics are essential to understand how a complex system interacts with the environment and how it adapts to the challenges it faces. For what concerns infrastructures, evaluation metrics are those that determine the level of operative performance, the resiliency to perturbations, the speed of recovery and the adaptive capacity of the system. Without them, it would be nearly impossible to properly comprehend the dynamics that govern the efficiency, resiliency and sustainability of interconnected systems

Nevertheless, it's important to underline that there isn't a shared universal metric across all systems. In fact, each system has its own peculiarities and, therefore, evaluation metrics must be chosen based on the specific context and objectives. Sometimes a metric might be suitable for a system and less for a similar yet different one, which makes some precise metrics for a system sometimes useless for a different one.

#### **Main metrics categories**

Evaluation metrics, although different, can be grouped into different categories, based on their function and the aspect of the system they intend to measure. These categories can be presented as follows:

- ***Operational Performance Metrics***: these metrics represent the capacity of an infrastructure to provide its services in nominal conditions, ensuring efficiency, reliability and continuity of the services, and are particularly useful to detect the deviations that may indicate emerging systemic weaknesses.

According to UTRC ([152] P. Nelson, 2016), indicators like 'availability', 'service continuity', 'efficiency ratio' and MTTF (mean time to failure) measure the basic performance level of the system. Other studies ([153] F. Figueiredo et al., 2018) highlight the fact that the performance analysis must

go beyond the local efficiency, including also their systemic impact: an infrastructure might be efficient and yet be one of the reasons for the system's instability if its optimization reduces the overall quality of the operation of the system.

- ***Resilience and Robustness Metrics***: resiliency metrics evaluate the ability of the system to resist an unforeseen event, maintaining its key functions, not only for the survival of the individual system, but for successful management of all the interconnected infrastructures.

The Organisation for Economic Co-operation and Development report ([153] F. Figueiredo et al., 2018), highlights that resilience depends on the reliability and maintenance of critical infrastructures, the integration of risk prevention measures, and the ability to ensure continuity of essential services under stress. Robustness is therefore linked to the capacity of infrastructure systems to absorb shocks, adapt operations, and recover functionality without significant loss of performance.

Other sources ([152] P. Nelson, 2016) integrate this vision with quantitative approaches, measuring the change in functionality over time ( $Q(t)$ ) and the area of resilience loss.

In interconnected urban contexts, resilience is hence a property that derives from coordination between autonomous subsystems, not from a single technical domain.

- ***Recovery Metrics***: These metrics measure the speed and efficiency of a system to restore its operation following a disruption and how harmonised this recovery is among dependent systems. Multiple different indicators can be considered, some of the most widespread are the 'MTTR' (mean time to repair), 'recovery efficiency' and 'residual loss', which quantify both the speed of recovery and the quality of the service restored. ([152] P. Nelson, 2016) OECD adds the fact that the recovery is not merely technical, but also institutional. The presence of coordinating and multi-level governance procedures accelerates the return to a working status.
- ***Adaptability and Evolution Metrics***: Adaptability and evolution metrics evaluate the capacity of the system to learn, evolve and adjust its behaviour

adapting to environmental and technological changes, it's like a smart form of resilience, necessary in urban environments undergoing constant changes.

Linkov et al. ([154]I. Linkov et al., 2013) affirm that adaptability is a superior form of dynamic resilience, allowing the system to reorganize avoiding to collapse after disruptive events. Common indicators found in literature often refer to 'learning capacity', 'organizational innovation' and 'policy flexibility', underlying how smart infrastructure management should be seen as a developing process and not just as a static control operation.

- ***Interconnection and Dependency Metrics:*** Interconnection and dependency metrics measure the intensity, direction and vulnerability of interdependencies that link the different infrastructures. These metrics are particularly relevant in urban systems where infrastructures are tightly coupled and a disturbance in one domain can cascade through others, amplifying risks and revealing hidden vulnerabilities.

To measure the way a breakdown or a variation in a domain impacts the other ones, some widespread tools are 'dependency matrices', 'cascading impact factors analysis' and 'coupling strength indicators'. ([152] P. Nelson, 2016) It's crucial however, to integrate these measurements with institutional and informative data, identifying those criticalities where a lack of coordination amplifies the risks.

- ***Governance and Coordination Metrics:*** Last but not least, governance metrics evaluate the institutional and managerial capacity to coordinate interconnected systems, assessing the efficiency of institutions to do so and determining whether technical resilience can translate into systemic stability.

Urban resiliency is not just the result of robust infrastructures, it also derives from a well-managed and coherent governance, with synchronised communication channels, data sharing and decision-making processes. In order to quantify this metric indicators like 'institutional coordination index', 'policy coherence', 'stakeholder engagement' and 'data

interoperability' are used. ([153] F. Figueiredo et al., 2018))

Governance can be seen as the network of cognitive feedback of the urban system. An infrastructure can only adapt and improve only as long as the institutions that manage it learn and cooperate.

The table 3.1 provides a useful summary to quickly assess the main focus of each category.

Table 3.1: Summary of the main metrics categories

Category	Main Focus
Operational performance	Efficiency and reliability in nominal conditions
Resilience	Capability of absorbing shocks and maintaining the functions
Recovery	Speed and quality of recovering from a disruption
Adaptability	Learning and system reorganisation
Interconnection	Propagation in the system and intensity of dependencies
Governance	Institutional coordination and consistency in decision-making

### Examples of specific metrics

In literature multiple proposed metrics can be found to quantify the quality of infrastructures and their interconnections. Many with a particular focus on the resilience and robustness of the systems, or some other characteristics relatable to the categories described. Below some practical and common examples will be listed, showing an operative basis to evaluate the capacity of a system to resist, adapt and recover following disturbances.

- 1) **Availability** ([168] M. Faccio, 2024)

$$A = \frac{MTTF}{MTTF+MTTR} \times 100$$

where:

- $MTTR = \frac{\text{Total downtime}}{\text{Number of breakdowns}}$  represent the average time needed by the system to recover from a disruption
- $MTTF = \frac{\text{Total uptime}}{\text{Number of breakdowns}}$  represent the average time the system operates continuously without interruptions

Context: Evaluates the operative performance of an infrastructural system in ideal conditions and under stress, providing the percentage in which the service is operative.

Advantages: Easy to communicate and widely used in operational management.

Limitations: Does not reflect dependencies, temporary service degradation, or resilience to disruption.

Applicability: This metric is best suited for infrastructures with measurable and continuous operational cycles, such as power grids, transport services, or communication systems.

## 2) Coupling Strength ([152] P. Nelson, 2016)

$$C = \frac{\text{Number of critical inter - system flows}}{\text{Total number of flows}}$$

It's a conceptual formula that expresses the measurement of the degree of dependency between subsystems

Context: Interconnected infrastructures where failures in one subsystem can propagate (energy ↔ transport ↔ ICT).

Advantages: highlights systemic vulnerabilities, “cascade” points.

Limitations: the formulation is often non-standardised and requires data on relationships between systems that are not always available.

Applicability: This is appropriate mostly for tightly connected technical networks, like transport with energy and ICT.

3) **Resilience Index** ([155] B. M. Ayyub, 2015)

$$R = \frac{\int_{t_0}^{t_1} Q(t)dt}{100(t_1 - t_0)}$$

where:

- $Q(t)$  represents the quality or performance of the system (expressed as a percentage)
- $t_0$  the moment when the disruptive event occurs
- $t_1$  the moment when the system recover all its functionalities

Context: A widely used metric for generically assessing the resilience of critical infrastructure (energy, transport, water networks). It measures the average functionality maintained by the system in the period between the event and recovery.

Advantages: It takes into account both the depth and duration of performance loss, allows for comparison between scenarios or mitigation strategies, and has a continuous formulation that can be generalised to different types of systems.

Limitations: It requires accurate temporal data for  $Q(t)$ , which is often difficult to obtain. Interpretation depends on how the “functionality” of the system is defined and does not directly represent the effects of interdependencies between complex systems.

Applicability: This metric fits continuous-service infrastructures (for example power or water networks) where temporal evolution of performance can be monitored.

4) **Adaptive Capacity** ([156] M. Taleb-Berrouane and F. Khan, 2019)

$$AD = \frac{\int_{t_d}^{t_r} [S(t) - M(t)] dt}{\int_{t_d}^{t_r} W(t) dt}$$

where:

- $t_r$  is the moment of recovery or stabilisation
- $t_d$  is the moment of the disruption
- $S(t)$  represents the effective performance of the system throughout time
- $M(t)$  is the minimum acceptable or expected performance
- $W(t)$  is a weight function that reflects the importance of performance

The numerator  $\int_{t_d}^{t_r} [S(t) - M(t)] dt$  measures the performance improvement compared to a minimum acceptable threshold during the recovery period. The denominator  $\int_{t_d}^{t_r} W(t) dt$  normalizes the result, weighing up the importance of different moments in time. A value of  $AD > 1$  means that the system has surpassed the expectations showing adaptation or improvement, while  $AD < 1$  reflect a recovery that is only partial or inadequate.

Context: This metric is designed to assess the adaptive capacity of complex systems, such as urban infrastructure, energy networks or emergency management systems, to modify their behaviour or improve their performance after a shock. It measures not only how quickly a system recovers, but also how much it improves or adapts compared to its previous state.

Advantages: It captures the evolutionary and learning capacities, not just the resistance. Moreover it is useful to evaluate adaptive improvement and it allows comparative analysis between different management scenarios through time.

Limitations: Requires detailed time series of performance data, which is often difficult to obtain, the choice of the weight function introduces subjectivity and in general it fits better analytical or simulation studies rather than quick on field decisions.

Applicability: Ideal for systems that evolve dynamically through feedback and learning, an example could be adaptive energy management.

5) **Benefit-Cost Index** ([155] B. M. Ayyub, 2015)

$$\beta_{B/C} = \frac{\mu_B - \mu_C}{\sqrt{\sigma_B^2 + \sigma_C^2}}$$

where:

- $\mu_B$  and  $\mu_C$  are the expected mean values of costs and benefits
- $\sigma_B$  and  $\sigma_C$  are the standard deviations of costs and benefits

Moreover, also the probability that the cost exceeds the benefit can be calculated:  $P_{f,B/C} = P(C > B) = 1 - \Phi(\beta_{B/C})$  where  $\Phi$  is the standard normal cumulative function.

Context: It is used to evaluate and compare investment alternatives in infrastructure resilience (e.g., improvements, retrofits, adaptation solutions). In particular, it helps to quantify in economic terms the relationship between intervention costs and expected benefits in a context of uncertainty.

Advantages: It provides a quantitative index that summarises the relationship between benefits and costs, allows for comparative decisions between different scenarios or interventions, and integrates the economic-financial approach with the assessment of resilience, facilitating the justification of investments.

Limitations: Richiede che benefici e costi siano stimabili in forma monetaria e che le loro distribuzioni siano caratterizzate (media, deviazione standard), dati che sono spesso difficili da reperire. Inoltre l'indice assume che benefici e costi siano "commerciabili" e comparabili, il che potrebbe non riflettere pienamente i valori sociali o ambientali impliciti e potrebbe trascurare aspetti non monetizzabili della resilienza e la complessità delle interdipendenze infrastrutturali.

Applicability: Useful for financial and strategic evaluation of resilience investments.

Even though these metrics are useful examples (summed up in the Table 3.2), it's important to remember that in most cases they are not all necessary or relevant, and each type of infrastructure is treated differently. The choice of metrics must be tailored to the system and its needs.

Table 3.2: Examples of common metrics

<b>Metric</b>	<b>Formulation</b>	<b>Function</b>
Availability	$A = \frac{MTTF}{MTTF+MTTR} \times 100$	It evaluates the operative performance of a system in ideal conditions and under stress
Coupling Strength	$C = \frac{\text{Number of critical inter - system flows}}{\text{Total number of flows}}$	It expresses the measurement of the degree of dependency between subsystems
Resilience Index	$R = \frac{\int_{t_0}^{t_1} Q(t)dt}{100(t_1 - t_0)}$	It measures the average functionality maintained by the system in the period between the disruptive event and recovery

Adaptive Capacity	$AD = \frac{\int_{t_d}^{t_r} [S(t) - M(t)] dt}{\int_{t_d}^{t_r} W(t) dt}$	It assesses the adaptive capacity of complex systems to modify their behaviour or improve their performance after a shock
Benefit-Cost Index	$\beta_{B/C} = \frac{\mu_B - \mu_C}{\sqrt{\sigma_B^2 + \sigma_C^2}}$	It's used to evaluate and compare investment alternatives in infrastructure resilience

### **Considerations for urban-interconnected infrastructure**

In the context of urban interconnected systems, which combine the likes of transport, energy, communication and more, evaluation metrics should reflect the complexity and interdependency of these systems. It's worth repeating that interconnected infrastructure are not isolated bodies, but networks that enforce and influence each other.

It is therefore vital to keep in mind some considerations:

- Interdependencies: As deductible from the literature in an urban system the malfunctioning of a network can have a serious impact on other connected systems that it's interdependent with. A breakdown in the energy infrastructure for example is very likely to also impact heavily other infrastructures such as the transport one. Therefore, it's important that the chosen metrics also consider the relationships among the different subsystems.
- Time dynamics: it's also important to consider the impact that time can have on decisions and disruptive events. The timeframe impacted varies depending on the issue, and so do the possible solutions and the metric chosen for a proper analysis. Per say, a quick recovery from an apparently small problem, might have repercussions in the long term if other impacted systems recover too slowly from it.
- Scalability and emergency: Another important aspect to remember and keep constantly in mind is that metrics must be sensitive to changes in scale. What

works for a small urban area may not be applicable to a metropolis, where complexities and challenges are amplified.

- Simplicity vs complexity: Another thing is that metrics must be simple to implement, but also complex enough to capture all the crucial aspects of the system, which is not always that easy. Careful selection of metrics is therefore essential to avoid overlooking important information or overloading the analysis with superfluous data.

### **3.4 Risk and Resilience Management**

#### *The Concept and role of risk and resiliency in interconnected infrastructures*

Urban infrastructures' risk management has gradually developed from a vulnerability-based approach to a perspective based on resiliency, intended not just as the capacity to resist shocks, but also to adapt and restore its functions in short times. This passage reflects a conceptual shift in the interpretation of what the sustainability of cities and complex infrastructure systems are. ([157] K. Jingjing et al., 2019)

Urban infrastructures are, as said, a System-of-Systems, where the likes of ICT, power grid, water and transport networks are like different layers that influence each other. This multi-level interdependency (Figure 3.2) is simultaneously both a source of efficiency and a vulnerability. Disruptive events by damaging one infrastructure can generate a cascading effect that amplifies the impacts on a bigger scale.

Therefore, resiliency is not just restrained to a structural level, it also requires adaptive capacity and systemic learning, consistent with the complex adaptive systems (CAS) approach. ([158] Y. Shi et al., 2021) Urban resiliency is hence an emerging characteristic of the system, as it is the result of dynamic interactions between subsystems, resources and governance actors.

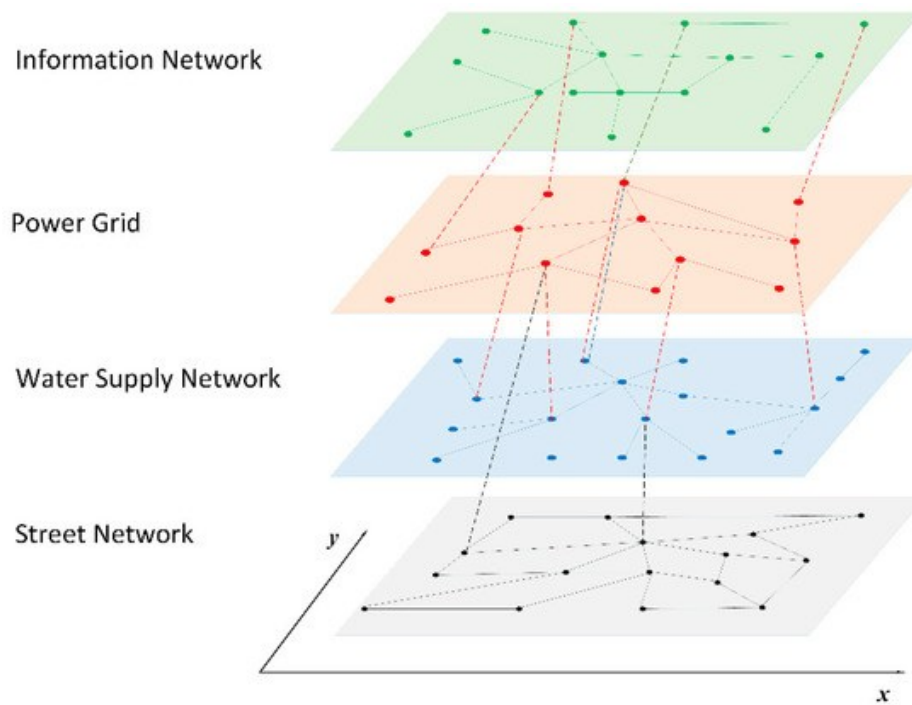


Figure 3.2: Interdependent infrastructure system model ([158] Y. Shi et al., 2021)

### Resilience model and metrics

The work developed by Simonovic et al. ([157] K. Jingjing et al., 2019) quantifies the resiliency of interconnected systems through a dynamic approach that derives from the ‘Multidisciplinary Center for Earthquake Engineering Research (MCEER)’ model. This formulation distinguishes two key complementary components: proactive capacity (absorptive), associated with the robustness and redundancy of the system, and reactive capacity (restorative), linked to the effectiveness of recovery strategies and the speed of functional recovery.

The performance curve of the system (Figure 3.3), pictures graphically this concept, showing the functionality losses after a disturbance and the following recovery. The horizontal axis shows time, while the vertical axis shows system performance compared to normal conditions. After the initial impact, the curve shows a drop to minimum operating capacity, followed by a gradual recovery phase. The area below the curve represents the cumulative loss of performance, while the portion ‘recovered’ with respect to full functionality expresses overall resilience. As deductible, a system with adaptation measures experiences a smaller loss and a quicker recovery, resulting in a higher level of resilience.

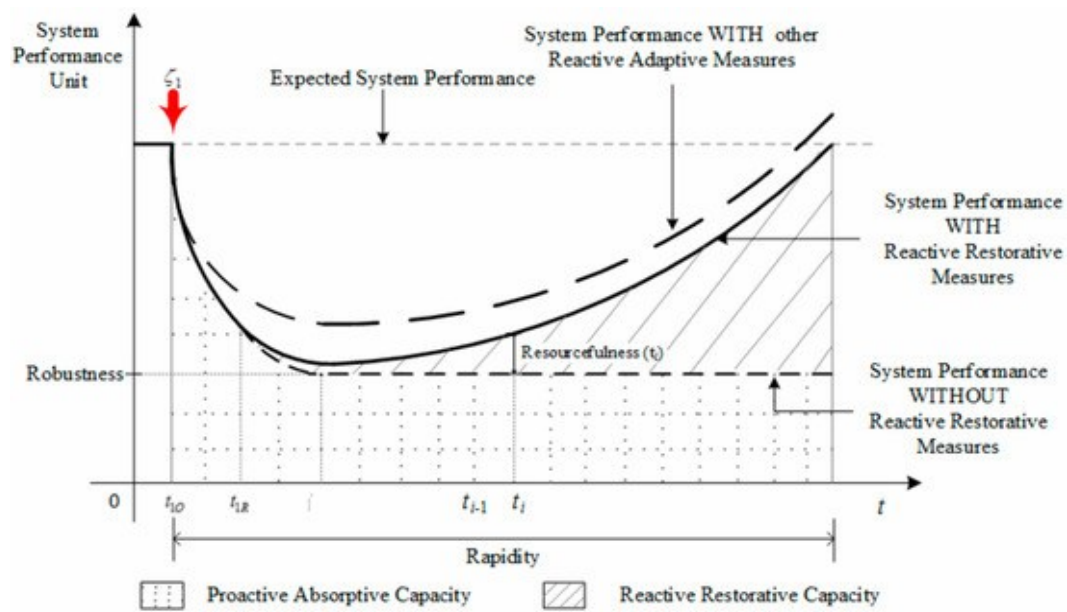


Figure 3.3: Typical performance of an infrastructure system with a disturbance ([157] K. Jingjing et al., 2019)

The associated metrics of this representation are:

- ❖ Robustness, the capacity to maintain the minimal functionality during the disturbance
- ❖ Resourcefulness, the capacity to mobilise and manage resources in response to recover
- ❖ Rapidity, the speed at which the system restores its full functionality

In the framework of Shi et al. ([158] Y. Shi et al., 2021), these dimensions converge into the broader adaptive capacity, which integrates redundancy and organisational flexibility, highlighting the dynamic and multidimensional nature of resilience.

### *Risk management and recovery strategies*

To achieve the aimed recovery results, it's vital to control the interdependencies that link the different systems. Physical, functional, geographical and cyber dependencies, when combined, generate three possible types of impact:

- Hidden impacts, related to non-obvious dependencies in nominal conditions, yet decisive in case of a crisis
- Chain impacts, resulting from chain effects between nodes (components or units that connect the networks) and networks
- Cycle impacts, in which failures feed back into each other, generating systemic blockages

To face these vulnerabilities, there are multiple different approaches, called restoration strategies, that vary based on the situation. Some prioritize speed over coordination; others emphasize interdependencies and systemic balance. It's very important however to recognize the hidden functional links between infrastructures, even if slower at first, as they prevent cascading failures and ensure a more stable long-term recovery. ([158] Y. Shi et al., 2021)

## **3.5 Governance of interconnections**

The real challenge in a smart city is not just to enable the communication between different infrastructures, but also to govern their relationships, dependencies and flows that come from this interconnection. To manage interconnections, it's necessary to build a structure where different actors (public, private and citizens) operate on autonomous systems in a coordinated manner, with efficiency and resiliency.

### **Institutional architecture for interdependencies**

OECD's report 'Good Governance for Critical Infrastructure Resilience' ([159] OECD, 2019) discusses the fact that an efficient governance of critical interconnected infrastructures requires a multi-level architecture where national authorities, local businesses and private operators collaborate to establish common goals, standards and protocols. For convenience, from a managerial perspective it can be represented as a "meta-control system":

- definition of general goals (e.g. service continuity, interoperability)
- operative translation through standards, contracts and protocols among operators
- performance monitoring and review of the interconnected system

In an article written by Aksel Ersoy ([160] A. Ersoy, 2017) were analysed some case studies (of Bristol and Milton Keynes, UK) and the result highlights that the design of smart cities has generated new spaces for experimental decision-making. However, it also found out that a recurring risk is to fossilise the pre-existing institutional structure (in this case "silos") that separated the infrastructures.

Therefore, a key element is the institutional capability. Organisations need to be in possession of resources, competencies and structure valid processes to govern the interactions between infrastructures, as just having the right tools is not enough.

### **Coordination, trust and information sharing**

Governance of interconnections requires strong foundations based on trust and transparency between actors that usually operate separately. OECD insists on the importance of information-sharing, as for the different entities and operators it is vital to acknowledge as much as possible what concerns the other infrastructures as well, to address cascade scenarios and systemic vulnerabilities. In fact, multiple countries have established information-sharing platforms facilitating this process and strengthening the resilience of the infrastructures. ([159] OECD, 2019)

Moreover, Ersoy in his article adds that in smart cities' projects the efficiency depends heavily on "collaboration, inclusion and institutional capacity" ([160]

A. Ersoy, 2017). From a managerial perspective it's reasonable to affirm that it means:

- build formal exchange platforms and protocols between networks/sectors (energy, transport, ICT, water)
- define rules that guarantee safety during the information exchange (privacy, safety, data ownership)
- set incentives so that operators share all data, also vulnerabilities not just positive performance

Without these mechanisms, interconnections might be responsible for hidden vulnerabilities and operators might be unaware of the fact that their decision might also affect a different system.

### **Decision-making and distribution of responsibilities**

One of the most difficult moments to manage is when an interconnected infrastructure faces an interruption. In those situations it's important to know exactly who has to act and how they should do so. OECD's report ([159] OECD, 2019) highlights the need for governance models in which roles, responsibilities and incentives are made explicit in advance. To facilitate these moments, when designing and managing the system, there are three main points to keep in mind:

- Mixed (public-private) decision-making bodies need to be set up for interconnected infrastructure. These bodies should be able to analyse systemic impacts, prioritise interventions and manage trade-offs between sectors.
- Define multilateral contracts or inter-sectorial agreements that establish who bears the costs and benefits of resilience investments.
- Introduce common performance indicators monitoring network of interconnections and not just the single infrastructure

Both case studies analysed by Ersoy in his article ([160] A. Ersoy, 2017), confirm the fact that the ambiguity over who is in charge of the process and who benefits from the infrastructural integration limit the potential for collaboration.

## **The evolution towards adaptive governance**

Last but not least, governance of interconnections must be adaptive to react to technological and organizational changes. The model is shifting from ‘compliance with regulations’ to ‘system performance’, which requires the integration of continuous learning mechanisms that include post-event evaluations, protocol updates, and feedback loops. This also requires including new actors (start-ups, data platforms, citizens) in decision-making processes, redesigning broader governance networks, and equipping those involved with digital tools for the visibility of interdependencies (cross-sector dashboards, digital twins of urban networks) that support rapid and coordinated decisions. ([159] OECD, 2019)

Smart cities can hence act as infrastructural governance laboratories where it’s possible to experiment with new forms of coordination between different networks and actors. However, technological experimentation is not sufficient if not joined by the institutional capacity of skills, rules and processes for managing interdependence between systems. Only an integrated vision allows to transform pilot projects into stable cooperative models, overcoming the sectorial fragmentation and turning innovation into mature and adaptive urban governance. ([160] A. Ersoy, 2017)

To summarise how the governance of interconnections should be managed to become an opportunity for systemic governance and urban resilience rather than a vulnerability, the following four points express properly the generic steps that must be followed:

- 1) define an institutional architecture for infrastructure dependencies
- 2) build trust and protocols among operators for coordination and information exchange
- 3) define joint decision-making mechanisms and a clear distribution of roles and responsibilities among the actors involved
- 4) evolve adaptively by incorporating technology, actors and continuous learning

This analysis about the interconnections of the smart cities, brings out how adopting system thinking makes it more efficient to face the complexity of organizational and economic challenges in this field. Decisions are not judged just on the immediate effects, rather on the whole impact they generate on the system of relationships in which they are placed. Managing all this, also from an engineering perspective, means designing processes, structures and strategies capable of adapting to non-linear dynamics, recognizing the importance of feedback, interdependencies and emerging variables.

From an operative perspective this goal can be realized through tools and techniques oriented towards the support of an integrated vision. Modelling complex systems, using SD approaches to analyze feedback loops, mapping processes through interconnected information systems, adopting systemic performance indicators (KPIs that measure efficiency and complex effectiveness) and applying lean management practices (like continuous improvement) oriented towards organisational learning are some of the main ones.

Therefore, system thinking is not a theoretical alternative, it is a necessary extension of engineering logic as it enables a shift from an analytical view of problems to an integrated and dynamic one, which is more suited to the complex and constantly evolving contexts in which organisations operate.



## **Chapter 4 - Case Study: The Smart City of Copenhagen**

This chapter examines Copenhagen as an advanced example of smart infrastructure integration. It analyses how digitalisation, governance stability and long-term investment enable coordinated energy, mobility and data systems. While not intended to validate the theoretical model, the case provides an empirical reference illustrating opportunities and practical constraints.

### **4.1 The choice of Copenhagen**

The analysis of the previous chapters demonstrates how urban infrastructures, especially the energy one, are evolving towards models featuring greater integration, digitalization and coordination capacity between sectors that were once isolated. However, it is necessary to contextualise what has been discussed within a real context.

This case study relies exclusively on secondary data drawn from scientific publications, institutional reports and technical documentation. This choice is consistent with the exploratory and qualitative nature of the thesis and reflects the complexity of smart city systems, which would require resources and timescales not compatible with a master's thesis for primary data collection. Rather than producing new empirical evidence, the aim here is to reinterpret existing material through the analytical framework developed in the previous chapters.

Copenhagen, Danish capital, is one of the cities that for over a decade has stood out as one of the most advanced European contexts in terms of the transformation of

energy systems, urban infrastructure and governance models geared towards sustainability. This choice as case study is driven by the will of finding empirical evidence on whether the illustrated principles are reflected in a consolidated urban context, characterised by structural constraints and the direct involvement of public and private actors and citizens.

For these reasons, it is undoubtedly more meaningful to analyse a case such as Copenhagen rather than realities such as the previously mentioned Masdar City which, despite being a highly advanced technological experiment, is a city built from scratch, hence developed under highly controlled conditions and therefore not very representative of the real challenges faced by most existing cities. Copenhagen, on the other hand, allows the observation of integrated energy solutions, digitalization and infrastructural innovations, showing how they can be gradually introduced into an already established urban environment with history and cultural aspects to be respected, offering a more realistic basis to assess the transferability and limitations of the theoretical models discussed. The Danish capital manages to combine two dimensions that rarely coexist in the same context today:

- 1) Strong political ambition and long term planning
- 2) Real technical experimentation on energy smart management, data and infrastructures' interconnections

The aim of this chapter is hence not to provide a general description of the city, but to assess the extent to which Copenhagen actually puts the concepts discussed into practice. Energy infrastructure as the backbone of smart urban systems, interdependence between different networks, the critical role of digitalisation and also the importance of multi-stakeholder governance. It also highlights the limitations and challenges of implementing these concepts, seeking to avoid the simplified narrative that often accompanies the topic of smart cities.

## 4.2 Strategic vision and governance of the smart city

Copenhagen's urban governance is a key element for understanding how energy, digital and physical infrastructure can operate as an integrated system, following the principles described in the previous chapters. The city, in fact, adopts a long-term planning strategy capable of combining strategic guidelines, operational coordination and systematic data management. As highlighted by Petrea and Ursache ([161] M.I. Petrea, I.M Ursache, 2023), this approach is what allows the translation of sustainability goals into tangible technical actions and coherent infrastructural projects.

Operatively speaking, Copenhagen's governance is based on three main mechanisms:

- *Structured multi-stakeholder coordination*

Municipalities, energy utilities, district heating operators, transport companies and research institutions cooperate through platforms designed to project networks and services as parts of an integrated system. This model is the first brick of initiatives such as EnergyLab Noerdhavn, a living lab where building development, electricity networks, heating networks, electric mobility and digital infrastructure are analysed together towards the achievement of green heating and e-mobility goals. ([162] J. Wang et al., 2017)

- *Integration of data into decision-making processes*

The digitalization described in the European Commission reports ([163] B. Alpagut et al., 2022) and IDASC (Intelligent Data Use in Smart Cities)'s documents ([164] S. Ben Amer et al., 2021) enables data from sensors, smart meters and IoT platforms to be used to optimise the entire urban system. Their application includes the likes of predictive heat demand management, controlling the charging loads of electric vehicles based on the availability of renewable energy sources, and urban simulation through

digital twin models. The data is hence the cognitive infrastructure that sustains the operative and strategic decisions that are taken.

- *Modular planning of energy infrastructure*

The city does not implement new infrastructure as a single monolithic system, instead it introduces interoperable technologies progressively, ensuring flexibility, compatibility and the time to update the existing urban environment. The strategies adopted in Copenhagen align with the framework outlined by Lund et al. ([165] H. Lund et al., 2014), describing how urban energy networks should be planned to operate in a flexible and integrated manner. Consistent with this approach, the city has introduced heat pumps, thermal and electrical storage systems and coordinated control strategies that integrate the electricity grid with district heating networks. These components are not deployed as isolated interventions, but as interconnected modules that progressively support the decarbonisation of the system. The interventions are assessed separately and, if the desired benefits are achieved, implemented, taking into account their connection with buildings and other existing infrastructures.

Despite the strengths, criticalities related to data quality, platforms interoperability and the scalability of some solutions remain. These issues confirm that the process requires competent governance and a well-defined strategic vision, capable of coordinating complex systems and heterogeneous actors to achieve the established objectives.

### **4.3 The energetic infrastructure as the backbone of the city**

In Copenhagen the energy infrastructure is being developed as a modular and interoperable technical system, able to integrate electricity, heat, storages and operative data. This approach, as just mentioned, is coherent with the ‘4th Generation District Heating’ (4GDH) described by Lund et al. ([165] H. Lund et al., 2014), which affirms that heating networks must operate at low temperatures,

be strictly related to the electricity network and support the overall flexibility of the system.

The 4GDH principles are being implemented practically in the Danish capital with:

- Centralised heat pumps, connected to the electric network to exploit energy surpluses derived from renewables
- Large-scaled thermal storages, used to modulate the heat demand and reduce peaks
- Electric storage tanks, to stabilize the network during moments of wind and solar variability
- Digitalised substations and control systems, regulating temperatures and flows in real time

These interventions are introduced as autonomous but compatible modules, therefore updating progressively the infrastructure without having to completely redesign it. A

Particularly interesting is the case of the district of Nordhavn, where the project 'EnergyLab' ([162] J. Wang et al., 2017) proves that these components are working together. As cities aim to lower their carbon emissions, integrating intelligent energy systems that can adapt to the fluctuation of renewable energy is vital. Nordhavn, a newly developed district in Copenhagen, exemplifies future city districts by showcasing and testing flexible energy system solutions.

- The district heating network and the electricity grid are connected via high-efficiency heat pumps, with a battery energy management system supporting grid fluctuation that reduces heating consumption by 68%
- Buildings are equipped with control systems that regulate thermal demand based on weather forecasts and utility signals
- Electric vehicles charging is smart managed to avoid overloads and simultaneously exploit peaks in renewable energy production
- Shared data platforms allow the coordination between network operators and building managers

EnergyLab Nordhavn demonstrates how the integration of electricity, heat, energy-efficient buildings and electric transportation in city districts can significantly reduce carbon emissions. ([166] L. Aagaard, 2024)

This evolution is showing how Copenhagen is not implementing a monolithic smart grid, but an incremental energy infrastructure, updated step by step and designed to be integrated with buildings, electric mobility and digital networks. The results obtained in Nordhavn, especially in the integrated management of loads and in the ability to stabilise the thermal and electrical network, confirm the validity of the theoretical principles discussed in the previous chapters.

#### **4.4 Digitalisation, data and smart platforms**

Copenhagen confirms how digitalisation in smart cities is not a marginal addition, but a key element for energy management. Sensors, smart meters and IoT systems are responsible for the real-time collection of data about the operation of networks, buildings and facilities, building an informative layer to support predictions, advanced controlling and the coordination of different infrastructures, therefore allowing continuous monitoring and optimizing the flows. This asset confirms the fact that without a digital platform capable of interpreting data and leading operative decisions, an urban infrastructure cannot really be considered smart.

The European report about digitalization in urban energy systems ([163] B. Alpagut et al., 2022) focuses on how this information gets integrated in utilities daily processes. The data collected from buildings, heat pumps, storages and substations allow the adjustment of the network temperature according to the loads, the regulation of production according to the renewable sources and the optimization of electric vehicles charges. Thereby, the network operation switched from static logic to predictive models that foresee demand, weather, facilities conditions and more.

Simultaneously, the final report of the IDASC project ([164] S. Ben Amer et al., 2021) shows how the city is developing a data governance orientated towards

interoperability. In fact, in the report the authors recommend the cooperation between various bodies (like municipalities, utilities and service providers) to overcome the fragmentation allowing a more comprehensive integration of datasets related to consumption, production, storage and building infrastructure. Indeed, the availability of shared information across them permits an easier and more efficient intervention on electricity and heating networks, when needed, reducing inefficiencies and duplication.

The efficiency of this approach has once again been proven in Nordhavn, where the project EnergyLab ([162] J. Wang et al., 2017) has tested it with on field applications. In particular the digitalization there, has been supporting predictive systems that modulate the thermal demand of buildings and activate heat pumps and storage units according to system conditions, synchronising energy requirements with the availability of renewable production. The results show that if the heat pump is managed in a ‘flexible’ manner, it is possible to save around 13% on heating bills.

These tools enable the stabilisation of flows between the electricity grid and the district heating network, proving that digitalisation is an essential operational element for the management of multi-vector systems.

Other tangible benefits related to the digitalization and the use of smart platforms are found in IDASC project’s report ([164] S. Ben Amer et al., 2021), shown in the following table [Table 4.1]

Table 4.1: table summarizing the main monetary and environmental benefits reported from data-driven optimization and control of district heating systems and building energy systems.

<b>Intervention</b>	<b>Type of saving</b>	<b>Estimated value</b>
Lower return temperature in district heating	Monetary	240 – 790 million DKK/year
Smart LED lighting in public buildings	Monetary	~3.4 million DKK/year
Network loss reduction / efficiency improvement	Monetary	~5.5 million DKK/year

CO <sub>2</sub> / Energy reduction	Environmental	Not quantified; potential significant reduction
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However, some critical issues remain. Data quality is not always consistent, legacy systems still limit interoperability, and the scalability of the solutions tested requires technical standards and additional investment. These limitations confirm that digitisation is a necessary condition for infrastructure integration but requires mature data governance to be fully effective on an urban scale.

#### 4.5 Networks' interconnection: the role of sector coupling

Sector coupling, where the just discussed digitalisation lays as its foundation, is the driving principle in Copenhagen to integrate electricity, heat, storage and mobility into a single comprehensive system. The white paper published by 'State of Green' ([166] L. Aagaard, 2024) is stressing on the importance of the interconnection between energy carriers to manage the high variability of renewable sources and improve the overall efficiency of urban infrastructure. As discussed it is not about just combining different technologies, but especially ensuring that networks operate as parts of a single, flexible system that can be optimised in real time. Obviously it is not an easy task and there are multiple aspects that must be considered, mainly the following:

##### ❖ *Electricity–heat integration*

For Copenhagen the most relevant coupling is the one between the electricity network and district heating, enabled by the adoption of centralised heat pumps and thermal storage systems. Heat pumps transform the renewables' electric surplus into useful heat for the network, reducing peaks and reducing the usage of fossil fuels for thermic purposes. This is one of the pillars of sector coupling and is perfectly aligned with the principles of the 4GDH. ([165] H. Lund et al., 2014)

❖ *Role of storage and flexible management*

Thermal and electrical storages are used to temporarily separate supply and demand, improving the system's stability. The mentioned white paper ([166] L. Aagaard, 2024) explains how the presence of buffers on both carriers allows for more efficient integration of Danish wind power production, as well as other renewable sources although in smaller amounts. In Copenhagen the result is a higher degree of predictability of the heating network and a reduction in the need for conventional generation during peak periods, significantly improving energy efficiency.

While the most efficient method of storage is to store energy as electricity in batteries, conversion to energy sources such as heat, gas or methanol through Power-to-X technologies can also be highly valuable when seeking to couple different sectors together. ([166] L. Aagaard, 2024)

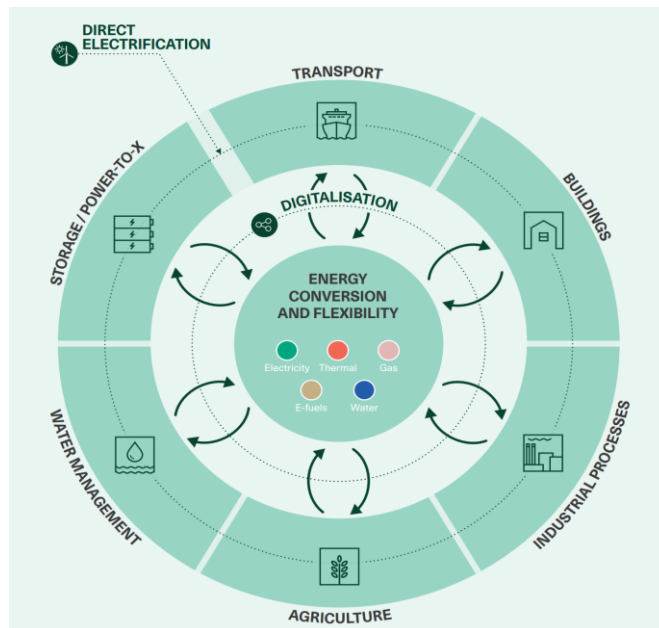
❖ *Electric mobility as an energy component*

Electric mobility is managed through a modulated recharge logic, where the power of charging stations is adjusted according to the condition of the network and the availability of power produced by renewable energy sources. This approach, as well described in the white paper ([166] L. Aagaard, 2024), makes mobility an integral part of the energy system rather than an additional burden.

In the Nordhavn living lab, the integration between carriers has been tested in operational conditions. Heat pumps, thermal storage systems, buildings' control technologies and charging platforms are interconnected through a single data hub that coordinates electricity, heat and mobility. The district operates as a multi-carrier system in which predictive algorithms simultaneously modulate heat demand, heat pump output, and electric vehicle charging, thereby demonstrating the practical feasibility of urban sector coupling.

As shown in figure [4.1] the management of this system involves different parties and, despite these promising results, several challenges remain. Data

standardisation, interoperability between different existing platforms and their adapting costs are still difficult obstacles to overcome. However, the ‘District



Energy’ white paper ([167] S.Green, 2024) confirms that Denmark already possesses a good infrastructural foundation, among the best in Europe, that will allow it to expand on a national scale. Consequently, Copenhagen is well placed to transform sector coupling from a local experiment into a long-term urban strategy.

Figure 4.1: Simplified model of sector coupling, showing the main interactions between energy sectors and resources ([166] L. Aagaard, 2024)

#### 4.6 Results, benefits and limitations in Copenhagen

The Copenhagen case proves that the integration of different networks and their interoperability can generate tangible results both in terms of efficiency of the system and operative stability. The implemented solutions , especially in Nordhavn living lab, showcased that sector coupling is indeed a theoretical model but with an approach that is already applicable in complex urban areas.

### Observed benefits and results

The data collected in the pilot projects indicate several actual improvements.

The flexible management of heat pumps and the combined exploitation of thermal storages, as said, is responsible for a 13% reduction in the costs related to heating, thanks to the optimization of the moments of energy withdrawal. Moreover, the integration between the different carriers allows the absorption of a greater share of renewable power, concurrently reducing energy peaks in the electric grid. ([162] J. Wang et al., 2017)

At the same time, the implementation of predictive models has enhanced the operational stability of the thermal system, while mitigating overcapacity and improving demand management under variable conditions. These results confirm the fact that digitalisation and energy infrastructure's modularity empower a growth in the urban system's overall efficiency even without invasive interventions on existing buildings.

### Existing limitations and necessary conditions for scalability

Despite the benefits, there still are some criticalities that limit the scalability of these applications in the whole city. The digital platforms used are not all yet fully interoperable, and the quality of the collected data can vary significantly depending on the technology used in the different districts. ([164] S. Ben Amer et al., 2021)

Scalability also requires major infrastructure work, such as the extension of storages, the modernisation of substations and the spread of low-temperature heating networks, which are inevitable preliminary conditions to implement sector coupling on a large scale. ([166] L. Aagaard, 2024) Moreover, most advanced solutions already tested need stable governance and regulations, capable of managing interactively the different energy sources.

### Overall evaluation

All in all, Copenhagen offers a practical thorough demonstration of the validity of the principles discussed in the previous chapters. When led by a long-term

investment, urban infrastructure can become functioning interconnected systems when supported by digitalisation, advanced control models, and modular planning. At the same time, the case highlights that infrastructural integration needs an adequate balance between technological innovation, well-targeted investments and a regulatory framework capable of supporting the transition. And last but not least, also citizens and all the involved parties play a crucial role in the accomplishment of the final goal.

The one of the Danish capital however, is not a model that can be easily replicated in every city, it is instead a plausible benchmark to understand the technical, institutional and infrastructural conditions needed to create a resilient smart city, leading as one of the most viable examples for other cities to follow towards a greener and more efficient future.

So, while Copenhagen represents one of the most advanced and coherent examples of infrastructural integration, its model cannot be transferred mechanically to other urban contexts. The effectiveness of smart city solutions depends not only on technological choices but also on institutional structures, governance arrangements, socio-cultural conditions and the historical path of each city. Other cases, such as Barcelona and Vienna, depict how different priorities, political visions and urban fabrics lead to various interpretations of what “smart” means in practice. Therefore, Copenhagen, that for its goals and values it’s a very accurate fit for the sake of this thesis, should be regarded not as a universal blueprint, but as a useful reference point from which other cities can draw inspiration, provided that strategies and technologies are carefully adapted to local needs, constraints and opportunities.

## **Conclusion**

The analysis carried throughout this work shows how smart cities are complex systems where energy, mobility, ICT and governance are linked by strong interdependencies. The energy infrastructure, mainly through the smart grid, confirms to be an enabling factor for the integration of renewables, flexibility management and the evolution of urban services, even though it carries some significant challenges in terms of interoperability, security and coordination between different actors. The systemic approach emphasises that these dynamics cannot be understood through a sectoral logic, but require models capable of capturing interactions, feedback and continuous adaptations.

The Copenhagen case shows how an integrated vision, supported by competent governance and long term investments, can turn theory into practice with important results. Simultaneously, it suggests that those results are not transferable into any other random environment, as institutional context, administrative capacity and digital maturity profoundly influence the outcome of smart strategies. Furthermore, structural issues remain unresolved, as highlighted in the literature. Topics like the risks of technological lock-in, digital inequalities and dependence on models are difficult to adapt to different contexts.

This paper adopted a qualitative and reconstructive approach, based exclusively on second-handed sources and does not include primary empirical investigation or original modelling. This might represent a constraint for certain aspects, but is consistent with the objective of constructing an integrated analytical framework rather than developing original models or empirical evidence. Future research would be useful to further explore these dynamics through more extensive comparative analyses, socio-technical assessments based on primary data, or models capable of integrating technical, institutional, and behavioural dimensions. Understanding how to adapt smart solutions to different contexts remains, in fact, a central challenge for the future that is still evolving.



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