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Various Facets of Sustainable Smart City Management: Selected Examples from Polish Metropolitan Areas

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Abstract: Sustainable City solutions can become an essential element of the development of contemporary urban communities. This development path can also provide opportunities for organisations operating in cities and metropolises. An inherent feature of the organisation which a city constitutes is that it enables the people who make it up to cooperate. Climate packages, including the Green Deal and Fit for 55, are implemented in Europe, while in Poland decarbonisation processes are underway. The main challenges in this area include, on the one hand, a search for savings of energy consumed, and, on the other hand, a reduction in pollution resulting from the use of transport or heat or energy sources. Cities and metropolises will become green only when they manage to cope with these problems. The article aims at showing various facets of sustainable smart city management. With relations, information and knowledge gaining importance as the key organisational resource, cities have become, as organisations, an essential element of contemporary societies and organisations. In recent times, the harmful emissions from heating installations have drawn the attention of the public opinion in Poland. Polish municipalities distribute heat which mostly comes from local, most often district heating systems where energy is generated on a wide scale from coal combustion. This study compares the results of an air quality survey and those of a case study to assess the potential for the implementation of an automated heat control system in cities. On the basis of solutions implemented in the Warsaw Metropolis, the possibility of their implementation in the Upper Silesian (GZM) and Poznań Metropolises, too, was also assessed. Throughout Poland, there is a large potential for the application of innovative smart technologies in district heating systems to reduce the levels of harmful emissions. These reductions, which are still possible, could translate into a significant improvement in the attractiveness and competitiveness of municipalities. Finally, practical recommendations are being provided.

Keywords: network management; smart city; district heating; smart heat grid solutions; decarbonisation; energy efficiency; energy benefits

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1. Introduction

The present energy raw material markets prompt questions about the drivers of their rallies and a search for solutions to achieve tangible savings and efficiency in heat, electricity or gas consumption. The rapidly progressing industrialisation in Poland exerts a significant impact on the natural environment [1–3]. Despite its continuous growth in recent years, at present, amid the COVID-19 pandemic [4–7], the Polish economy must find a new path which would take into account the pledge of a digital transition and stakeholders' expectations [8,9]. The energy sector is at the centre of attention in these processes, since it reflects both challenges and opportunities for economic growth [10]. In the past, energy was available in different forms and little attention was paid to the impact of its generation methods on the natural environment [11,12]. The growing demand for smart technologies designed to reduce the maintenance costs of cities makes it necessary to adapt the instruments of decision-making processes initiated by authorities. They should take into account advanced technologies, public actions with the character of cooperation with the inhabitants and mechanisms supporting social capital [13–16]. The GZM Metropolis has already experienced a similar process during the modernisation of its transport network, as a result of which its operation by users has improved due to the integration of carriers and smart technologies [11,17]. District heating exemplifies the area of application of network management where an increase in the potential of soft competencies, especially the building of confidence among stakeholders, can bring about higher energy efficiency and support the implementation of the objectives of the European Green Deal [18–20].

The originality of this study lies in presenting various aspect of smart city management in areas of smart buildings, smart mobility or smart heat control from unifying perspectives of network management and emission reduction. Moreover, on top of the previous research [19] which relied on actual energy savings, significantly reducing the level of error compared to interpolation or statistical data, the heat savings were calculated for another Polish metropolitan area.

The concept of the Smart City emerged from the research on smart urban environments [21]. The term "smart city" denotes a city having a certain intellectual ability, which refers to innovative sociotechnical and socioeconomic aspects of growth [22]. It can be considered in six dimensions [23]: smart people, smart living, smart economy, smart mobility, smart environment and smart governance.

N. Komninos defined three stages of the development of a smart city, respectively: Smart City level 1, Smart City level 2 and Smart City level 3 [24]. This definition is subject to continuous evolution, currently concept of Smart City 4.0 is being getting more and more attention [25].

Smart City 1.0 refers to intelligent cities in the earliest phase of creation and predominantly technology driven. ICT companies are the drivers of the change, implementing various solutions irrespective of whether they are necessary for the cities or not. A notable example is the city of Songdo, South Korea [26,27].

In Smart City 2.0 predominant role is played by public administration. The use of modern technologies is initiated by local authorities, and the introduction of new solutions is aimed at improving the citizens' quality of life. According to the Smart City researcher, Boyd Cohen, today, most cities implementing Smart City projects belong to the 2.0 generation.

Since 2015, a new approach to the creation of smart cities has been observed—the Smart City 3.0 model. Cities are encouraging the active approach of their citizens. The role of local authorities is shifted towards creating the space for and opportunities to use the various potential of their citizens.

Smart City 3.0 relies on the new technologies to improve the quality of life in cities, yet the scope of its interest has expanded to comprise social, equity, educational, and ecological issues. City authorities welcome the increasingly influential participation of citizens. Evolution of the Smart City has been depicted in Figure 1.

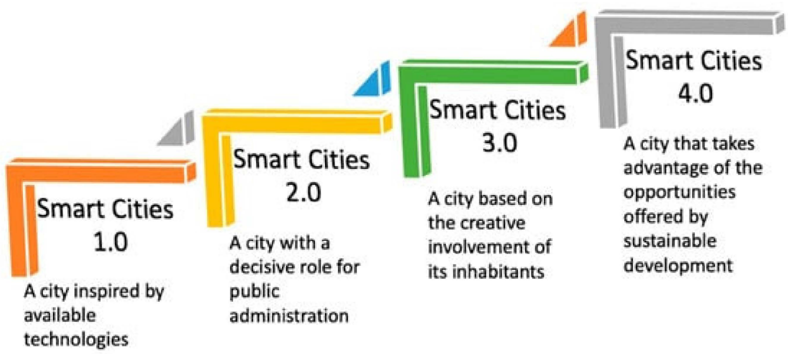

Figure 1. Next stages of development of smart cities. Source: Own study on the basis of [28].

The European Union has adopted three Directives to address the problem of air pollution: Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants (the so-called LCP Directive), Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants (the so-called MCP Directive) and Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (the so-called IED Directive). These documents primarily focus on reducing relative emission levels [29,30]. The EU policy led to a significant reduction in the emissions of total suspended particulates (TSP) from 1156 kt in 1990 to 343 in 2019. In 1990, the greenhouse gas emissions amounted to 382 Mt and in 2019 to 322 Mt [31–33]. This study presents the contribution of the solution based on the Hubgrade system to reducing the harmful emissions from the district heating network in Warsaw and the simulation of its application in the district heating systems operated within the Upper Silesian and Zagłębie Metropolis (hereinafter referred to as the GZM Metropolis). Its results were also referred to the Poznań Metropolis.

The GZM Metropolis is a term which refers to an association of 41 municipalities, towns and cities in the southern part of Poland. All the goals of the cities, municipalities and the Metropolis can be achieved using a variety of means, provided that they meet the ambitious standards set out within the framework of the European Green Deal [34–36]. However, there is a reason why climate neutrality has been set out as the first strategic goal of GZM. Moreover, the goal in question is consistent with the idea of the European Green Deal which provides that energy efficiency must be at the centre of attention and the energy supply in the Member States of the European Union must be safe and affordable to individual customers and businesses [34,37–39].

The abovementioned goals can be achieved in various ways. In order to minimise energy consumption the idea of sharing economy can be utilized [38]. However, in order to meet the high requirements of the European Green Deal [40], all the objectives presented here need to be accomplished at the same time, including not only business objectives [41,42]. One of them is improving energy efficiency [43,44]. The relatively high population density and an extensive network of district heating systems within the GZM offer a large potential for savings due to the application of smart technologies in district heating systems.

The choice of GZM provides, therefore, an opportunity to gain broader knowledge of the approach to the Smart City concept in many cities which function, at the same time, together within the GZM. In this context, the studies on GZM and its participants, as well as a search for new, effective forms of cooperation, become particularly important [45].

In order to benefit from the favourable geospatial conditions, it is necessary to assure sufficient level of coordination of actions among stakeholders. GZM can play a pivotal in this process [46].

The effects of the implementation of smart technologies in district heating networks have not been fully addressed in the literature on the subject, although this thread appeared in different references [47,48]. This study sums up the application of smart solutions in the Warsaw district heating system where heat consumption is comparable to that in the GZM. On the basis of this summary, the authors simulated the possibility of saving energy and reducing harmful emissions within the GZM and also, on the basis of 2020 data, for Poznań. It is important to add that, in contrast to electricity markets, the monopolistic character of the sector of district heating systems is a natural phenomenon, but, unfortunately, it leads to their stagnation [40,49].

2. A Review of the Literature on the Network Management of a City

With the growing importance of information and knowledge as a key organisational resource, networks have become an essential element of contemporary societies and organisations. An inherent feature of the organisation is that it enables the people who make it up to cooperate [50,51]. It is due to cooperation, based, among other factors, on talent, tolerance and trust, that it is possible to achieve organisational objectives in the most efficient way, more effectively, and to attain objectives which one person could not implement. The development of technologies and the growing complexity of the business environment have produced an increasingly conspicuous trend to establish inter-organisational ties—to manage the relations with entities in the environment of the organisation [52,53]. The concept of network cooperation enables us to describe these relations. The inter-organisational network consists of points (also called network nodes) connected with one another with links, also called ties, with a multiple, complex and excessive character. In order for a network to exist, entities need to be characterised by durability, dependence and interpersonality. One of the researchers [54] building on a model proposed by another scientist [55], has come to the conclusion [56], that the most recent studies on the processes of managing and modelling socio-spatial relations question the hierarchical approach, demanding that more attention should be paid to the spatial extent of different networks which intertwine in urban areas. Other researchers [57], describing the conditions of network cooperation in the management of public organisations, indicate that there are seven main problem areas related to the management of public networks. They include: the essence of tasks and functions associated with the management of networks, the process of cooperation in groups, the flexibility of a network, the responsibility for oneself and network partners, the factors determining the coherence of a network, governance and its effect on problem solving within a network and the outcomes of the management of a network [58]. They also indicate that the largest number of controversies concern the process of governance and decision-making and the implementation of changes. One of the researchers [59] points out that market operators act in agreement not only in respect of prices, contracts or official orders, but also in respect of social ties, prestige or behaviour standards. Originally, attempts were made to place these phenomena between markets and hierarchies, and then it was proposed that a network should be understood to be a temporary hybrid; however, the role of trust in the coordination of cooperating enterprises was quickly recognised. The relational or social coordination of cooperation is based not only on trust between the parties, but also on the behaviour standards in effect in a given community, supported by an intensive exchange of information.

In turn, another researcher [60] analyses an important issue of the answer to the question about the role of information and communication technologies in the process of the social construction of certain narratives on sustainable development, pointing out that a network society is defined as an example of a new socio-economic formation, based on a combination of two most important pillars of civilisation: technology and values. This provides a good starting point for reflections on the linkages between the network aspects and the issue of emissions in the urban context.

3. A Review of the Literature on Smart Buildings and Smart Mobility

IT technologies are used in many fields of life. They are also often applied in residential buildings and also other types of properties. The implementation of innovative IT technologies has made it possible to carry out projects to design properties classified in the group of "smart buildings" or "smart homes". These terms denote a site which "efficiently manages in an integrated manner the resources, services and their mutual linkages in order to satisfy the changing needs of tits users, while, at the same time, minimising the costs and continuously respecting the natural environment" [61]. Therefore, it follows from this that in the case of investment in properties of the "smart" type IT technologies need to be applied to optimise the investment costs, mostly in the scope of environmental protection and modern usability of the property.

The term "smart home" was used for the first time in 1984 in the United States by the American Association of House Builders. This pivotal moment brought the insight that what made a property smart was not its efficiently used space or robustness of its structure, but rather the interactive technologies contained in it [62–65]. Subsequently, this led to building management systems, consisting of various of subsystems, including: heating, ventilation, air-conditioning and lighting systems [66–68].

In the literature on the subject, however, it would be difficult to find a universal definition of the concept of "smart". As interpreted by the Intelligent Building Institute in the United States and the European Intelligent Building Group in the United Kingdom, two aspects can be distinguished: the economic and the environmental ones. "A smart building is one that maximises the efficiency of the building's occupants, while at the same time enabling competent management of resources with the least operating costs" [61,69], whereas in the Japanese approach the modernity in the scope of the usability of a property for its user has become a key feature.

According to Bellini, evolution of smart cities and growth of importance of IoT goes hand in hand. He perceives IoT as the key drivers for smarter innovation and sustainable development [70].

In a general approach, Richard Harper [60], defined a smart home as a residence equipped with modern IT technologies which can anticipate and respond to the needs of its occupants. The management of these systems should continuously aim at promoting and improving the occupants' comfort and safety in the scope of an efficient use of this system and limiting, among others, the energy consumption costs in the residence [71–73].

Despite such a formulation of efficiency, initially, there was a slight demand for the use of this type of installations on properties. The principal factors limiting the development of smart solutions included [74,75]:

- A lack of motivation to improve economic and environmental efficiency on the property;
- The users' limited awareness reflected in preferences for this type of solutions;
- High costs of the assembly of installations which limited the demand;
- Little involvement of users of the technology in the process of the design and development of this technologies.

As Barlow and Gann [74], found, in order for consumers to be interested in the purchase of modern technological solutions, the producers need to meet the following conditions:

- The solutions need to meet increasingly sophisticated and higher than standard expectations of the users of the property;
- In the scope of their operation, these solutions need to offer ease of use, affordability, functionality, reliability and easy maintenance;
- Upgradability of the system to include new functionalities, flexibility, adaptability and ease of installation of equipment;
- Sustainable consumption of the energy needed;
- Cheap and reliable equipment with a limited amount of wiring.

With the development of smart solutions used on properties, the users' expectations have also changed and, as a result of this, a building is only capable of reproducing the intelligence programmed by the design engineers using different types of control algorithms [76–78], which provide the basis throughout the process for taking decisions regarding the functionalities of the building property.

Therefore, integrated control and automation systems [29,30], so-called Building Automation and Control System (BACS), have been developed to manage properties of the smart type. They are responsible for ensuring comfort, safe use of the building, energy efficiency and environmental protection [79–81].

In order to improve the system for the management of a smart building, the Building Management System (BMS) is used. It provides the monitoring, control and optimisation of the operation of the installations and technical equipment with which the building is equipped, including the control of internal and external lighting of the building, the adjustment of space heating and cooling, the control of ventilation, as well as air filtration, the control of fire protection systems and the integration of everyday use systems present on the property [77,80,82,83].

The main components of the BMS type system include [84]:

- Components responsible for data collection—sensors;
- Actuators (servos);
- The user interface enabling control via an Internet-based search engine;
- A wired or wireless IT network;
- The control unit—a computer.

The Building Automation Solutions (BAS) is a system which ensures the integration of all the subsystems. It enables the management of automation installations, i.e., the systems which efficiently enable the control of equipment with which the building has been equipped, e.g., motion sensors in rooms, those controlling temperature, lighting or monitoring air quality [23,85]. Another relevant concept is the one of the Smart Building which is an extension of a smart home. It incorporates zero-emission renewable energy sources, electric vehicle charging infrastructure and potentially Vehicle to Grid (V2G) solutions [86].

With the development of IT technologies and the existence of the Internet, it has become possible to implement the vision of a fully automated smart property. This can be achieved by using the technology of the Internet of Things. According to Guinard and Trifa [87] "the Internet of Things is a system of physical objects which can be detected, controlled and interacted with by using electronic equipment ensuring communication via different web interfaces and the possibility of connecting to the wider Internet".

The aim of the Internet of Things is to improve the users' comfort and the efficiency of cooperation among smart and automated objects in a better and more secure environment [88]. The newest structures of the Internet of Things focus on conferring identity to application domains which are necessary to ensure the efficient course of the process [89–91]. It is extremely important to identify application categories, which include: monitoring and control, data collection, business analytics and the provision of information, as well as their cooperation [92].

In turn, for the users of smart equipment applied on smart properties, it is pertinent to explain how these services can be available. In consequence, this leads to the explanation of the role of a "cloud" in software, which is, in fact, an environment that integrates devices, along with the tasks entered by the user [93,94]. A cloud "promises high reliability, scalability and autonomy" and the further development of the application of the Internet of Things depends on the opportunities which the cloud of that application enables.

Looking at the mobility domain, Sustainable Urban Mobility Plans (SUMPs) are some of the most widespread tools for addressing the problems of transport and mobility in urban and suburban areas.

Horizontal integration is a difficult process when multiple departments of local governments are being involved to manage energy, transport and mobility issues [26].

Another relevant issue is vertical integration and strategic planning [95,96] leading to introduction of incoherent policies and sectoral measures [97]. It is not difficult to imagine that such an environment can struggle with providing reductions in emissions in the area of urban mobility. Network management could constitute a partial remedy to the problem, which is believed to intensify as new forms of mobility gain significance [98].

Transport sector in EU is currently responsible for around 25% of greenhouse gas emissions in the European Union with forecasts of further growth [99–101].

For the above mentioned reasons, from the municipal perspective it is imperative to consider energy, building and spatial planning as well as transport and mobility jointly. This will require adoption of new management systems or modification of the existing ones, including adoption of network management.

4. A Review of the Literature on the Factors Affecting the Energy Transition in Municipalities

In consequence of the technological revolution and changes resulting from an evolution of the urban environment, contemporary district heating networks do not resemble those that were built two hundred years ago [102]. In order to compare the types of existing networks, a separate nomenclature of district heating systems was established, to evolve when they did.

The history of district heating systems started with their "first generation" which came at the end of the 19th century in the United States and Western Europe and used steam as the heat carrier, with its temperature reaching 150 °C.

A feature of the "second generation" of heating systems was the change of the heat carrier to water under high pressure, with its temperature exceeding 130 °C. It was distributed by means of steel pipes without good insulation, running in concrete ducts. This technology was used from the 1930s and it enjoyed popularity until 1970s, particularly, in socialist countries, including Poland. Both generations were characterised by high heat losses at the distribution stage.

The technology which can be found most often in district heating systems as this article is written is the "third generation" system [47]. The main difference between this generation and the previous ones is the prefabrication technology applied to build pipes. Prefabrication means that pipes are produced with integrated insulation. Third generation systems are supplied with pressurised water, but its temperature seldom exceeds 100 °C.

It is difficult to characterise the "fourth generation" of district heating systems and this group of solutions does not enjoy large popularity yet. Since the improvement of energy efficiency became a global trend, it has been impossible to stop the evolution of the district heating technology. The future district heating systems will have to meet such challenges as the capacity of delivering, at the same time, heat to existing buildings and new built sites with low heat demand, reducing heat losses in the network circulation or the ability to integrate the existing heat sources with renewable energy sources (RES) [95,96,103–105]. Therefore, it can be expected that as part of the fourth generation equipment will be supplied with water having a low temperature falling within the range from 30 to 70 °C [106]. In order to improve the thermal efficiency and meet the standards mentioned above, there is a need for coordination between the performance of buildings and district heating systems. Intelligent performance control and monitoring of the operation of the network, along with exact weather forecasts, can play a key role in the optimisation of heat consumption [45]. Intelligent algorithms and remote valve control make it possible to predict the demand for heat and to deliver it to a building without a surplus, thus maximising energy efficiency. According to Li and Nord [48,105] smart district heating systems, thus including their fourth generation, consist of three principal components: the physical network, the Internet of Things and intelligent decision systems. The assembly and integration of these components can be beneficial in terms of the flexible meeting of the needs of building, since their concrete structures are used as short-term heat storage systems [107,108].

The idea of the "fifth generation" systems (district heating and cooling systems) has not been disseminated yet. Its core concept is the combination of district heating and cooling systems. The heat carrier used in them has a very low temperature. The maximum use of renewable energy sources is expected, in accordance with the principles of closing circuits to as large an extent as possible [109,110]. The difference between the third and fifth generations of district heating systems is so large that the return temperature in the third generation can be the supply temperature in the fifth generation. Such a solution was proposed for the urban renovation project in the Hertogensite district in Leuven (Belgium) [108,109,111].

5. The Smart Heat Control System for a Smart City Selected for the Study

Authors utilized the data from the Hubgrade system. Building Energy Services-Hubgrade (BES-Hubgrade) is a solution provided by the Veolia group [112]. Optimisation of heat consumption in buildings is achieved by using smart remote management systems. Reduction in the heat consumption in the buildings is achieved by use of continuous monitoring of the network parameters, analyses of weather forecasts, multi-point temperature measurements and the remote control to ensure thermal comfort. This leads to lower carbon footprint of the heat production and lower heating costs for the clients. It is important to mention that BES-Hubgrade service is primarily offered in the region where about 90% of the heat is produced from coal combustion [113].

Smart Heat Grid Solutions™ and Smart Heat Building Solutions™ are business offers of smart management systems from the company NODA Intelligent Systems [114]. NODA Smart Heat Building is a solution which has sensors which enable the system to continuously monitor the temperature, to calculate the energy balance of the property and to adjust the heating management system installed in the substation. Due to the control of the interaction between the production conditions and the consumer demand, NODA Smart Heat Grid is able to better cool the return water, which translates into higher efficiency of electricity production in cogeneration systems with a steam turbine and into improved overall energy efficiency.

Smart Active Box (SAB) is a predictive maintenance system provided by the Swedish company Arne Jensen AB, designed for managing the condition of pipes in a district heating network [115]. The system has different functions than those of the previously mentioned systems. It is a service which consists in collecting strictly specified data on acoustic vibrations (Delta-t®), enabling the prediction of leakages in a district heating network. Such a solution enhances the efficiency of the use of pipes and thus minimises its cost and carbon footprint generated by the energy-consuming production of pipes.

iSENSE™ is another smart solution designed for district heating networks. It has been designed by the Finnish company Vexve Oy [116].

6. Material and Methods

The multiple threads of the research required the utilisation of various research tools. Quantitative methods aimed at calculating thermal energy savings, a case study was used along with studies based on public statistics (air quality). The plan for the research is shown in Figure 2.

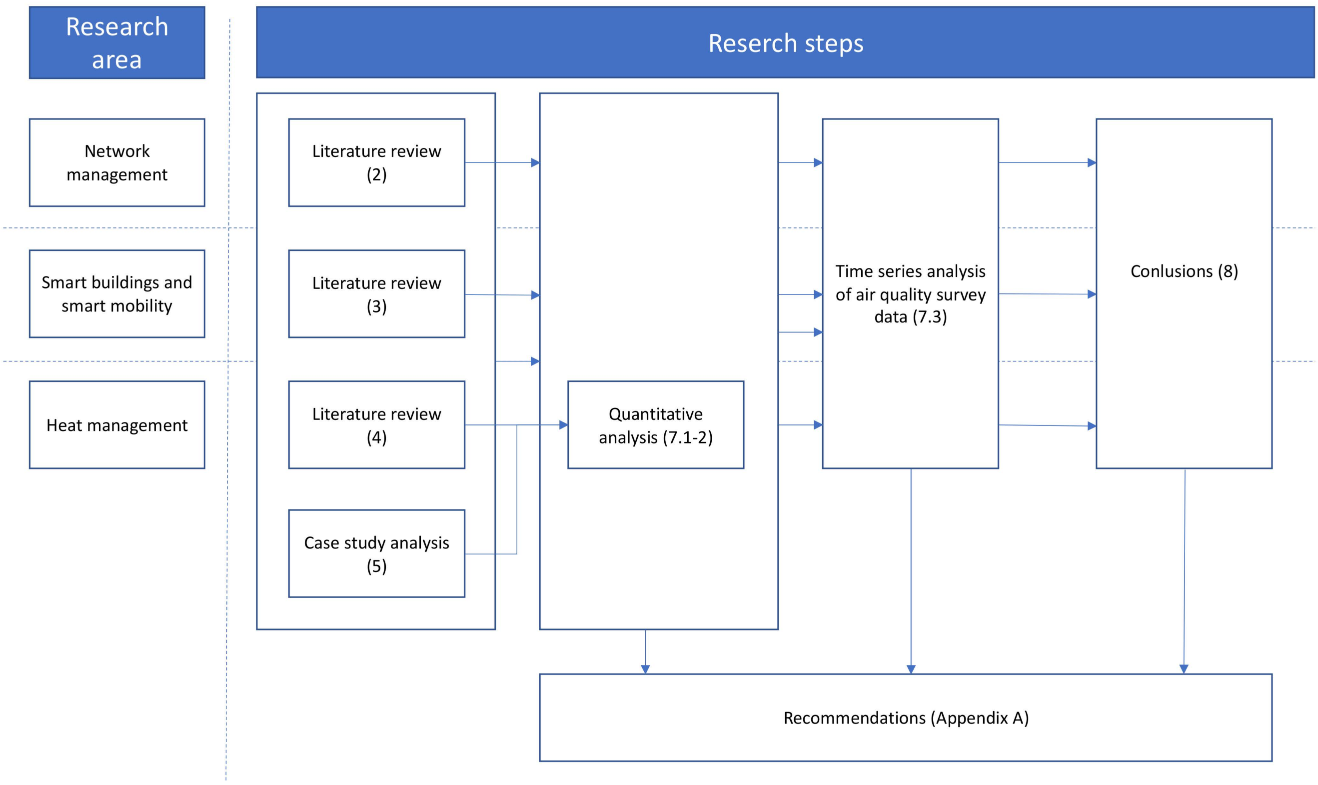

Figure 2. Research plan.

Starting with a preliminary understanding of research areas related to network management, smart buildings and heat management stemming from a literature review and case studies of heating systems, primary data have been collected and analysed. The next step was to refine and revise findings from previously gathered data using insights from time series analysis of air quality survey data. Eventually, closing conclusions and recommendations have been drawn.

This research constitutes further development of previous research of authors which solely focused on emissions related to district heating systems [11]. In this article both the geographical and research scope has been expanded to include Poznań area and network management, smart building respectively.

6.1. Assumptions on the Administrative Boundaries of the GZM, Poznań, and Warsaw Metropolises

In the further part of this study, the term "GZM Metropolis" or GZM denotes the group of counties which are part of it. The boundaries of the Upper Silesian and Zagłębie Metropolis which were established in 2017 covering 41 municipalities, including 13 towns with the rights of a county and 13 urban municipalities. It can be represented as the Upper Silesian conurbation consisting of major Polish cities, by presenting it as a group of adjacent cities in Śląskie Voivodship, including Gliwice, Zabrze, Katowice, Bytom, Świętochłowice, Siemianowice Śląskie, Sosnowiec, Dąbrowa Górnicza, Jaworzno, Czeladź, Mysłowice, Będzin, Tychy, Ruda Śląska, Piekary Śląskie, Chorzów, Mikołów, Tarnowskie Góry, and Knurów.

GZM has an area of 2553 km^2. It is inhabited by about 2,300,000 persons.

The Poznań Metropolis is inhabited by 30.2% of the population of the Voivodship. In the Poznań Metropolis, which is strongly urbanised, 47.0% of the total number of apartments in the Voivodship have been commissioned. The employed in the Poznań Metropolis represent 41.4% of those employed in the Voivodship, while the registered unemployment rate is 20.9%. The Poznań Metropolis occupies 10.3% of the area of the Voivodship. In 2020, the association of the Poznań Metropolis included: Poznań, the municipalities of Poznań County, Oborniki, Skoki, Szamotuły, and Śrem. The area of the Poznań Metropolis is 3082 km and its population is more than 1,050,000 inhabitants.

The Warsaw Metropolis, consisting of the Capital City of Warsaw, is the largest city in Poland in terms of its population and area. It is also the only Polish city whose administrative system has been established by a separate law. Since 2002 it has been an urban municipality with the status of a city with the rights of a county. It consists of 18 auxiliary units, i.e., the Districts of the Capital City of Warsaw. Warsaw is an important scientific, cultural, political and economic centre. Among others, the seats of the President of the Republic of Poland, the Lower and Upper Houses of the Parliament, the Council of Ministers and the National Bank of Poland are here. Warsaw is also the seat of the Frontex Agency, which is responsible for the security of the external borders of the European Union, and the Office for Democratic Institutions and Human Rights (ODIHR), which is a body of the OSCE. Warsaw has an area of 517 km^2 and a population of about of 1,800,000 inhabitants.

6.2. Methodology for Calculating Heat Savings

A special index of heat consumption was developed to account for the fact that the weather conditions are different every year. Following formula is used for this purpose [19]:

$$KPI(n) = \frac{Q(n)}{HDD(n)} \quad (1)$$

where $KPI(n)$ is the index of heat consumption over the period (n), $Q(n)$ is the heat consumption reading over the period (n) and $HDD(n)$ is the sum of the daily differences over the period (n) between the reference temperature of 18 °C and the average outdoor temperature during the day, expressed in °C, as calculated for average daily temperatures not exceeding 14 °C.

The heat consumption index in the successive years is calculated from formula (2):

$$KPI(n+1) = \frac{Q(n+1)}{HDD(n+1)} \tag{2}$$

The theoretical base heat consumption, $(Q)_{base}$, is calculated monthly as the product of the heat consumption index in the base year, $KPI(M)_{base}$, and the number of HDDs in the corresponding month. $KPI(M)_{base}$ is the product of the heat consumption, $Q_{ave}(M)$, and the number of heating degree days, $HDD_{ave}(M)$, over the previous five years.

$$KPI(M)_{base} = \frac{Q_{ave}(M)}{HDD_{ave}(M)}$$

$$Q(M)_{base} = KPI(M)_{base} \times HDD(M)$$

Finally, the heat savings achieved due to the intelligent control of the heating subsystem are calculated by detracting the actual monthly heat consumption readings from the theoretical base heat consumption.

$$\Delta Q = Q(M)_{base} - Q(M)$$

6.3. Comparison of the District Heating Systems

Table 1 demonstrates that the choice of the Warsaw district heating system as the reference point is justified, because of the comparable length of the network (which is only 17% smaller), the cubic space of the heated buildings (which is 37% higher in Warsaw than in the GZM Metropolis) and the volume of the sold heat, which is 25% larger in Warsaw, although with its 19% lower value per 1 dam.

Table 1. Comparison of the Warsaw district heating system and the aggregated data on the district heating systems operated in the GZM Metropolis. Source: Own elaboration based on [28–30].

Name of Unit	Length of Heating Network	Cubic Space of Heated Buildings	Volume of Sold Heat
Warsaw district heating system	1847 km (2019)	341,270 dam^3 (2018)	26,443 TJ (2019)
GZM district heating systems (total)	2168 km (2019)	213,340 dam^3 (2018)	19,731 TJ (2019)
Poznań Metropolis	703 km (2019)	90,783 dam^3 (2018)	7209 TJ (2019)

6.4. Air Quality Surveys

Extremely important issues in air quality measurements include their reliability and quality [117]. In accordance with the requirements of Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (OJ L 152 of 11.06.2008, p. 1) and the Act on the Inspectorate of Environmental Protection, the National Reference and Calibration Laboratory (KLRiW), with its registered seat in Cracow, which was established in 2011 at the Chief Inspectorate of Environmental Protection, is responsible for ensuring the correct operation of the management system in air monitoring networks, approving measurement systems and coordinating quality assurance systems in Poland.

As part of its routine activities, KLRiW provided the air quality measurement networks with the possibilities of calibrating individual analysers, e.g., following their malfunction, and checking cylinders holding gas mixtures, calibrators and mass flow controllers.

In order to confirm its competences and to expand its knowledge of the state-of-the-art monitoring systems, KLRiW participated in international comparative studies and meetings of the National Reference Laboratories associated in the AQUILA (AQUILA—the European

Network of National Reference Laboratories operating as part of the Joint Research Centre of the European Commission) European network.

The CIEP took action to unify the measurement methods at the national scale, participated in the introduction of new measurement and analysis methods and disseminated knowledge of new standards on air quality measurements [117].

In order to strengthen the capacity of KLRiW, in the period from 2016 to 2018, as part of the Operational Programme Infrastructure and Environment, its calibration and adjustment infrastructure was modernised and expanded by purchases of a calibration bench, calibration lines for the purposes of adjustment and comparative testing of analysers for surveys of gaseous pollutants in the air and specialised equipment, among others, for the weighing room [117].

The surveys were carried out in the period from 2003 to 2020. Table 2 provides basic descriptions of selected measured data.

Table 2. Descriptions and units of the measurements and pollutants. Source: [118].

Index	Statistical Code/Field	Description
All	Averaging period	The basic data averaging period at a measurement site. The results of measurements are averaged in the form of annual series in accordance with that period.
All	Average	The average annual concentration.
SO_2	L > 350 (S1)	The number of hours in a calendar year when the average 1-h concentration exceeded 350 $\mu g/m^3$ (rounded to an integer).
SO_2	L > 125 (S24)	The number of hours in a calendar year when the average 24-h concentration exceeded 125 $\mu g/m^3$ (rounded to an integer).
NO_2	L > 200 (S1)	The number of hours in a calendar year when the average 24-h concentration exceeded 200 $\mu g/m^3$ (rounded to an integer).
NO_2	19th max. (S1)	The 19th maximum value in an annual series of results—1-h averages, in [$\mu g/m^3$].
PM_{10}	L > 50 (S24)	The number of hours in a calendar year when the average 24-h concentration exceeded 50 $\mu g/m^3$ (rounded to an integer).
PM_{10}	Max. (S24)	The maximum average 24-h concentration in a year.

7. Results

7.1. Assumptions for Measurements of Heat Savings in the Metropolises

As already mentioned in this article, in order to compare the real impact of the solutions adopted, account was taken of the number of heating degree days as the baselines for given years.

The performance assessment of the Hubgrade system in terms of the level of savings achieved was started by rejecting incomplete data and selecting complete datasets on the consumption and savings in the period from 2018 to 2020. Its results are shown in Figure 3.

Subsequently, the question was posed as to whether the application of the Hubgrade solution had contributed to the level of savings or not. The correlation coefficient calculated for the application of the Hubgrade system to achieve savings is close to 1, which implies that there is a close relationship between the application of Hubgrade and heat savings.

The average level of heat savings in the period from 2018 to 2020 was 13.8%. It should be added that the overwhelming majority of buildings in Warsaw covered by the assessment had undergone thermal modernisation.

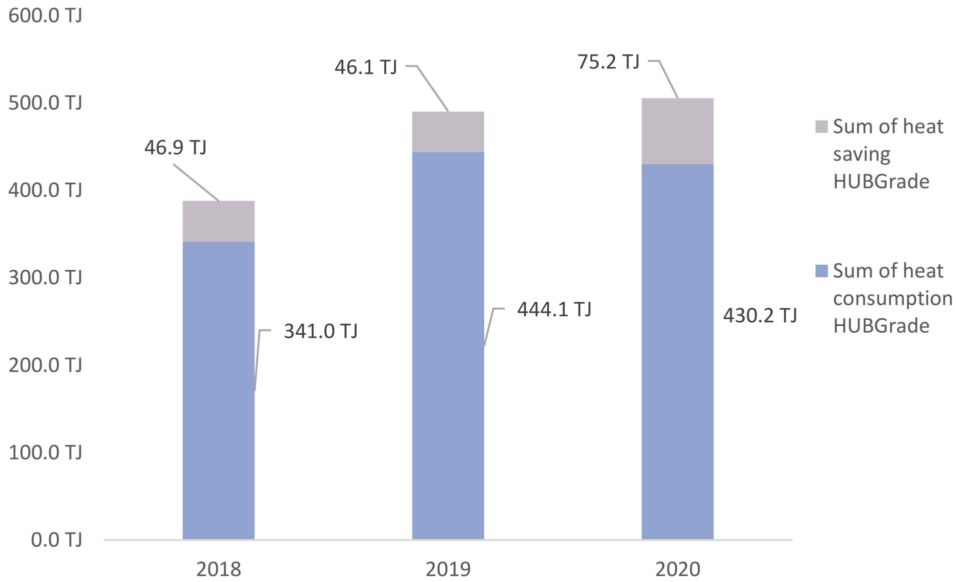

Figure 3. The levels of heat consumption and savings in the period from 2018 to 2020 relative to the baseline in the district heating network in Warsaw. Own elaboration based on data from Hubgrade UBGRADE in Warsaw.

On the basis of the comparative results achieved for the district heating systems in Warsaw and the GZM Metropolis, the following thesis was proposed: both Warsaw and the GZM Metropolis have the same potential to apply the Hubgrade system and, since both are located in the same climate zone, it will be possible to achieve similar results. Figure 4 shows a simulation of the implementation of the Hubgrade system in the district heating systems in Warsaw and the whole of the GZM Metropolis.

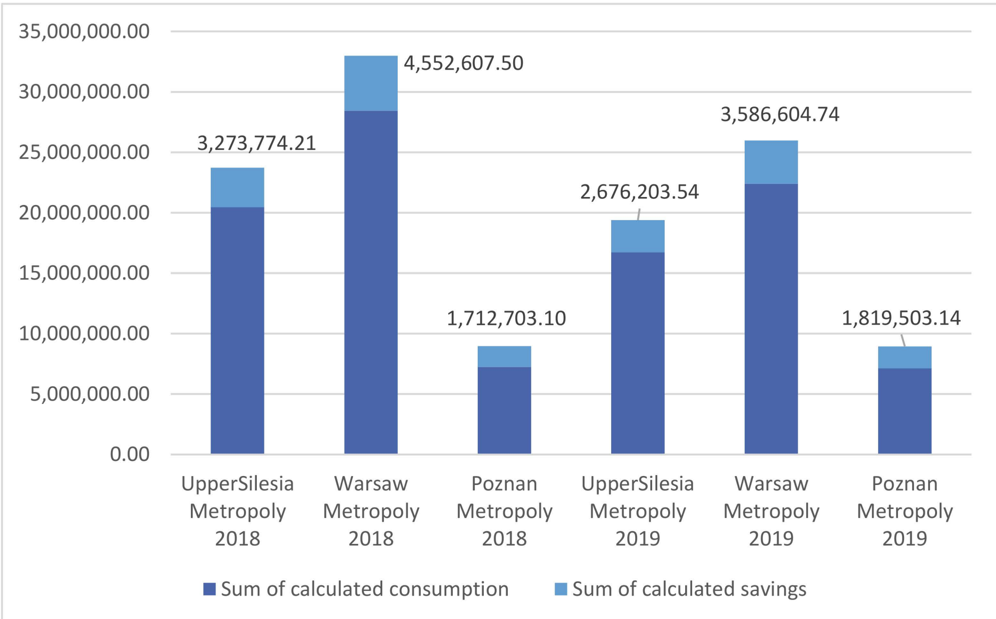

Figure 4. The results of a simulation of the installation of the Hubgrade system in all the district heating systems in the GZM, Poznań and Warsaw Metropolises (GJ). Own elaboration based on data from HUBGRADE in Warsaw and data on the emissions in GZM and Poznań.

The total heat savings in the GZM Metropolis and Warsaw can reach 7044 TJ, i.e., a sufficient amount to heat the whole of Chorzów or Tarnowskie Góry County.

7.2. Comparison of the Local Energy Generating Sources for the Purposes of Estimating the Levels of Harmful Emissions

Figure 5 shows the structure of gases emitted in the GZM Metropolis and Warsaw. The data in Figure 4 were drawn from the official reports of the local heat producers and are shown below.

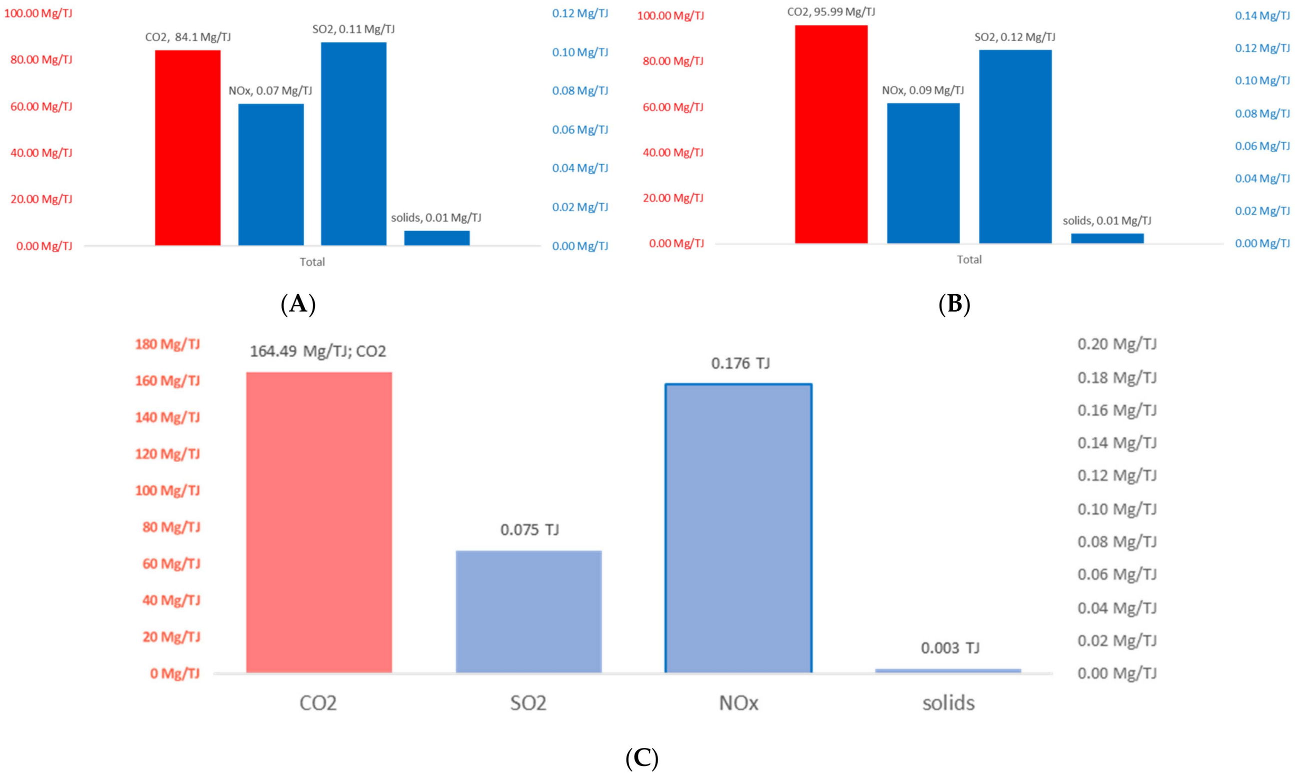

Figure 5. Comparison of total emissions in three Metropolises. (**A**) Emission levels in the GZM Metropolis: total emissions. (**B**) Emission levels in Warsaw: total emissions. (**C**) Emission levels in Poznań: total emissions. 2019. Own elaboration based on data from Hubgrade in Warsaw and the study reports on the Smart City project.

The levels presented above would translate into emission reductions according to the data in Table 3.

Table 3. The total potential for a reduction in the emissions in the GZM Metropolis. Source: Own elaboration based on data from studies of Hubgrade in Warsaw as referred to the GZM emissions.

Substance Emitted	Unitary Emissions	Energy Savings in 2019	Emission Reductions
CO_2	84.13 Mg/TJ	3273.8 TJ	275,424.8 Mg
SO_2	0.11 Mg/TJ		360.1 Mg
NOx	0.07 Mg/TJ		229.2 Mg
TSP	0.01 Mg/TJ		32.7 Mg

The calculated levels of the reductions in harmful emissions indicate that there is a potential for reductions by applying a smart control system in a local substation. It shows that the levels of emissions of suspended solids from district heating sources are low compared with local, uncontrolled heat sources. When these results are referred to the Poznań Metropolis, it can be expected that CO_2 emissions will fall by about 91 Mg in successive years after the full Hubgrade system is implemented.

7.3. The Results of Air Quality Surveys

1-h average survey series are presented below for SO_2, NO_2, PM_{10} and $PM_{2.5}$. Table 4 shows the measured SO_2 levels as averaged annual values from 1-h measurements. Analyses for selected years in the period from 2003 to 2020 are also provided for three major metropolises, describing the highest and lowest values.

Table 4. The results of SO_2 measurements as averaged annual values provided for three metropolises in Poland in the period from 2003 to 2020. Source: Own elaboration based on measurements [109].

Year	GZM Metropolis	Poznan Metropolis	Warsaw Capital Metropolis	Cumulative Averages
2003	34.52	6.98	6.89	14.64
2004	36.09	4.79	10.75	16.57
2005	23.16	5.11	9.46	13.20
2006	25.91	6.75	11.06	14.70
2007	14.14	5.12	7.72	9.81
2008	14.38	4.54	7.54	10.00
2009	15.75	5.89	7.59	11.17
2010	19.35	5.63	6.88	13.37
2011	16.04	3.81	6.35	10.83
2012	16.22	3.16	7.51	11.24
2013	13.98	3.30	6.91	10.75
2014	11.80	3.14	7.02	9.36
2015	13.12	3.09	5.48	9.91
2016	11.92	3.06	4.52	8.97
2017	12.77	3.25	3.83	9.42
2018	9.92	3.77	3.44	7.62
2019	8.52	2.79	2.37	6.36
2020	7.54	3.39	2.81	6.43
Cumulative averages	16.66	4.56	7.84	11.45

The lowest levels are marked in green and the highest ones are marked in red, while all the intermediate hues represent the intermediate indications of annual averages. The highest average annual SO_2 concentration was found in the most industrialized Upper-Silesia Metropolis in the initial survey years in the period from 2003 to 2006. The lowest concentrations were found in the Poznań Metropolis and, in recent years, in the Warsaw Metropolis, too. The results are also shown in Figure 6 below.

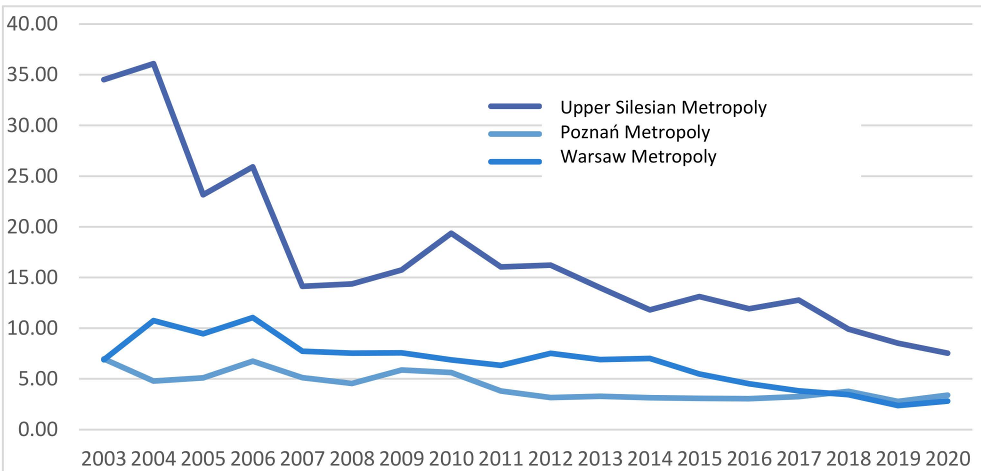

Figure 6. The results of SO_2 measurements in three metropolises in Poland in the period from 2003 to 2020. Source: Own elaboration based on measurements [109].

The period from 2003 to 2020 was also selected for NOx measurements and annual averages were prepared. Figure 7 below shows the results, with the largest decreases found for the Poznań Metropolis. In contrast, increases in annual averages were found for the Warsaw Metropolis in the period from 2012 to 2013. This resulted from the exclusion of natural areas associated with a national park from the survey.

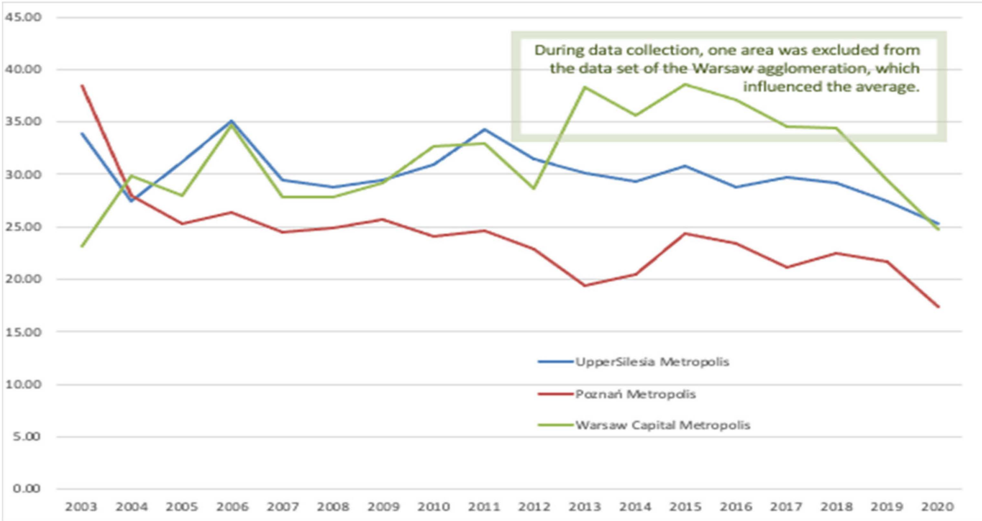

Figure 7. The results of NOx measurements in three metropolises in Poland in the period from 2003 to 2020. Source: Own elaboration based on measurements [109].

In order to illustrate the PM_{10} particulate matter levels, the data on the period from 2003 to 2020 were prepared as annual averages from the stations included in the surveys. Figure 8 shows the air measurements in averaged form.

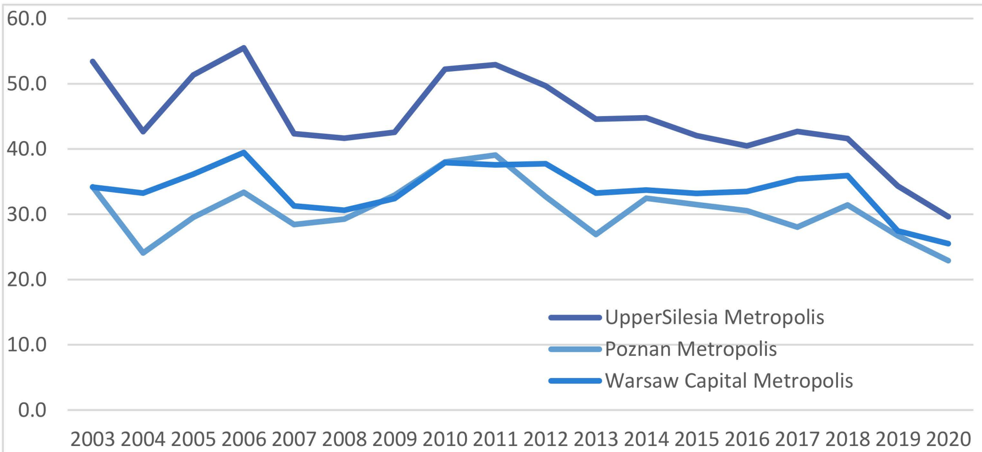

Figure 8. The results of PM_{10} measurements in three metropolises in Poland in the period from 2003 to 2020. Source: Own elaboration based on measurements [109].

In order to complement the results of measurements on particulate matter, solid pollutants of the order of 2.5 were also analysed as annual averages. Figure 9 shows averaged data on the period from 2009 to 2020 for all the three metropolises surveyed. Unfortunately, the data on the previous years were incomplete and prevented a reliable analysis.

The geographical differentiation of the results of the analysis is also reflected in the level of industrialisation and the level of the systems implemented to regulate the heat and electricity consumption. Substantial decreases in the metropolises examined were essentially found for all the pollutants surveyed, including SO_2, NOx, PM_{10} and $PM_{2.5}$, meaning that this did not result from one specific action only, but rather from overall processes associated with decarbonisation in these regions.

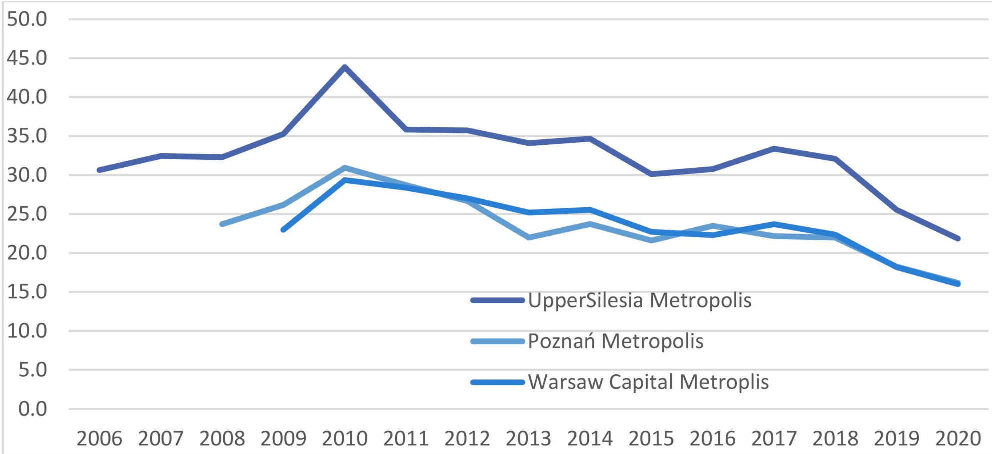

Figure 9. The results of $PM_{2.5}$ measurements in three metropolises in Poland in the period from 2003 to 2020. Source: Own elaboration based on measurements [118].

8. Conclusions

Emissions reduction is a significant challenge for many cities [119]. It is prudent to allocate resources where the improvement can be to the largest scale and the fastest. Network management of the city can be useful in achieving this goal.

There is no doubt that it is possible to implement smart control systems in the towns and cities of the GZM Metropolis, achieving tangible benefits for air quality in the towns and cities and their surroundings. Throughout Poland, there is a large potential for the application of innovative smart technologies in district heating systems to reduce the levels of harmful emissions. These reductions which are still possible can translate into a significant improvement in the attractiveness and competitiveness of municipalities [120–123]. The presented simulation of the emission reduction in GZM by 275 kt CO_2 demonstrates that a reduction of the order of 16% is possible, while, in turn, for the Poznań Metropolis this causes a reduction by 91 kt CO_2. The costs of the application of the Hubgrade system is lower than the cost of replacing the heat production technology; the system also contributes to significant achievements in environmental protection without worsening the thermal comfort of end-users and also ensuring the sustainable development of urban functional centres [124].

A comparison of similar district heating systems indicate that there is still a large diversity of the means of heat production; as a result of which, the total emissions in one region of Poland can be different from those in others. The results of the analysis demonstrate that the total emissions in the GZM Metropolis are lower than those from the district heating in Warsaw, while the potential for reducing harmful emissions in this area is still very large. There is a similar situation in the Poznań Metropolis, where a heat control system has already been partly implemented. Regulatory systems such as the HUBgrade project should be implemented, but at the same time observe changes in the level of pollution, the pace of implemented changes must be higher.

In a more dispersed system, the extent of a reduction in harmful emissions can still be larger. Moreover, at the same time, the number of methods for emission reductions is growing, e.g., by using centrally controlled heat pumps together with existing district heating systems. A reduction in the emissions from the district heating sector or the emissions associated with mobility [125] translates into an improvement in the quality of life and, in consequence, stimulates the development of 4T potentials. Issues of this type will be addressed in further research.

Recommendations presented in Appendix A can have a practical value for decision makers in cities and metropolitan. Furthermore, they constitute a starting point for further research for the authors and hopefully for other researchers.

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Abbreviations

Abbreviation	**Meaning**
BES	Building Energy Services
DHCS	District heating and cooling system
DHN	District heating network
MSC	municipal heating system
EU	European Union
GZM	Upper Silesian and Zagłębie Metropolis
H2020	Horizon 2020: A framework programme for research and innovation for 2014–2020 funded by the European Union
HDD	Heating degree days: the number of days when the average outdoor temperature does not exceed 14 °C
IDS	Intelligent decision system
IED Directive	Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions
IoT	Internet of Things
KPI	Heat consumption index
LCP Directive	Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants
MCP Directive	Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants
PN	Physical thermal network
RES	Renewable energy sources
SAB	Smart Active Box, a predictive maintenance system designed by the company Arne Jensen AB
STORM	Smart Freight Transport and Logistics Research Methodologies, a project funded by the European Union
TSP	Total suspended particles

Appendix A

Table A1. Practical Recommendations.

	Recommendation
1	The concept of "smart home", defined as a site which efficiently manages in an integrated manner the resources, services and their mutual linkages in order to satisfy the changing needs of tits users, while, at the same time, minimising the costs and continuously respecting the natural environment, can be scaled up from the micro level (of a single room or apartment) to the macro level (a city or a metropolitan area). Such a fractal approach to the issue makes it possible to identify the possible savings of investment outlays and operating costs or energy efficiency improvements because of simplification of organisational processes.
2	The carbon dioxide reduction targets cannot be achieved by using one technology or when it is applied only in one area. It is necessary to apply a multi-aspect approach using different technologies affecting all the areas of life in a city, including, among others, the generation, transfer and use of energy carriers, construction, spatial economy or mobility. To effectively manage such a complex system, it is necessary to use (implement or develop) Smart City solutions and, at the same time, to adapt management tools in local administration units.
3	Although local governments enjoy substantial autonomy in shaping their own transport policy and use it in preparing their strategic documents, such as SUMPs, these documents are often not implemented and/or organisational or investment decisions are in contradiction to the assumptions of strategic documents. The Authors discern the reason for this situation in the growing complexity of the urban mobility ecosystem and the silo character of organisational structure and recommend correspondingly the introduction of network management tools and a revision of the organisational architecture in a manner raising the creative capital level among the staff of local governments.
4	Sustainable development also entails the development of social capital and intersectoral cooperation, specified as multidimensional support for actions to strengthen or sometimes to restore the quality of the natural environment. In this case, communication and an exchange of information will be important. The intersectoral cooperation can be developed using such tools as e.g., urban labs, multifunctional dialogue platforms, formal and informal meetings leading to the creation of partner projects.
5	Low Carbon will be better known and understood as a policy when systemic education on Smart City will be launched and a consistent brand of a metropolis will be built and strengthened both in external relations at national and international levels and inside the metropolis. This systemic education on Smart City should be developed as one addressed, in particular, to local government officials, as well as to children, youth and senior citizens, in combination with an increase in the importance of the educational potential of the metropolis, including the university level-based one.
6	The emission reduction levels in the areas of transport/mobility will depend on the mix of selected tools. The most effective solutions—active mobility, collective transport and modern forms of shared mobility—require far-reaching changes in the inhabitants' awareness and cooperation among the participants in the mobility ecosystem in order to prepare an attractive proposal as an alternative to the use of private cars. Therefore, an indispensable step is to understand the structure and relations among the participants in the mobility network.
7	It is possible to improve air quality, particularly, in the heating season, essentially by reducing low emissions. By applying the network approach to the management of district heating systems, it is possible to reduce total emissions and also raise the attractiveness of district heat with respect to its clearly more emission-intensive alternatives by improving technological efficiency and cost-effectiveness using Smart City solutions. Given its unique position, GZM can assume the orchestrator's role and bring about a partial or full technological integration of district heating systems operated in its area, delivering an added value for its inhabitants and district heating companies.

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