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Review

Exploring Social Capital in Situation-Aware and Energy Hub-Based Smart Cities: Towards a Pandemic-Resilient City

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Abstract: Although the severity of the COVID-19 pandemic has appears to have subsided in most parts of the world, nevertheless, in addition to six million deaths, it has yielded unprecedented challenges in the economy, energy, education, urban services, and healthcare sectors. Meanwhile, based on some reports, smart solutions and technologies have had significant success in achieving pandemic-resilient cities. This paper reviews smart city initiatives and contributions to the prevention and treatment of coronavirus disease, as well as reducing its destructive impact, leading towards pandemic-resilient economic and health systems. Furthermore, the situational awareness contributions are reviewed in pandemic-resilient governance. The main contribution of this study is to describe the construction of social capital in smart cities as a facilitator in creating a pandemic-resilient society in crisis through two analyses. Moreover, this research describes smart cities' energy as interconnection of energy hubs (EHs) that leads to a high level of resiliency in dealing with the main challenges of the electricity industry during the pandemic. Energy-hub-based smart cities can contribute to designing pandemic-resilient energy infrastructure, which can significantly affect resilience in economic and health infrastructure. In brief, this paper describes a smart city as a pandemic-resilient city in the economic, energy, and health infrastructural, social, and governmental areas.

Keywords: smart city; social capital; situational awareness; energy hub; resilience; COVID-19 pandemic

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1. Introduction

From the Athens plague in 430 BC to the Zika epidemic in 2015, pandemics have caused considerable effects on human life, beyond causing thousands of deaths. While the world was confident in the advances of medical science and did not expect the emergence of a new epidemic, the coronavirus brought a destructive pandemic of new dimensions and strength [1]. Although it seems that the severity of the disease has subsided in most areas of the world, this pandemic has infected about 676 million people to date and caused 6 million deaths, according to the World Health Organization's reports [2]. Governments have acknowledged that the coronavirus pandemic has challenged the world in different sectors, including the economy, energy, education, urban services, and healthcare. Meanwhile, researchers and scientists have suggested the smart city concept as a framework that can play a significant role in handling the challenges of the crisis [3,4].

Smart cities, through advanced technologies and innovations, in addition to supporting citizens' wellbeing during the pandemic, can be useful in improving the general health of citizens beyond the pandemic [3,4].

We introduced social capital as a resiliency facilitator in a situation-aware smart city during the COVID-19 pandemic, in [5]. Moreover, in [6], we emphasized that a smart city as an energy hub (EH) can provide flexibility for smart cities' energy during the COVID-19 pandemic.

This paper, as an extended complementary of [5,6], reviews the state-of-the-art utilization of smart city technologies in COVID-19 crisis management. Additionally, this paper introduces the smart city as a concept that can be effective in achieving resilience against pandemics. In the existing literature, less attention has been paid to the assessment of all aspects of urban resilience against the COVID-19 crisis. In this regard, the urban resilience dimensions have been enumerated, and the innovative smart city solution has been discussed for improving resilience in these dimensions, as summarized in Figure 1. Moreover, this paper portrays the construction of social capital in smart cities as a facilitator in creating a pandemic-resilient society, through qualitative and quantitative analyses.

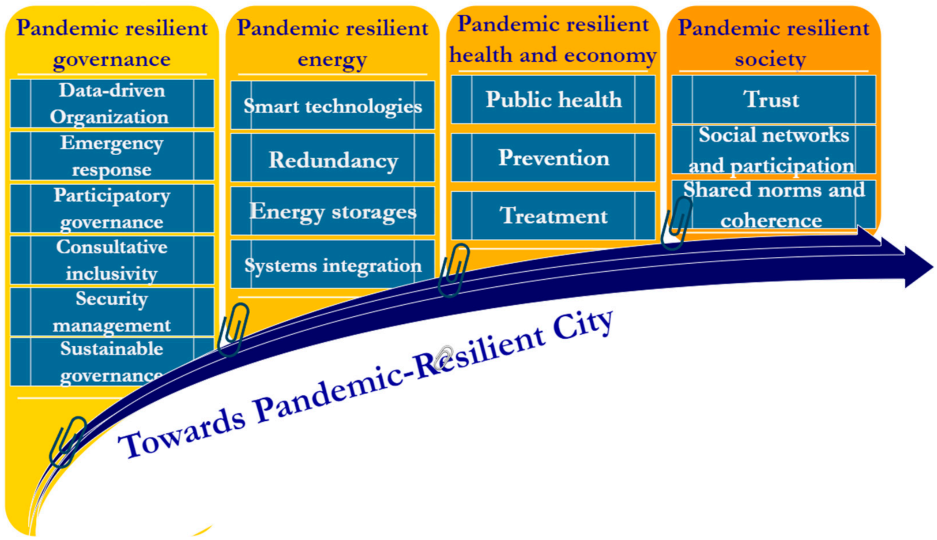


Figure 1. Smart cities' contributions towards resilience in the COVID-19 pandemic.

Furthermore, in the urban energy infrastructure in particular, introducing a resilient framework dealing with the consequences of the COVID-19 crisis constitutes a research gap. Hence, this paper describes smart city energy as interconnected EHs that can lead to a high level of resiliency in dealing with the main challenges of the electricity industry during pandemics. Energy-hub-based smart cities can contribute to designing pandemic-resilient energy infrastructure, which can significantly improve resilience in the economic and health aspects of smart cities.

The contributions of this paper can be summarized as follows:

- Portraying social capital realization in smart cities as a facilitator in creating a pandemic-resilient society.
- Reviewing the state of the art in utilizing smart city technologies in COVID-19 crisis management towards pandemic-resilient economy, health, and governance.
- Describing smart cities' energy as interconnected energy hubs (EHs), which contribute to designing pandemic-resilient energy infrastructure.

The rest of this paper is organized as follows: Section 2 describes the research methodology, and in Section 3 the main concepts and definitions are introduced. Section 4 reviews the existing literature related to the effective implementation of smart city technologies during the coronavirus pandemic. Section 5 discusses the social capital realization in situation-aware smart cities that leads to a pandemic-resilient city. In Section 6, the pandemic-resilient energy-hub-based smart city framework is discussed and analyzed. Finally, after the discussion in Section 7, the last section concludes the study.

2. Research Methodology

The reference research methodology leading to the present manuscript is depicted in Figure 2. After establishing the basis for the definitions and concepts associated with this research, the documents reporting innovative research or implementations of smart city technologies and initiatives for the prevention and treatment of coronavirus disease are reviewed. Subsequently, while enumerating the dimensions of smart cities' resilience, the use of these innovations in striving towards a pandemic-resilient smart city is discussed in terms of the economy, health, governance, and social aspects.

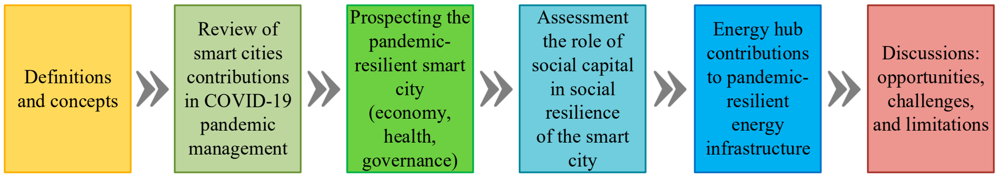


Figure 2. Research methodology for exploring social capital in situation-aware and energy-hub-based smart cities: towards a pandemic-resilient city.

In the exploration of the pandemic-resilient smart city in social terms, further to the assessment of the social capital asset, its role as the principal source of social resilience in smart cities is analyzed based on qualitative and quantitative methods.

In addition, the contributions of energy-hub-based smart cities to designing pandemic-resilient energy infrastructure are introduced. In the energy aspect, in addition to reporting numerical indices for evaluating resiliency from two case studies, energy hubs' contributions to the fulfillment of resilient energy infrastructure are analyzed. Finally, opportunities, challenges, and limitations in achieving pandemic-resilient smart cities are discussed as the closing comments on this research.

3. Definitions and Concepts

3.1. Smart City

The IEEE IoT Initiative's Smart Cities Working Group defines a smart city as an urban area that employs technological or non-technological products to improve the quality, performance, and interactivity of urban services, reduce resource consumption and costs, and ensure the ethical and social wellbeing of its citizens, as well as increasing their connection with the government [7]. IEEE Smart Cities highlights the smart city indicators in technology, government, and citizen integration, including smart living, smart governance, smart people, smart mobility, smart environment, and smart economy [8]. However, with respect to energy, smart cities can be defined as energy-efficient cities that utilize renewable energy sources and smart technologies as much as possible [9–11].

3.2. Social Capital

Social capital has been mentioned as a key factor in economic and social phenomena in recent years. Social capital is centered on social relationships and defined as a collective asset in the form of shared values, cohesion, networks, participation, trust, and relations that promote cooperation for mutual benefits. Social capital is a concept whose structure is social relationships, and its content is trust. However, some researchers believe that trust can be seen as the output of the other attributes of social capital. When social capital is seen as a social network of people and organizations, it can be advantageous in reducing the effects of a crisis [12,13].

3.3. Situational Awareness

Situational awareness can be defined as understanding what is happening, a more technical view of environmental events according to time or place, and interpreting and projecting the future state. Situational awareness is known as a fundamental element in successful decision-making in a wide range of situations. Law enforcement, traffic control, aircraft guidance, ship navigation, medical care, defense missions, and even control of a nuclear power plant can be considered processes in which situational awareness plays a significant role in their success. Therefore, the necessity of increasing situational awareness to make an effective and successful decision, especially in a crisis, is undeniable [14–16].

3.4. Energy Hub

The energy hub (EH) concept is defined as an efficient management framework for the generation, conversion, storage, and consumption of different types of energy carriers. As such, EHs represent a significant possibility for the integrated and synergistic management of multiple energy systems, and they can supply energy from different sources continuously and improve the energy supply's efficiency and resiliency [9,17–19].

3.5. Resilience

Resilience in any system means dealing with disasters that disturb the system's normal functionality. Resilience describes the system's capacity to absorb or adjust to damages, adapt to new conditions, and quickly recover the normal functionality of the system. In other words, a resilient system is a system with planning, absorption, recovery, and adaptation abilities in situations of disruptive change [20,21].

4. Review of Reported Smart Cities' Contributions to COVID-19 Pandemic Management

According to reports, smart cites' functionalities have been beneficial in dealing with the challenges of the COVID-19 pandemic in various sectors. Hence, in the following section, some capabilities of smart cities' components and features against the COVID-19 pandemic are described. Smart cities have components—also called characteristics, domains, features, concepts, or aspects—that can contribute to the effective management of crises [22,23], as demonstrated in Figure 3.

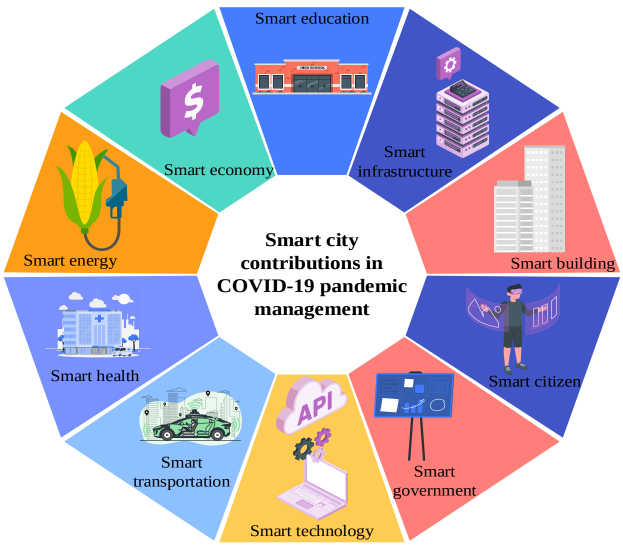


Figure 3. Smart cities' characteristics contributing to pandemic management.

4.1. Smart Public Health Systems

Beyond pandemics, smart health systems can be achieved with the integration of smart transportation, smart infrastructure, smart governance, smart citizens, smart healthcare, and smart technologies, and can be considered a promising tool in improving healthcare quality. This system's integration in the smart city framework can be effective in monitoring patients in a hospital to guide patients to less crowded centers, managing the supply chain of medical equipment, tracking and directing medical staff in the city to prioritize them, and developing new screening methods to recognize and guide new cases before referring them to the hospital, especially during pandemic crises [22,24–28].

According to [29], electronic health and mobile health can be considered among the foundations of smart health. In this regard, classical health essentially does not need information and communication technologies (ICT) and the internet of things (IoT); electronic health utilizes the databases of patients' medical information and electronic health records; and in mobile health (M-Health), patients can check their prescriptions using their mobile devices. Furthermore, in smart health (S-Health), the patient receives information from the closest hospitals and pharmacies, which helps them be aware of the areas that can prove to be hazardous for their health conditions. Through the integration of smart city components, m-Health can be amplified with S-Health. In this state, an automatic notification will be sent when an accident occurs for a cyclist equipped with a smart bracelet or smart helmet. When the systems receive the notification, an ambulance will be dispatched through the best-selected route, which is selected based on the traffic evaluation and traffic light adjustment [29–31]. One of the successful experiences in employing a smart health system for dealing with the pandemic is in Wuhan. Researchers believe that the developments implemented to make Wuhan a smart city played an effective role in controlling the pandemic in this city [32,33].

4.2. Prevention Technologies

Most components of a smart city can be significantly effective in prevention. However, the role of the smart education, smart economy, smart infrastructure, smart transportation, and smart technology sectors is more prominent in this sector.

4.2.1. Smart Healthcare Applications and Technologies

Smart healthcare applications are among the most popular technologies that help citizens to raise health awareness and provide more information about their health status, as well as to recognize the riskiest areas. These applications can provide accurate information about the pandemic and prevent false news. Corona hotlines are also among the other cases that have been useful for health monitoring and communication with citizens.

Smart imaging technology is also employed for online body temperature monitoring through thermal cameras and warns people whenever they leave the house without respirators. Furthermore, helmets and smartwatches can be useful in measuring body temperature, preventing the transmission of respiratory droplets, and protecting medical staff, and they can warn people if symptoms are observed. The use of ultraviolet robots and drones to disinfect urban surfaces and passages, along with disinfection tunnels and the use of self-driving vehicles, are other technologies used for prevention [25–28,34].

4.2.2. Smart Supply Chain and Delivery

In addition to the significant effects on citizens' health, the pandemic has caused serious challenges to some functional systems, especially in the supply chain of essential food and health goods, which smart city technologies can help organize as follows:

- Monitoring and limiting purchases by each citizen when detecting unusual patterns in shopping centers.
- Optimizing supply chains by giving priority to transporting essential food and health goods.
- Prevention of hoarding through monitoring and transparency in the supply chain with the help of smart platforms [35].

Furthermore, the distribution of food, medicine, and necessities to citizens in the infected area using drones, robots, mobile phone technology, and smart boxes is among the most important applications in pandemic conditions.

4.2.3. Smart Social Distancing

Smart distancing technologies can be considered to be among the most fundamental functionalities of a smart city against this epidemic, as explained below:

(1) Monitoring the health instructions' implementation

Smart transportation and smart parking systems can be significantly useful in providing information about the traffic situation with the help of their big data systems. Locating high-traffic areas can help in identifying highly crowded areas that should be controlled in terms of maintaining social distance [4].

(2) Determination of infected areas

Smart applications providing information about the highly infected cities can be useful in issuing warnings about the necessity of maintaining social distancing. Moreover, helmets and smartwatches can send warning messages to citizens when entering highly infected or crowded cities and areas [4].

(3) Tracking infected citizens

Smartwatches, public transport cards, bank cards, and automated teller machines (ATMs) that the patient has used, along with mobile phone tracking, are useful in tracking infected citizens [36].

4.3. Treatment Technologies

Effective smart technologies for facilitating treatment are described in the following subsections.

4.3.1. Smart Support and Transportation

On-time supply of resources and medical equipment can be guaranteed by automatic notification to the support center and guiding the support team through low-traffic streets and adjusting traffic lights. Moreover, IoT-based smart parking and IoT-based smart transportation systems, along with autonomous vehicles, can be helpful for transporting infected people and hospital employees, or for transporting infectious waste [4,32,37].

4.3.2. Telerobots

Telerobots can be useful in monitoring disinfection, surgery, temperature, blood pressure, and oxygen levels, without any need for nurses to be close to the patient [35].

4.3.3. Collaborative Robots

These robots are designed to work alongside humans and are ideal in the operating room to perform low-risk surgeries [35].

4.3.4. Autonomous Robots

These robots are able to perform autonomous actions with minimal interaction with human operators. UV disinfection robots for sterilization, wheeled mobile robots for reading and automatic recording of patients' vital signs, and mobile robots for logistics purposes can be mentioned in these classes [35].

4.3.5. Wearable Technologies

Wearable technologies can provide information to the patient and their doctors. Wearable technologies such as smart clothes can receive vital signals from patients and provide information to the doctor in case of abnormal conditions [35,38–40].

4.3.6. Smart Medical Beds

Smart medical beds are described as integrated solutions for the care, assistance, and monitoring of patients. Smart medical beds can be utilized for online monitoring of the patient's condition, even from the house. Furthermore, in hospitals, smart beds can be useful in transmitting patients' symptoms without contacting the medical staff [35,41].

4.4. Gamification Technologies

Smart cities utilizing game-based approaches (gamification) can facilitate interactions and support during pandemics through the following areas:

4.4.1. Smart Citizens

Gamification technologies can provide connections between humans and places in a digital space during lockdowns [42].

4.4.2. Smart Economy

Self-identification technologies for online personas can facilitate interactions and advance local retail businesses. Furthermore, gamification innovation can provide essential economic benefits in the tourism industry [42,43].

4.4.3. Smart Governance

Gamification can be used for self-identification technologies to develop democratic approaches, as well as self-contact tracing and organizing remedies for COVID-19 [42].

4.4.4. Smart Health

Gamification in pandemic conditions can develop various approaches for prevention, health promotion, and self-management through improving patient engagement in health information technology [44].

4.4.5. Smart Education

During the pandemic, e-learning platforms replaced conventional education. However, for overcoming dropout and low completion rates, which increased remarkably during the lockdown period, gamification is proposed, which can significantly improve students' motivation and engagement [45,46].

4.4.6. Smart Energy

Gamification technologies based on IoT monitoring systems in smart homes can be utilized for increasing energy awareness among citizens and supporting energy-efficient consumption patterns in the lockdown period [47,48].

4.5. Institutional Technologies

4.5.1. Data-Driven Organization

Smart cities can effectively support urban organizations through data-driven approaches in decision-making processes. This approach can create networks between citizens, local governments, organizations, technologies, and decision-makers [49,50].

4.5.2. Emergency Response

Smart city technologies can provide efficient emergency management systems to tackle emergencies, as well as minimizing losses and costs. Event-driven focusing service (EDFS) methods through cyber–physical infrastructures, coordinated management, and emergency response (CMER), and digital surveillance and movement control through integrated control command centers (ICCCs) are some frameworks that can be achieved through smart cities to manage pandemic conditions more efficiently [51–53].

4.5.3. Participatory Governance

Smart cities can be mentioned as an effective platform for community-based and citizen-centric decision-making, or the same for participatory governance. Participatory governance can facilitate social pluralism and inclusive management, as well as democratic, effective, and efficient decision-making in smart cities [54–56].

4.5.4. Consultative Inclusivity

Efficacious pandemic management requires active community participation and a decentralized or new mode of governance. This can be achieved via a consultative inclusivity framework through citizens' participation in smart city management, including planning, appraising, approving, releasing funds, managing, and implementing [57,58].

4.5.5. Security Management

Smart city infrastructure management systems can contribute to the improvement of safety and security in smart cities during crises. In the smart city framework, data acquisition, data sharing, and data utilization resulting from smart infrastructure and technologies, while maintaining privacy issues, can play a significant role in security management during crises [57,59].

4.5.6. Sustainable Governance

A smart city that employs ICT, IoT, and artificial intelligence in its interactions with citizens can provide transparency, accountability, stakeholder involvement, and citizen participation as the main principles of sustainable governance [60].

Figure 4 summarizes the use of smart city technologies in the fight against the COVID-19 pandemic.

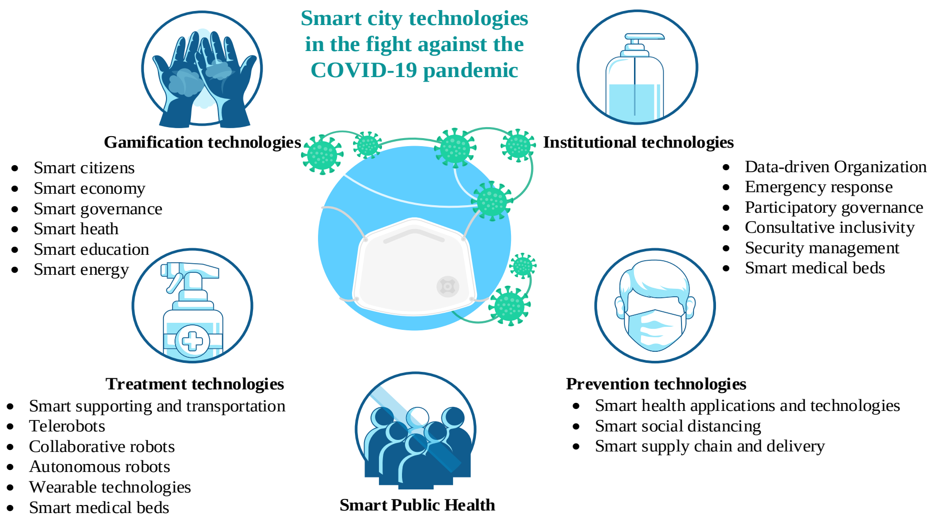


Figure 4. Contributions of smart city technologies in the fight against the COVID-19 pandemic.

5. Prospects for a Pandemic-Resilient Smart City

5.1. Smart City Resilience Dimensions

What is frequently discussed today in the management of the world's cities is the issue of urban resilience, which can affect adaptation and transformation toward sustainability. As natural disasters, crises, and human actions are considered to be unpredictable urban threats, cities must react faster and more effectively to minimize the consequences and dangers involved. Hence, governments increasingly devote attention to resilience in the urban management process, as crises can have significant consequences in environmental, socioeconomic, and political terms. Urban resilience, which describes a city's ability to deal with crises and disruptions such as natural disasters, infrastructure failures, economic downturns, and complexity overloads, can be mentioned as an essential element in the successful management of cities [61,62].

In recent years, researchers in the field of disaster risk reduction have formulated and recommended various metrics that aim to measure urban resilience. However, as researchers have acknowledged that urban resilience is a multifaceted concept, there is no consensus index or framework to quantify resilience in the city context [63]. In the city context, [63] collected and described what is measured by different resilience frameworks and how city ideas are reflected in these frameworks.

The Organization for Economic Co-operation and Development (OECD) Ministerial Council's statement introduced four dimensions for evaluating resilience in cities including economic, social, institutional/governmental, and environmental/infrastructural aspects, as shown in Figure 5 (the figure was sketched by the authors, considering the ideas taken from [64–66], while modifications were made in line with the topic of this paper) [64–66]. The three-year COVID-19 pandemic had a strong impact on urban systems, including the economy, society, and public health, and highlighted the inadequacy of urban resilience to prevent and minimize the consequences of such public health events [67]. In this section, the performance of smart cities in achieving and improving resilience during the COVID-19 pandemic is discussed based on the aforementioned dimensions. In this regard, as social changes and balances are coupled with the city's development and affect the required interventions, resilience in social dimensions is specifically discussed. In addition, from the energy point of view in the infrastructural dimension, a resilience framework is introduced for designing a resilient energy system [68,69].

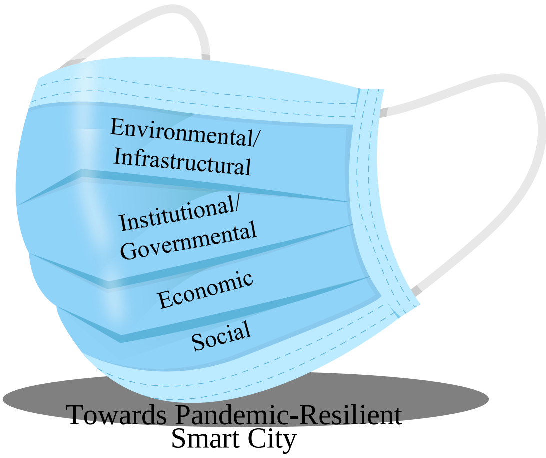


Figure 5. Smart city resilience dimensions, illustrated based on the OECD statement.

5.2. Pandemic-Resilient Economy and Health Aspects of Smart Cities

Resilience in infrastructural dimensions can assess the infrastructure's response and its recovery capacity during the crisis. A literature survey on smart cities' contributions to COVID-19 pandemic management reported that smart city technologies in public health, prevention, and treatment can provide resilience in the health infrastructure area.

However, the economic dimension of urban resilience refers to the response and adaptation of individuals and communities, as well as their ability to reduce economic damage. Improving economic resilience will reduce the economic losses incurred from a crisis over time for citizens in urban areas. In another respect, resilience can be considered as a promoter of welfare gains. This point of view holds that strengthening the economic assets of communities and citizens will help them to be more resilient in dealing with the economic consequences of crises. Economic resilience includes two key components: the capability of economic beneficiaries in urban areas to withstand or absorb an economic shock, and their capability to adapt to changing circumstances and strengthen themselves to react to the potential economic consequences of future crises [70,71]. Smart city technologies can be effective in preventing nationwide lockdowns, which cause industrial and business closures and significant economic damage. Applying smart lockdowns during pandemic crises by isolating the infected people and monitoring the infected areas can be useful in avoiding the nationwide closure of businesses, industries, and commercial centers. Furthermore, smart shopping and delivery technologies can be useful in maintaining the dynamism of the economy and access to services during the epidemic, in addition to curbing the spread of coronavirus.

5.3. Pandemic-Resilient Governance Aspects of Situation-Aware Smart Cities

Institutional and governmental resilience in cities can be defined as the capacity of the cities' organizations to manage, react, and adapt to crises without system failure and collapse, avoiding the weakening of trust in the institutional performance. Institutional resilience can be promoted by encouraging cooperation in this area to identify and perform based on local experience, knowledge, and sources of resilience. Furthermore, institutional resilience can be improved by extending and repeating local-level successes, and by leveraging an institution's social capital to improve society–state relations [72,73].

Situation-aware smart cities with extensive use of digital technologies and devices such as traffic cameras, public transport cards, and environmental sensors can effectively realize resilient control and management of the city, especially in crisis conditions. Data collected through these devices, along with the information and digital footprints that are continuously produced by citizens, can provide accurate information about the city or, in other words, awareness of the situation. Some of the most important advantages of achieving situational awareness in a smart city include real-time monitoring of the citizens' utilization of transportation systems, traffic flow, environmental conditions, mobile networks, overcrowding in public centers, noise pollution, car accident locations, crime-prone areas, and social networks, as shown in Figure 6 (the figure was sketched by the authors, considering the idea taken from [74], while modifications were made in line with the topic of this paper) [74].

Figure 6. Situational awareness in smart cities.

Particularly, employing a wireless sensor network in a smart city that is capable of sensing, collecting, and transmitting data [75] can be mentioned as an effective facilitator in achieving situation-aware smart cities. Furthermore, situation-aware smart cities utilizing IoT-based technologies can provide data-driven organization, emergency response, participatory governance, consultative inclusivity, security management, and sustainable governance—or, in brief, can provide institutional or governmental resilience against the pandemic. Situation-aware smart cities facilitate efficient real-time decision-making through IoT devices to collect and collaboratively process streamed data [74,76,77].

5.4. Pandemic-Resilient Society by Social Capital Realization in Smart Cities

5.4.1. Social Capital Realization in Smart Cities

Social capital, as a key form of capital in urban societies, is considered to be the foundation of the economic, social, and physical development of cities. However, social capital has not received as much attention as it deserves in urban development [77,78]. According to Table 1, based on the definitions, the main attributes of social capital include social networks, shared norms, and trust, which can be effectively realized in a smart city as described in this section [79,80].

Table 1. Descriptions of social capital attributes, 1988–2022. Blue color indicates the presence of the attributes in the relevant reference (adapted from [79,80]).

Ref.	Years	Social Networks	Shared Norms	Trust
[81]	1988		■	■
[82]	1994	■		■
[83]	1995		■	■
[84]	1998	■		■
[85]	1998	■		
[86]	1998	■	■	
[87]	2000	■		
[88]	2000	■	■	■
[89]	2005	■	■	■
[90]	2008	■	■	■
[91]	2009	■	■	■
[92]	2022	■	■	■

(1) Shared norms and coherence in smart cities

As shared norms and coherence among communities' assets of social capital are mentioned as key attributes, they can be mentioned as important factors in social resilience during crises. Strong social capital is associated with norms that encourage participation in social actions. Sociologists believe that all social actions flow from social norms and values. As social cohesion refers to the strength of relationships and the sense of solidarity in the community, norms can act as essential factors to create a sense of solidarity among people. Advanced ICT technologies employed in smart cities can promote shared norms and coherence as two of the main aspects of the social capital investigation. Smart technologies in smart cities, by amplifying and confirming social values and norms in the local language and using the special methods appropriate to the culture, history, and religion of each region, can encourage citizens' social actions and participation [93–98].

During a pandemic, the sympathetic activity of different volunteer groups in disinfecting the city and helping treatment staff can be integrated, encouraged, and effectively coherent based on shared norms and values through smart city technologies. In addition, citizens' cooperation in helping the affected people in the form of food, medicine, and services based on shared norms and values can provide coherent management in the smart city. Also, a coherent network of medical staff and services can provide more effective responses.

(2) Social networks and participation in smart cities

Social networks are defined as the interconnecting relationships between people. However, the networks preferred by a few in the community may not be conducive to collective participation and action, which is an important factor in social capital. Collective action, as one of the main attributes of social capital, can be defined as the voluntary action and shared effort by a community or stakeholders to achieve a common result and outcome. However, if the stakeholders follow selfish interests, collective outcomes cannot be achieved. Urban managers can encourage citizens' collective engagement by providing a venue to engage in the management process and some other public issues. This collective engagement can be mentioned as an essential factor in realizing a cohesive community, as well as improving citizens' sense of ownership of their city. Collective engagement, as facilitates the realization of social capital, can be noticeably beneficial in building a resilient city [99].

The first condition to achieve collective engagement and social participation is to raise the awareness of society. In a city where people are not knowledgeable of the nature of social issues, opportunities for social participation and a strong cooperative sense in social networks will not be evident [93,100–103]. Smart city technologies have significant potential for improving the knowledge and awareness of citizens during pandemics. Furthermore, facilitating membership and participation in voluntary activity, the possibility of participating in management seminars that can be embedded in smart health systems, and the use of smart urban visual tools to inform and strengthen participation in complying with the guidelines are some examples of facilitating participation in smart cities in a pandemic situation.

(3) Trust in smart cities

Trust is one of the most important aspects of human relationships and the foundation of collaboration and cooperation among society members. Trust can be mentioned as a key significant aspect of effective crisis management by governance. As the people's trust in the government's action increases, more rapid recovery after a crisis can be guaranteed. For example, despite the rapid spread of the coronavirus, public protests against the implementation of lockdowns have been observed in different countries, showing a lack of trust in governments and public health systems. The first step in aligning public behavior with health policies and earning the public's trust is to employ interactive smart technologies, as well as providing reliable information and reports to citizens [93,103,104].

The utilization of interactive smart technologies encourages citizens to share and record their data associated with epidemics. At the same time, smart cities' managerial technology collects, analyzes, and reports these data, facilitating effective decisions by governance. However, the misuse of data causes a decrease in public trust and the withdrawal of citizens from sharing information. Therefore, creating a balance between technology and privacy concerns is inevitable.

5.4.2. Social Resilience in Smart Cities

The evaluation of social capital, like its definitions, has different assessment methods, including indirect and direct methods. In the indirect methods, social capital is assessed by using symptoms that appear in the absence of social capital, such as self-esteem reduction, morale destruction, and social collapse and crime. In the direct methods, scientists consider the number of groups and the number of their members (i.e., the percentage of participation in voluntary activities, the percentage of people who are members of associations and clubs), as well as the trust index, as very important variables [105–107]. In the following sections, we try to evaluate social resilience with the help of a direct method based on quantitative and qualitative methods.

(1) Qualitative assessment of social resilience

Social resilience is defined as the ability of society, communities, and people to deal with crises and shocks, which is associated with community preparedness, disaster response, and post-disaster recovery [108]. Social resilience, including the resilience of people and communities, generally refers to the capability of social entities to absorb, tolerate, manage, or adapt to disturbances [62,109]. Social capital, as a key form of capital in urban societies, is mentioned as an asset for cities' development and a resource for social resilience. Hence, social resilience derived from social capital can be considered to be the foundation of the economic, social, and physical development of cities. Social resilience is defined based on collective actions and social reorganization for dealing with the destructive impacts of crises. A resilient society, through absorption and recovery from the anxieties and destruction caused by crises, maintains its essential functions and adapts to continual change. This complex capacity of a resilient society results from the integration of different aspects by local authorities to increase cities' resilience [110].

Social capital is mentioned as the center of understanding and evaluation of society's resilience during crises. Researchers believe that social capital is a powerful predictor of society's post-disaster recovery. Social capital can be linked to the evaluation of society's resilience during crises in the individual and community dimensions. As a community asset, it includes features such as trust, shared norms and coherence, and participation. As a characteristic of individuals, social capital includes an individual's relationships with social resources [111,112]. Since a smart city can effectively improve the shared norms and coherence, social networks and participation, and trust (as discussed in Section 5.4.1), as the main attributes of social capital, it can effectively realize and promote social resilience in dealing with pandemic crises.

Social resilience during the COVID-19 pandemic refers to the capability of people, communities, and societies to maintain their main functionalities, as well as to minimize the impacts and other societal consequences of the pandemic [113]. Several studies have reported better health outcomes in areas with higher levels of social capital, both in general and during the pandemic. The local social networks of smart cities are also important from the point of view of providing a platform to collectively and locally solve citizens' problems. Furthermore, researchers have shown that people who live in close-knit areas with more networking and social relationships have fared better during the pandemic [93,102,114,115].

Furthermore, residents' satisfaction levels and social capital indicators can improve significantly by implementing area management in the context of smart cities, through local governments. In other words, top–down and bottom–up strategies in the management process can lead to improvements in the indicators of social capital [98]. London is given as an example in [116], which integrates bottom–up and top–down strategies in smart cities. The Minato Mirai 21 district in Yokohama has also been studied as another example of area management. In this regard, containing aspects of infectious disease control by the area management can be effectively beneficial in the prevention and control of disease crises, like the COVID-19 pandemic [98].

(2) Quantitative (Analytical) assessment of social resilience

In this research, social resiliency is evaluated through the resilience triangle. The resilience triangle represents the amount of loss in system functionality and the amount of time it takes for the system to return to normal performance levels after a crisis, as shown in Figure 7 (the figure was sketched by the authors, considering the idea taken from [117], while modifications were made in line with the topic of this paper). Although in some references the resilience trapezoid has been used for the resilience evaluation of the system, in this research, to facilitate the expression, the resilience triangle was used, which is the same from the conceptual and basic point of view [117–119].

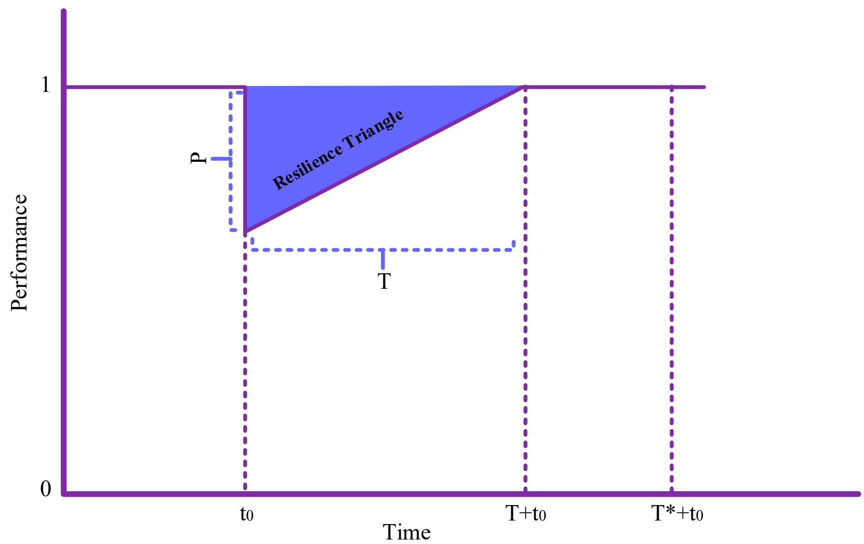


Figure 7. Smart city resilience triangle.

According to Equation (1), low values of R indicate high system resilience. In this equation, P is the percentage of performance lost after a crisis, T is the time needed to recover to normal performance, and T^* is a suitably long time interval [117].

$$R(P,T) = \frac{T^* - PT/2}{T^*} = 1 - \frac{PT/2}{T^*} \quad (1)$$

Also, as previously stated, in the direct method of evaluating social capital in civil society, the number of groups and the number of their members, as well as an important indicator called trust, are considered. Equation (2) can be considered an appropriate index for measuring the social capital of a society in which all three indicators—trust, shared norms and cohesion, and networks and participation—are modeled [107,120].

$$SC = \sum_i \frac{R_i^p C_i N_i}{R_i^n} \quad (2)$$

In Equation (2), i is the group indicator, N is the number of members of each group, C is the internal cohesion coefficient of the group, R^p is the radius of trust of the group, R^n is the radius of mistrust towards other groups, and SC is the amount of social capital.

As discussed, social capital is directly related to social resilience, because the attributes of social capital in civil society lie in Equation (2) in a way that can specifically affect the level of social performance during a crisis, the time needed for normal performance recovery, and the level of performance recovered after the crisis. Therefore, it can be said that smart city technologies can play an undeniable role in ensuring a high level of social capital in society, and they can be essential factors in reducing the loss of social performance during the crisis. In addition, the situational awareness and smart management infrastructure of the smart city play a major role in reducing the recovery time. Also, with the situation-aware transparent management of crises, it can be expected that the level of social capital after recovery will undergo significant growth compared to the initial state, due to the increase in societal trust in governance actions. This difference in recovered performance compared to pre-crisis performance has also been experienced in other areas, as shown in Figure 8 [121,122].

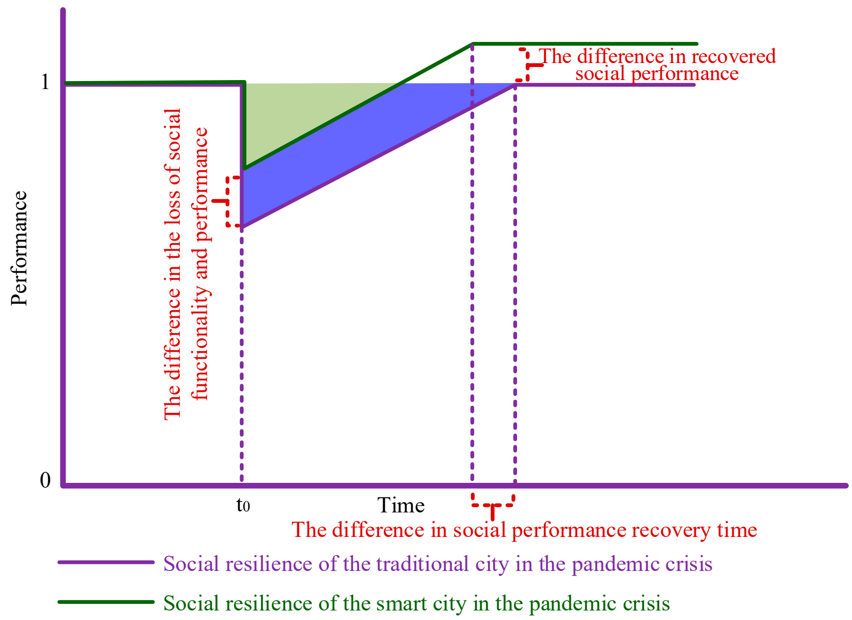


Figure 8. Smart cities' contributions to the resilience triangle formation in the pandemic crisis.

6. Pandemic-Resilient Energy-Hub-Based Smart Cities

This section describes energy-hub-based smart cities that can contribute to designing pandemic-resilient energy infrastructure. Furthermore, in addition to reporting resiliency evaluation indices from two case studies, energy hubs' contributions to the fulfillment of resilient energy infrastructure are expressed.

6.1. Pandemic and Energy Systems

The excessive integration of renewable units with uncertain generation will eventually face an obstacle called energy security. With the spread of the coronavirus, governments have been forced to close or reduce their commercial and industrial activities to reduce the spread of the virus.

These changes, in addition to increasing residential sector demand, have caused significant decreases in commercial and industrial demand and the entire demand on electricity systems. For example, in Ontario, Canada, a significant decrease in demand was created in April 2020 compared to the same period in the previous year, as shown in Figure 9 (data taken from [123]).

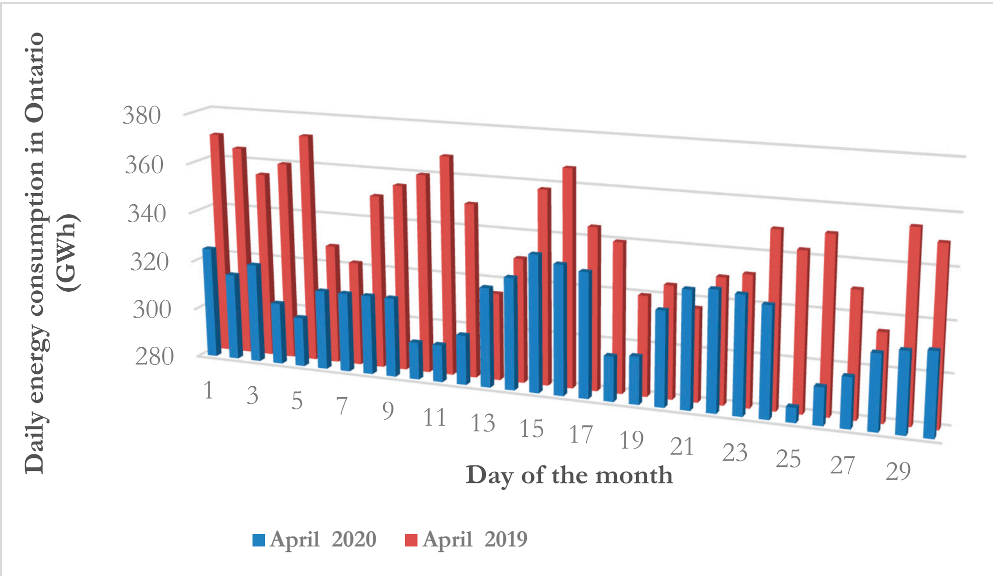


Figure 9. Comparison of Ontario' daily demand in April 2019 and 2020.

The excessive reduction in consumption during daytime hours can cause the deepening of the duck curve. The duck curve was introduced by California's energy system operator and shows the energy that the operator must provide during the day and in the absence of renewables through conventional generation resources. For example, in California, on a typical day, people use a lot of energy in the morning before going to work and at night when they return home. According to [124,125], in this case, the amount of power that the operator must add to the network during the day with the help of conventional resources to match the generation with the demand draws a shape called a "camel curve". In the meantime, when an electrical network has benefited a lot from solar energy, with solar energy generation increasing in the middle of the day, the net load over a day (i.e., the total electric demand minus renewable generation) is similar in shape to a duck, hence being named a "duck curve".

The realization of a duck curve in a pandemic period presents challenges to energy systems that include increasing startup and shutdown costs of power plants, reducing reliability as a result of reducing the committed conventional units with automatic frequency response capability, and continuous generation changes [1,123–132].

6.2. Energy Hubs' Contributions to Resilient Energy Infrastructure Fulfillment

Since, with the development of technology, most urban infrastructure—such as transportation, communications, water and wastewater, teaching, and health systems—is interdependent with energy, resilient energy infrastructure can lead to resilience in all of these systems, or infrastructure resilience. In other words, an urban energy system that is immune to damaging physical/cyber crises and integrated with a high percentage of renewables can be mentioned as a transformational development architecture for prospective smart cities [133].

Energy resilience is a significant strand of resilience that has not been well studied by urban studies researchers [134]. However, resilience and energy have been addressed together by some urban energy studies that aimed at designing resilient energy systems [133,135–138]. In [135], an overview of the research aiming to improve resilience against climate change in urban energy infrastructure was conducted. The researchers in [133] emphasized the necessity of achieving security and resiliency for future urban energy systems with the penetration of renewable energy sources. In this context, [136] aimed to describe the nexus between urban resilience and energy efficiency in the context of urban energy systems. The researchers in [137] described three major methods to achieve resilience in urban energy systems against earthquake disasters, including hardening the grid and demand side, the Monte Carlo method for the earthquake threat model, and the k-means method to determine the multiple vulnerable zones. In [138], a strategy is provided to promote energy performance through changing the urban physical environment as a design perspective for achieving resilient energy systems. This research emphasizes employing the EH concept in order to achieve resilience according to what is described below.

The existing critical, industrial, commercial, residential, and agricultural facilities in smart cities can be considered to be EHs, which are independent energy systems. The EHs in smart cities can be interconnected together through the existing urban power or/and natural gas distribution grids, as well as information infrastructure, as demonstrated in Figure 10 (the figure was sketched by the authors, considering the idea taken from [139], while modifications were made in line with the topic of this paper). The smart city, as a macro-EH (MAEH) consisting of interconnected micro-EHs (MIEHs), can provide a flexible and resilient energy infrastructure system [9,140]. This section describes smart city energy as interconnected energy hubs that can lead to a high level of flexibility in dealing with the main challenges of the electricity industry during pandemics.

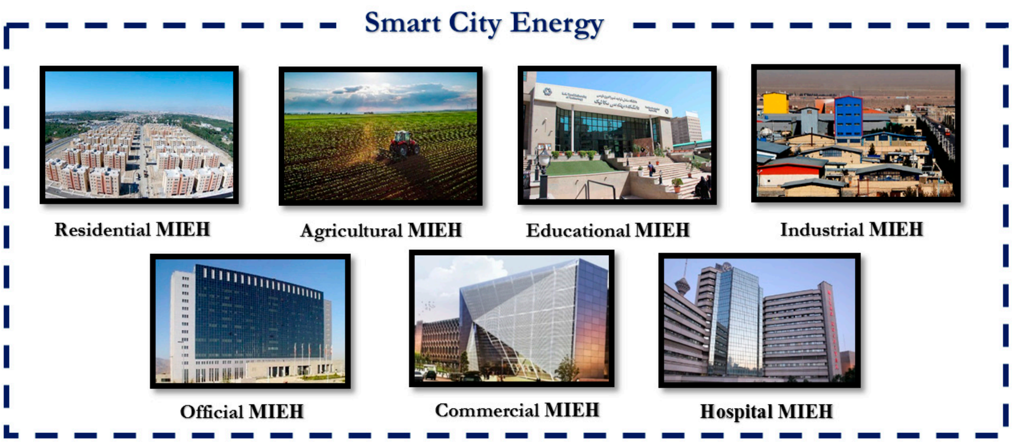


Figure 10. Smart city energy infrastructure, including micro energy hubs.

(1) Smart technologies

Smart EHs' contributions in providing smart metering, control, and automation solutions make them an effective framework compared to systems that need employees for maintenance and control. Furthermore, integrated demand response realization through smart EHs provides demand response policies with less pressure on consumers. Therefore, by decreasing the amount of electricity imported from the upstream network, EHs can provide energy during the peak load hours via gas injection and using cogeneration units. In addition, smart cities' energy system operators can provide integrated and distributed smart management of electricity, heat, and gas networks through urban information infrastructure and EHs [22,25–27,141,142].

(2) Redundancy

Energy-hub-based systems can establish additional connections between input and output through the generation, storage, and conversion units. This redundancy in supply leads to two important advantages: First, the reliability increases from the load point of view, as the supply of demand is no longer completely dependent on a unique network and unit. This is advantageous in a pandemic crisis, since the supply of electricity to hospitals and critical centers can be provided continuously and reliably.

As a second advantage, the degree of freedom in supply is increased, which provides the optimal supply of electricity demand. This can be advantageous in the face of economic impacts during pandemics, as energy supply costs in various urban areas, including residential areas, can be further reduced. Furthermore, energy carriers can be prioritized according to various criteria, including economic, emissions, and reliability criteria [31,143–145].

(3) Energy storage

Increases in renewable resource integration require flexibility improvements, which can be provided through energy storage systems. Although experts emphasize more need for flexible storage systems to prevent disruptions to the power system during pandemics, which affect the effective response of health services and hospitals, the energy storage installation trend is faced with risk due to the pandemic's destructive financial impact. Energy storage systems can be a promising option in maintaining the security and stability of networks and dealing with challenges raised by the creation of a duck curve. The potential of EHs for containing a wide range of energy storage adds to these advantages. Converting the excess generation of renewable resources to other forms of energy with the help of innovative storage technologies provides the possibility of long-term energy storage for use in other consumption sectors, such as transportation and heating. Among the promising technologies are power-to-gas systems, which convert excess electric energy from renewable sources into hydrogen or methane and store it [146].

(4) Infrastructure integration

The opportunities presented by EHs in energy infrastructure integration improve resiliency by providing efficient operation of renewable units and dealing with demand fluctuations. The possibility of integrating electricity and gas systems makes it possible to manage renewable resources' generation during the crisis period and prevent curtailments. Furthermore, this integration framework in EHs facilitates resilient supply through urban gas infrastructure when the electricity system fails, and vice versa. Briefly, important challenges that arose during the pandemic crisis, which warned against the integration of more renewables, have been solved through this resilient framework [140,147].

6.3. Case Studies

6.3.1. Background

The framework for energy-hub-based energy infrastructure is presented in [19,144,145], where the smart city energy infrastructure is modeled as critical, residential, commercial, industrial, and agricultural micro energy hubs (MIEHs), which are designed according to their reliability and resiliency priorities. In the frameworks presented in [19,144,145], reliability and resiliency priorities in the planning process are modeled by considering the customer interruption cost (CIC) and cost of energy not supplied (CENS) in the objective function. These MIEHs can operate either individually or interconnected through the urban natural gas and electricity distribution networks. The framework is intended to minimize the investment cost of multiple energy generation, conversion, and storage systems in MIEHs, as well as the CIC and CENS, while constrained by multiple generation, conversion, and storage systems as well as the electricity and natural gas networks' limitations. The mathematical formulations, as well as the electrical and heat loads, gas pipeline and electric distribution grid characteristics, multiple generation, conversion, and storage system parameters, and other information, can be found in [19,144,145]. The frameworks proposed in [19,144,145] are formulated as mixed-integer linear programming (MILP) models and simulated by GAMS software [148].

6.3.2. Case Study: IEEE 33-Bus Resilient Energy Infrastructure

Based on the framework proposed in [19], the performance of the proposed planning framework based on interconnected MIEHs in achieving a resilient smart city energy infrastructure was evaluated. The proposed planning model was implemented on the standard IEEE 33-bus distribution test system, as shown in Figure 11 (the figure was sketched by the authors, considering the idea taken from [19,145], while modifications were made in line with the topic of this paper). The problem statement, formulation, and more detailed information are available in [19]. According to Table 2, the preparation of the energy infrastructure based on the proposed framework in upstream grid interruption status resulted in acceptable values for the CIC and CENS.

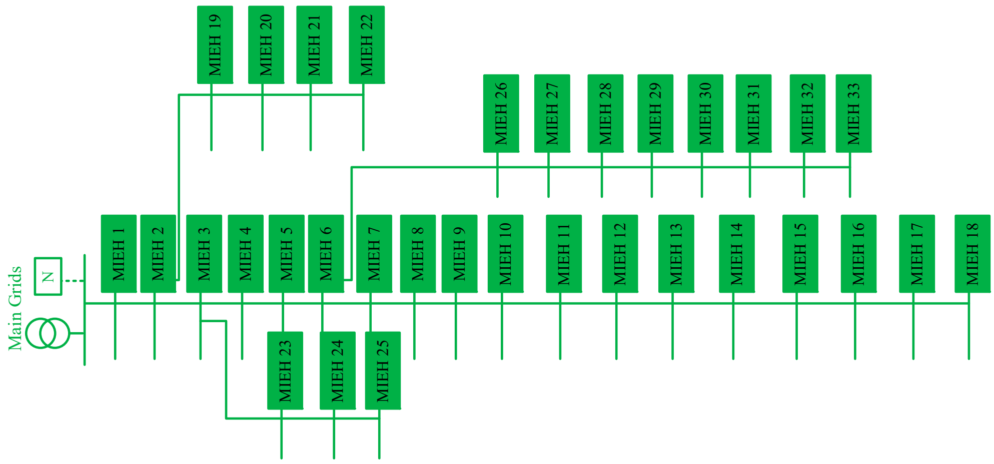


Figure 11. The standard IEEE 33-bus distribution test system, including MIEHs.

Table 2. Resiliency evaluation criteria resulting from case study (1) (adapted from [19]).

	CIC (p.u.)	ENS (p.u.)
Without preparation	1	1
Preparation based on DG allocation	0.625	0.784
Preparation based on interconnected MIEHs' planning	0.003	0.012

6.3.3. Case Study: Dättwil Resilient Energy Infrastructure

Based on the framework proposed in [144], the performance of the proposed planning framework based on interconnected MIEHs in achieving a resilient smart city energy infrastructure was evaluated. The proposed planning model was implemented in a real urban case study (the Dättwil area in Switzerland), as shown in Figure 12 (the figure was sketched by the authors, considering the idea taken from [144,149], while modifications were made in line with the topic of this paper). The problem statement, formulation, and more detailed information are available in [144]. According to Table 3, the preparation of the energy infrastructure based on the proposed framework in upstream grid interruption status resulted in appropriate values for the CIC and CENS.

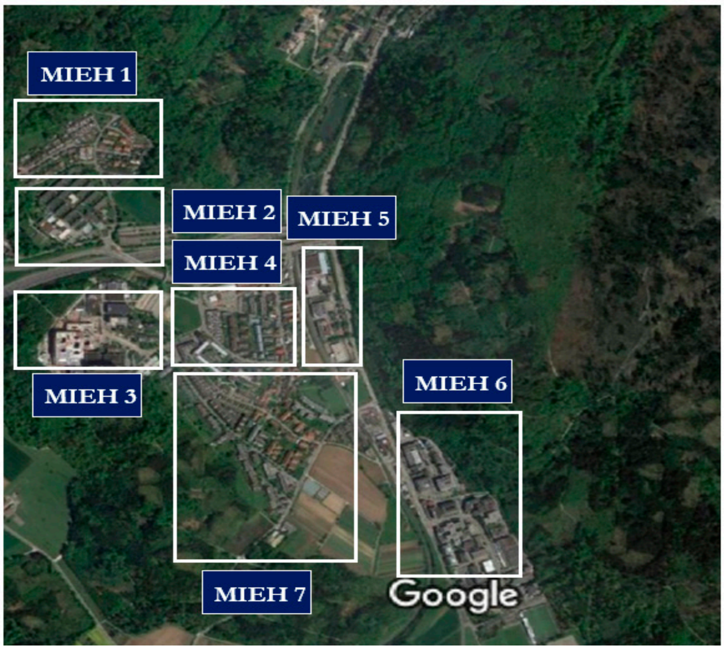


Figure 12. The Dättwil area in Switzerland.

Table 3. Resiliency evaluation criteria resulting from case study (2) (adapted from [144]).

	CIC (p.u.)	ENS (p.u.)
Without preparation	1	1
Preparation based on individual MIEHs planning	0.068	0.073
Preparation based on interconnected MIEHs planning	0.001	0.013

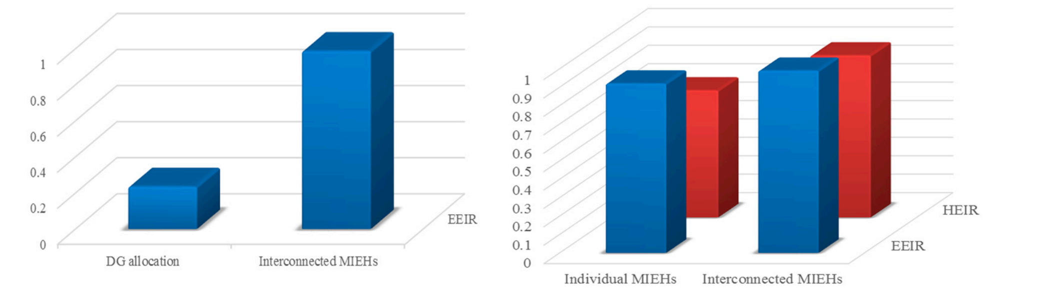
6.3.4. Analysis

As the values of CIC and ENS move away from 1 and approach 0, it can be seen that the method implemented in planning the smart city energy system is superior for achieving a resilient and reliable energy infrastructure.

As mentioned in Table 2, the resiliency criteria when employing the proposed planning framework based on interconnected MIEHs show significant improvements in designing a resilient smart city energy infrastructure compared to common methods based on diesel generator (DG) allocation. Furthermore, as described in Table 3, the resiliency criteria resulting from the proposed framework in a real urban case study (the Dättwil area in Switzerland) show significant superiority compared to the preparation of the smart city energy infrastructure based on individual MIEH planning, in terms of upstream grid interruption status.

In addition, the comparison of the energy index of reliability for both electrical systems (EEIR) and heat energy systems (HEIR) in case studies (1) and (2) indicates that the preparation of energy infrastructure based on interconnected MIEH planning resulted in significant success in increasing the system resilience, as shown in Figure 13. This can yield effective management of high-impact disasters in smart city energy infrastructure.

Briefly, it can be concluded that smart city energy infrastructure including interconnected MIEHs can lead to a high level of resiliency in dealing with the main challenges of the electricity industry during pandemics. Energy-hub-based smart cities can contribute to designing pandemic-resilient energy infrastructure, which can also significantly affect resilience in economic and health infrastructure.



(**a**) (**b**)

Figure 13. Comparison of EIR in (**a**) case study (1): IEEE 33-bus resilient energy infrastructure, and (**b**) case study (2): Dättwil's resilient energy infrastructure.

7. Discussion: Opportunities, Challenges, and Limitations of Pandemic-Resilient Cities

Achieving urban resilience against crises such as the COVID-19 pandemic presents intended and unintended opportunities and positive effects on a city's capability to react effectively to crises. These opportunities assist cities in preventing and decreasing the impact of shocks and stresses on infrastructure, the economy, people, and the natural environment.

However, in addition to opportunities, challenges are also associated with achieving and improving urban resilience during the COVID-19 pandemic. Divergent time horizons, diverse outcomes, extensive coordination, and maintaining adaptability might be mentioned as challenges that accompany the implementation of urban resilience. In particular, resilience resistance, as an important challenge, can be defined as an inherent barrier to the ability of governance systems to change and adapt through implementation [150,151]. Furthermore, while social capital is beneficial in creating a resilient society, its impacts within different societies and communities are not uniformly advantageous. This approach usually excludes community outsiders, such as ethnic minorities, religious minorities, and other vulnerable groups, increasing their vulnerability, and even renouncing them, which should be considered in further studies [111].

Furthermore, the implementation of the framework proposed in [19,144,145] towards a pandemic-resilient energy infrastructure in an energy-hub-based smart city faces practical limitations. The budget limitation is an important challenge for smart city energy operators and planners with regard to investment in multiple energy generation, conversion, and storage systems in MIEHs, while a people-centric approach is intended to tackle these limitations [152–154]. Moreover, the intermittent nature of renewable resource generation creates more limitations for energy-hub-based smart cities. The lack of vacant land for the installation of energy generation, conversion, and storage systems, and the requirements of existing gas and power distribution systems, are also other limitations of energy-hub-based smart cities [144].

8. Conclusions

The realization of the resilient city concept, which is one of the newest approaches to crisis management, is the result of changing the approach to crisis management from reducing vulnerability to upgrading the social and physical capabilities of the city. In this regard, there is a consensus that resilience in a city is a multifaceted concept with social, economic, governmental, and infrastructural dimensions, which have been investigated in this research.

This paper reviews smart cities' initiatives and contributions to the prevention and treatment of coronavirus disease, as well as reducing its destructive impact, aiming at achieving pandemic-resilient economic and health systems. Furthermore, the contributions of situational awareness to pandemic-resilient governance are reviewed. The main contribution of this study is to describe the realization of social capital in smart cities as a facilitator in creating a pandemic-resilient society in crises through two analyses. Furthermore, this research describes smart cities' energy systems as interconnected MIEHs that can lead to a high level of resiliency in dealing with the main challenges of the electricity industry during pandemics. Energy-hub-based smart cities can contribute to designing pandemic-resilient energy infrastructure, which can significantly affect the resilience of economic and health infrastructure. Briefly, this paper describes a smart city as a pandemic-resilient city in the economic, energy, and health infrastructural, social, and governmental areas.

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