Czech University of Life Sciences Prague

Faculty of Economics and Management

Diploma Thesis

Analysis of Air quality in Poland
From the Period 2013 to 2022

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Economics and Management

DIPLOMA THESIS ASSIGNMENT

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Thesis title

Analysis of Air quality in Poland from the period 2013 to 2022

Objectives of thesis

The thesis "Analysis of Air Quality in Poland from 2013 to 2022" seeks to provide a comprehensive overview of Poland's air quality situation over the selected time period. The study will concentrate on essential components of air pollution, such as industrial emissions, transportation, home heating, and coal burning. Particulate matter (PM2.5 and PM10), nitrogen oxides (NOx), nitrogen dioxide (NO2), sulphur dioxide (SO2), and ozone (O3) are among the primary pollutants being addressed. The first part of the study sets up a solid method for combining data from many sources, such as national air quality tracking networks, satellite observations, meteorological datasets, emission inventories, and health statistics. This also assesses the effectiveness of environmental policies, regulatory measures, and technological interventions made throughout the study period to reduce air pollution and enhance air quality in Poland. It involves assessing how emission reduction plans, fuel quality standards, car emission norms, industry emissions regulations, urban planning policies, green programmes, and renewable energy transitions affect air quality trends. At the end of the thesis, there are suggestions based on data that will help Poland improve its strategies for managing air quality, reducing pollution, and promoting sustainable development. The suggestions include ways to encourage cleaner transportation, switch to renewable energy sources, support green technologies, raise public knowledge, and make it easier for agencies to work together and involve stakeholders.

Methodology

Methodology is a planned approach that combines different types of data, study methods, and analytical techniques. First, the study will gather past data on air quality from reliable sources like the European Environment Agency (EEA), state environmental agencies, and monitoring stations all over Poland. Important air pollution like PM2.5, PM10, NO2, NOx, SO2, and O3 will be measured, along with weather conditions like temperature, humidity, wind speed, and atmospheric pressure.

After validating the data, the study will utilise statistical analytic methods including time series analysis, trend analysis, correlation analysis, and regression modelling to investigate temporal patterns, seasonal changes, and connections between air pollutants and factors that influence them. The data will be summarised and visualised using descriptive statistics, graphical representations such as charts, graphs, and maps, as well as statistical tests. These methods will aid in the identification of trends, outliers, and deviations, ultimately leading to the generation of useful insights.

In addition to qualitative analysis, the thesis will use qualitative research methods such as literature reviews, case studies and policy document analysis in order to explain the qualitative findings, better understand the broader environmental and socioeconomic context, and assess the impact of environmental policies and interventions on air quality.

Furthermore, the study will use a comparative approach to analyse air quality trends and levels among regions, urban versus rural areas, industrialised zones versus residential areas, and predetermined time periods within the study period. This comparison analysis will aid in identifying regional disparities, pollution sources, and the effectiveness of pollution control approaches across diverse environments.

The proposed extent of the thesis

60 pages

Keywords

Climate change, Air Quality, Pollution, Covid-19, Poland, Environmental health impacts

Recommended information sources

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Prague on 29. 03. 2024

Declaration

I declare that I have worked on my diploma thesis titled “Analysis of Air Quality in Poland from 2013 to 2022" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

In Prague on 29 March 2024

ROJADASAN RAJENDRAN

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I would like to thank Prof. Ing. Petr Procházka Ph.D., MSc, department of Economics, Czech University of Life Sciences, Prague, for his advice and guidance during my work on this thesis; also for his consistent and patient accommodation since the application for this course; and to my family, friends and work colleagues for their patience, understanding and support throughout the whole duration of my master's studies.

Abstract

The thesis "Analysis of Air Quality in Poland from 2013 to 2022" seeks to provide a comprehensive overview of Poland's air quality situation over the selected time period. The study will concentrate on essential components of air pollution, such as industrial emissions, transportation, home heating, and coal burning. Particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ozone (O_3) are among the primary pollutants being addressed. The first part of the study sets up a solid method for combining data from many sources, such as national air quality tracking networks, satellite observations, meteorological datasets, emission inventories, and health statistics. This also assesses the effectiveness of environmental policies, regulatory measures, and technological interventions made throughout the study period to reduce air pollution and enhance air quality in Poland. It involves assessing how emission reduction plans, fuel quality standards, car emission norms, industry emissions regulations, urban planning policies, green programmes, and renewable energy transitions affect air quality trends. At the end of the thesis, there are suggestions based on data that will help Poland improve its strategies for managing air quality, reducing pollution, and promoting sustainable development. The suggestions include ways to encourage cleaner transportation, switch to renewable energy sources, support green technologies, raise public knowledge, and make it easier for agencies to work together and involve stakeholders.

Keywords: Climate change, Pollution, Pandemic, Covid-19, Pollutants, Health impacts, Emissions.

Abstraktní

Diplomová práce „Analýza kvality ovzduší v Polsku v letech 2013 až 2022“ se snaží poskytnout ucelený přehled o situaci kvality ovzduší v Polsku ve zvoleném časovém období. Studie se zaměří na základní složky znečištění ovzduší, jako jsou průmyslové emise, doprava, vytápění domácností a spalování uhlí. Mezi primární znečišťující látky, které se řeší, patří pevné částice (PM2,5 a PM10), oxidy dusíku (NOx), oxid dusičitý (NO2), oxid siřičitý (SO2) a ozon (O3). První část studie stanoví solidní metodu pro kombinování dat z mnoha zdrojů, jako jsou národní sítě pro sledování kvality ovzduší, satelitní pozorování, meteorologické soubory dat, inventury emisí a zdravotní statistiky. To také posuzuje účinnost environmentální politiky, regulačních opatření a technologických intervencí provedených během sledovaného období s cílem snížit znečištění ovzduší a zlepšit kvalitu ovzduší v Polsku. Zahrnuje posouzení toho, jak plány na snížení emisí, normy kvality paliva, normy emisí automobilů, předpisy o průmyslových emisích, politika územního plánování, zelené programy a přechody na obnovitelné zdroje energie ovlivňují trendy kvality ovzduší. V závěru práce jsou uvedeny návrhy založené na datech, které pomohou Polsku zlepšit jeho strategie pro řízení kvality ovzduší, snižování znečištění a podporu udržitelného rozvoje. Návrhy zahrnují způsoby, jak podpořit čistší dopravu, přejít na obnovitelné zdroje energie, podpořit zelené technologie, zvýšit veřejné povědomí a usnadnit agenturám spolupráci a zapojení zúčastněných stran.

Klíčová slova: Změna klimatu, Znečištění, Pandemie, Covid-19, Polutanty, Dopady na zdraví, Emise.

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1. Introduction

The objective of this thesis is to undertake a comprehensive examination of the dynamics pertaining to air pollution in Poland prior to and during the COVID-19 pandemic. It is essential to direct one's focus towards significant pollutants such as nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), and particulate matter ($PM_{2.5}$ and PM_{10}). The primary objective of this study is to offer a thorough comprehension of the alterations in air quality within Poland. This includes determining the impact of the COVID-19 pandemic on the dynamics of air pollution, identifying the elements that contribute to it, and making practical recommendations to reduce air pollution in order to build a healthier and more sustainable environment.

According to the findings of this study, the COVID-19 epidemic has provided insights into the relationship between human activities and air quality in Poland. The study provides a framework for developing sustainable plans to enhance air quality by focusing on key pollutants and their sources, emphasising the need of ongoing efforts for a healthier and more environmentally sustainable Poland.

2. Objectives and Methodology

2.1 Objectives

The goal of this thesis is to look at the changes in Poland's air quality over the time period 2013 to 2022, focusing on important pollutants like ozone, sulphur dioxide, nitrogen oxide, carbon monoxide, and particulate matter 2.5 & 10. The primary objective of this study is to offer a list of the alterations in air quality within Poland. The point of this study is to find out how air quality affects public health, such as lung diseases like asthma, lung cancer, and COVID-19 infections, as well as the death rates linked to breathing in air pollution. According to the findings of this study, the COVID-19 epidemic has provided insights into the relationship between human activities and air quality in Poland. In addition, this study focuses on how the air quality changes in different parts of Poland based on location, how pollution levels change with the seasons, and how well current efforts to improve air quality are working.

To achieve this goal, the thesis will focus on providing useful information about the air quality in Poland during the chosen time period and suggest ways to improve air quality management methods to protect people's health and the environment. Lastly, the thesis will propose possible solutions to deal and reduce the effects of climate change in Poland.

2.2 Methodology

Methodology is a planned approach that combines different types of data, study methods, and analytical techniques. First, the study will gather past data on air quality from reliable sources like the European Environment Agency (EEA), state environmental agencies, and monitoring stations all over Poland. Important air pollution like $PM_{2.5}$, PM_{10}, NO_2, $NO_{x,}$ SO_2, and O_3 will be measured, along with weather conditions like temperature, humidity, wind speed, and atmospheric pressure.

After validating the data, the study will utilise statistical analytic methods including time series analysis, trend analysis, correlation analysis, and regression modelling to investigate temporal patterns, seasonal changes, and connections between air pollutants and factors that influence them. The data will be summarised and visualised using descriptive statistics, graphical representations such as charts, graphs, and maps, as well as statistical tests. These methods will aid in the identification of trends, outliers, and deviations, ultimately leading to the generation of useful insights.

In addition to qualitative analysis, the thesis will use qualitative research methods such as literature reviews, case studies and policy document analysis in order to explain the qualitative findings, better understand the broader environmental and socioeconomic context, and assess the impact of environmental policies and interventions on air quality.

Furthermore, the study will use a comparative approach to analyse air quality trends and levels among regions, urban versus rural areas, industrialised zones versus residential areas, and predetermined time periods within the study period. This comparison analysis will aid in identifying regional disparities, pollution sources, and the effectiveness of pollution control approaches across diverse environments.

3. Main Objectives

My thesis, "Analysis of Air Quality in Poland from the Period 2013 to 2021," aims to perform an in-depth and comprehensive assessment of air quality dynamics, trends, and determinants across diverse regions of Poland over the course of a decade. This study intends to achieve a number of specific goals.

Firstly, we will look at long-term changes in critical air pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and ozone (O_3) from 2013 to 2021. This research will involve reviewing historical air quality data collected from monitoring stations in urban, industrial, and rural areas to determine any major changes, improvements, or degradation in air quality levels.

Second, to find and study the main causes and factors to air pollution in different parts of Poland. Among other things, this means figuring out how human activities like industries, transportation, residences, farms, and other human-made sources affect air quality factors. The study's goal is to help come up with specific strategies and policy changes for reducing pollution by figuring out its main causes.

To reach this objective, the thesis will mainly focus on giving useful details about the air quality in Poland during the chosen time period and suggesting ways to enhance air quality management to safeguard individuals' health and the environment. The results of the research will help shape these suggestions. In the end, the thesis will suggest ways that Poland might be able to deal with and lessen the effects of climate change.

3.1 Introduction of Air Pollution and its Impacts

Air pollution is a persistent environmental concern that endangers human health, ecosystems, and quality of life around the world. Air pollution is defined as the presence of toxic or excessive amounts of pollutants in the air. It is caused by a variety of natural and manmade sources, including industrial operations, traffic, energy generation, and heating systems for homes. Over the last century, increased industrialization, urbanisation, and population growth have resulted in unprecedented amounts of pollution in the Earth's atmosphere, exacerbating the negative impacts on a local and global scale.

Air pollution comprises a wide range of contaminants, including gas, particulate matter, volatile organic compounds (VOCs), and heavy metals. The most prevalent pollutants include nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), particulate matter (PM), and volatile organic compounds (VOCs). These pollutants can come from a variety of sources, including industrial facilities, vehicle emissions, agricultural activities, biomass burning, and natural events like wildfires and volcanic eruptions. In metropolitan areas, motor cars are frequently the dominant source of air pollution, producing pollutants such as nitrogen oxides, carbon monoxide, and particulate matter from combustion engines.

The adverse health impacts of air pollution are well known, and they include a wide spectrum of respiratory, cardiovascular, and neurological problems. Air pollution has been linked to respiratory symptoms, asthma exacerbations, lung cancer, heart attacks, strokes, and early mortality.

3.2 Air Quality and Regulations

Air quality refers to the presence and quantities of contaminants in the air. It is an essential component of environmental health and an important indicator of human well-being. Good air quality is critical for sustaining life and supporting healthy ecosystems, whereas poor air quality can harm human health, the environment, and the economy. As a result, understanding, monitoring, and regulating air quality is vital to maintaining public health and environmental sustainability.

Governments and regulatory agencies play an important role in regulating air quality by enforcing air quality standards, laws, and management plans. These strategies may include emission controls, pollution abatement technologies, vehicle emission regulations, and land-use planning policies targeted at lowering pollutant emissions and minimising exposure to air pollution. Public awareness campaigns, community participation programmes, and international collaboration efforts are all necessary for effectively addressing air quality issues.

Despite advancements in air quality management, there are still significant hurdles to achieving and maintaining clean and healthy air for all. Rapid urbanisation, industry, population increase, and climate change remain complex and interconnected concerns that necessitate creative remedies and coordinated methods. To promote sustainable development, preserve human health, and maintain the environment for future generations, these problems will necessitate ongoing research, policy interventions, and stakeholder involvement.

3.3 Overview of Air Quality Standard

Air quality standards are critical regulatory tools that define allowed amounts of air pollutants in the atmosphere in order to protect public health and the environment. These guidelines serve as benchmarks for evaluating the quality of the air we breathe, directing regulators, lawmakers, and companies in their efforts to reduce air pollution. Air quality standards are critical for achieving environmental sustainability and protecting human well-being since they define allowable amounts of contaminants.

In addition to safeguarding human health, air quality guidelines may include requirements for environmental and ecosystem protection. Environmental standards address the biological effects of air pollution, including acid deposition, eutrophication, biodiversity loss, and habitat destruction. These standards seek to avoid or reduce pollution-related environmental impact, as well as to promote natural resource conservation and restoration.

Air quality guidelines are set at the international and national levels to address global and regional environmental concerns. International organisations, such as the World Health Organisation (WHO), and regional agencies, such as the European Union (EU), create air quality management recommendations and regulations that national governments can use as a reference. National governments, in turn, establish their own air quality standards based on local circumstances, goals, and legal frameworks.

Implementing and enforcing air quality standards necessitates collaboration among government agencies, regulatory bodies, industrial parties, and citizens. Governments set up air quality monitoring networks, emission control programmes, and regulatory systems to check standard compliance, identify pollution sources, and enforce environmental legislation. Public awareness campaigns, community engagement programmes, and citizen science efforts all play key roles in promoting compliance with air quality regulations and increasing accountability for pollution control.

3.4 Key Air Pollutants and their Sources

- Particulate matter (PM)
- Nitrogen oxides (NO_x),
- Sulphur dioxide (SO_2),
- Carbon monoxide (CO),
- Ozone (O_3)
- Lead

3.4.1 Particulate matter (PM)

Particulate matter (PM) is a complex mixture of solid particles and liquid droplets suspended in the atmosphere. These particles vary greatly in size, composition, and origin, ranging from coarse dust to fine aerosol. Particulate matter can be discharged directly into the atmosphere by a variety of sources or produced by chemical processes in the air. PM is categorised based on its aerodynamic diameter.

3.4.2 $PM_{2.5}$

Particles with a diameter smaller than or equal to 2.5 micrometres (µm). $PM_{2.5}$, also referred to as fine particles, has the ability to deeply penetrate the lungs and even reach the bloodstream, resulting in substantial health hazards. The primary sources of $PM_{2.5}$ consist of vehicle emissions, industrial operations, wildfires, and the secondary generation resulting from gases like sulphur dioxide and nitrogen oxides.

3.4.3 PM_{10}

Particles with a diameter smaller than or equal to 10 micrometres (µm). These particles are of a size that allows them to be breathed into the respiratory system and can consist of dust, pollen, mould spores, and bigger aerosols.

Particulate pollution can make people sick in a range of ways, depending on how much they are exposed to them. The most common signs of respiratory disease caused by air pollution are wheezing, coughing, dry mouth, and being unable to do certain things because of breathing problems. (Bentayeb et al., 2013; Marie-Thérèse Guillam et al., 2013; Gao et al., 2014)

People who are exposed to the current levels of PM in the air may have a much shorter life expectancy. The main reason for the drop in life expectancy is the rise in deaths from heart disease and lung cancer. (Zhou et al., 2014; Pelucchi et al., 2009; Jerrett et al., 2009)

3.4.4 Nitrogen oxides (NO_x)

Nitrogen oxides (NOx) are a collection of chemically reactive gases made up of nitrogen and oxygen molecules, with nitric oxide (NO) and nitrogen dioxide (NO_2) being the main components. These gases are generated during combustion processes characterised by elevated temperatures, such as those found in cars, power plants, industrial facilities, and biomass burning.

Nitrogen oxides are a major pollutant in the air that may make getting respiratory illnesses more likely (Chen et al., 2007). They mostly come from cars and trucks, so they are air pollution caused by traffic. They irritate the lungs deeply and can cause pulmonary edema if breathed in in large amounts. In general, they are not as dangerous as O_3, but NO_2 can clearly be harmful. Nitrogen oxide levels between 0.2 and 0.6 ppm are safe for people. (Hesterberg et al., 2009)

3.4.5 Sulphur dioxide (SO_2)

Sulphur dioxide (SO_2) is a colourless gas with a strong odour, made up of one sulphur atom and two oxygen atoms. It is mostly released into the atmosphere after the combustion of sulphur-containing fossil fuels like coal and oil in industrial operations and power plants. Furthermore, volcanic eruptions and natural sources like wildfires can emit large volumes of sulphur dioxide into the atmosphere.

In the atmosphere, sulphur dioxide can react to generate sulfuric acid (H2SO4) and other sulphate aerosols, which contribute to the development of acid rain and particulate matter. When people are exposed to high levels of SO_2, their main health worries are respiratory irritation and dysfunction, as well as heart disease that is already getting worse. The upper lungs are where most of the SO_2 is taken in. Because it is a sensory irritant, it can make people cough and make snot come out of their noses. Bronchitis could be very common in people who live in industrialised areas where SO_2 is present in the air, even at low levels (<1 ppm).

The Environmental Protection Agency (EPA) of the United States says that the yearly limit for SO_2 is 0.03 parts per million. Because it is easily dissolved in water, SO_2 causes acid rain and makes soils more acidic. This is because SO_2 lowers the amount of oxygen in the water, which kills sea plants and animals. $SO2$ can hurt the eyes (by making the cornea cloudy and lacrimal glands dry out), the skin (by making it red and blistery), and the respiratory systems.

3.4.6 Carbon monoxide (CO)

Carbon monoxide (CO) is a colourless, odourless, and tasteless gas made up of one carbon atom and one oxygen atom. It is formed by the incomplete combustion of carbon-containing fuels like petrol, natural gas, coal, and wood. Vehicle exhaust, industrial activities, domestic heating systems, and wildfires all emit carbon monoxide.`

Carbon monoxide is a strong atmospheric pollutant that harms both human health and the environment. It has a high affinity for haemoglobin in red blood cells, resulting in the creation of carboxyhaemoglobin, reducing the blood's ability to deliver oxygen to tissues. Inhaling high levels of carbon monoxide can result in headaches, dizziness, nausea, confusion, and, in severe cases, coma and death.

Carbon monoxide exposure is especially deadly in enclosed or poorly ventilated places, such as indoor environments and car interiors with combustion sources. Children, the elderly, and people with pre-existing health issues are more vulnerable to the negative consequences of carbon monoxide exposure.

(Allred et al., 1989) The data showed that premature angina can happen in these situations, but it's still not clear how likely it is that ventricular arrhythmias will happen. So, lowering the CO level in the air can lower the risk of myocardial attack in people who are already at a higher risk.

3.4.7 Ozone (O3)

3.4.7.1 Stratospheric Ozone

The ozone layer is made up mostly of stratospheric ozone, which is found between 10 and 50 kilometres above the Earth's surface. It protects life on Earth by absorbing the bulk of the sun's harmful ultraviolet (UV) radiation and prevents it from reaching the planet's surface. Stratospheric ozone depletion, mostly caused by human-produced chlorofluorocarbons (CFCs) and other ozone-depleting compounds, has raised worries about increasing UV radiation reaching the Earth's surface and its negative impact on human health, ecosystems, and climate.

3.4.7.2 Tropospheric Ozone

Tropospheric ozone is created closer to the Earth's surface, in the lower atmosphere or troposphere, by complex chemical reactions involving precursor pollutants including nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. Tropospheric ozone is a toxic air pollutant and a major component of smog, causing poor air quality, respiratory issues, and environmental damage. It can irritate the respiratory system, worsen asthma and other respiratory illnesses, impair lung function, and cause cardiovascular issues. Furthermore, tropospheric ozone can harm crops, forests, and ecosystems, reducing agricultural production and diversity.

Human activities such as transportation, industrial processes, agriculture, and fossil fuel combustion all contribute significantly to the creation of tropospheric ozone as precursor pollutants. Climate change, urbanisation, and population expansion can also have an impact on ozone levels and air quality.

The chemical name for O_3 is O_3. It is a colourless gas that makes up most of the atmosphere.It is thought that these routes start the spreading of lipid radicals and the self-oxidation of proteins and cell membranes. It also raises the chance of skin keratinocytes getting DNA harm, which makes the cells less effective.(McCarthy et al., 2013) O_3 has many harmful effects on people and test animals when it is present in large amounts in many cities.(Lippmann, 1989) Changes in shape, function, immunity, and biochemistry are some of these changes. Because it doesn't dissolve easily in water, a lot of the oxygen that is breathed in goes deep into the lungs. However, the nasopharynx of sleeping rats and humans blocks about 17% and 40% of its response, respectively.(Hatch et al., 1994;Gerrity et al., 1988) In terms of the environment, O_3 can stop trees from taking in carbon, which can lead to cutting down trees, which could affect the world's food stability in the long run.(Fares et al., 2013;Wilkinson et al., 2011)

3.4.8 Lead

Pb, also written as plumb, is a heavy metal that is poisonous and is used in many fields.(Habibollah Nemati Karimooy et al., 2010) Pollution with lead can come from both inside and outside sources. It comes from cars, especially ones that use gas that contains Pb tetraethyl. Pb also gets into the environment from smelters, battery plants, watering wells, and sewers.(Habibollah Nemati Karimooy et al., 2010) Pollution in the surroundings may be a cause of Pb exposure, as shown by the high levels of Pb in the blood of traffic police officers.(Manuela et al., 2012) Children and foetuses are very sensitive to even small amounts of Pb.(Farhat et al., 2013) Pb builds up in blood, bones, and soft tissues of the body. Pb can also hurt the kidneys, brain, nervous system, and other systems because it is not easily flushed out of the body. (*Comparison of Blood Lead Levels in 1-7 Year Old Children With and Without Seizure*, 2005)

How much PB is taken in by the lungs varies on the size and number of particles. About 90% of the Pb particles in the air that people breathe in are small enough to be kept. Toxic effects happen when retained Pb is taken through lungs. Pollutants like lead are very bad for your brain, and babies and kids are especially at risk. When kids are exposed to PB, it can lead to mental retardation, learning problems, memory loss, restlessness, and bad behaviour.(Lidsky & Schneider, 2006;Lidsky & Schneider, 2003)Because of this, lowering the amount of Pb in the air is very important.(Shannon et al., 2005)Pb poisoning is often long-lasting and doesn't show any clear signs.(Kianoush et al., 2011) Pb is harmful to the brain system more than any other part of the body. It can affect the cardiovascular, renal, and reproductive systems, among others.(*Clinical, Toxicological, Biochemical, and Hematologic Parameters in Lead Exposed Workers of a Car Battery Industry*, 2013) By blocking N-methyl-D-aspartate receptors, Pb changes the way that second messenger systems inside cells normally work.

3.5 Changes in air quality in Poland and eastern Europe during the covid-19 lockdown

The main goal of this project is to look into how the COVID-19 lockdown changed the air quality in Poland. The values of $PM_{2.5}$, PM10, NO2, and SO2 were compared to those from 2018 and 2019. The data came from automatic air quality tracking stations in the country's biggest cities. We also looked at the axial aerosol optical depth (AOD) and tropospheric NO2 amounts that were found with the Moderate Resolution Imaging Spectrometer (MODIS) and the Ozone Monitoring Instrument (OMI)(Filonchyk et al., 2021).The results could help with future efforts to protect the environment, after the outbreak, so that the area always has the best air quality.

3.6 Air pollutant monitoring using ground-based techniques

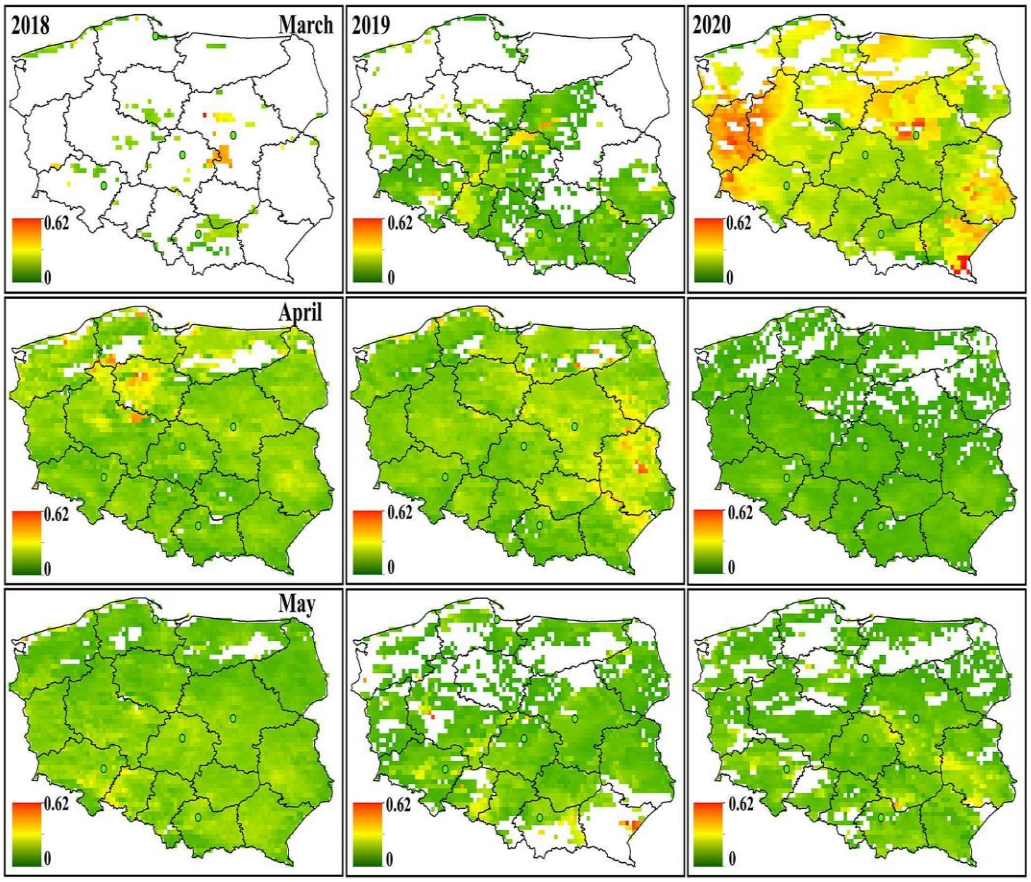
Based on hourly values of $PM_{2.5}$, PM10, SO_2, and NO_2 collected from the Chief Inspectorate for Environmental Protection (Evertop Sp. z o.o., n.d.), data on surface concentrations of air pollutants were derived. The five biggest cities in the nation, Warsaw, Wroclaw, Lodz, Krakow, and Gdansk, are home to automated air quality monitoring stations from which hourly data on mass concentrations of the four pollutants were obtained. Using hourly data averaging, daily mean concentrations of each contaminant were determined. 28 automated air quality monitoring stations spread across several geographies—urban, suburban, rural, and industrial zones—provided the data.

3.7 Observations based on satellite data

The Moderate Resolution Imaging Spectrometer (MODIS), a component of NASA's Earth Observing System, is located on board the Terra and Aqua satellites and offers high-resolution, continuous aerosol monitoring. This study will employ data acquired from the Aqua satellite since it crosses the Equator at 1:30 p.m., whereas the Aura satellite crosses at 1:45 p.m. Atmosphere Archive and Distribution System Distributed Active Archive Centre (LAADS DAAC) provided Level 1 and MODIS Level 2 Collection 6.1 aerosol products with a spatial resolution of 10 km. In order to integrate both Dark Target (over dark surfaces) and Deep Blue (over lighter surfaces) AOD retrievals, this work used the MODIS combined Dark Target and Deep Blue AOD retrievals technique, which uses high-quality AOD retrievals (Hsu et al., 2013). According to Remer et al. (2005), the anticipated error over land is $\pm 0.05 \pm 0.15 \times \text{AOD}$, while over the ocean is $\pm 0.03 \pm 0.05 \times \text{AOD}$.

OMI (Ozone Monitoring Instrument) observations aboard the NASA Aura satellite (Levelt et al., 2006)may be a more effective method for conducting a regional investigation of tropospheric NO2 concentration since this instrument combines relatively high spatial and temporal data resolution. The OMI device measures the solar radiation scattered by the Earth's atmosphere in the visible and ultraviolet regions of the spectrum with a spatial resolution of 13 × 24 km2 in nadir and a spectral resolution of approximately 0.5 nm. The full (horizontal) scanning takes place in less than 24 hours (in high latitudes, OMI may perform multiple measurements over the same area during daylight hours due to overlapping of neighbouring satellite orbits). The spectral range of 405–465 nm is used to assess the NO_2 level (Boersma et al., 2007). Direct measurement of the NO_2 concentration in the atmosphere's slant column is possible. The NASA GES DISC archive contains level-3 daily OMI tropospheric NO_2 product with a 0.25° spatial resolution, which is used in this work.

Figure 1:Spatial distribution of MODIS AOD at 550 nm during March, April and May from 2018 to 2020.

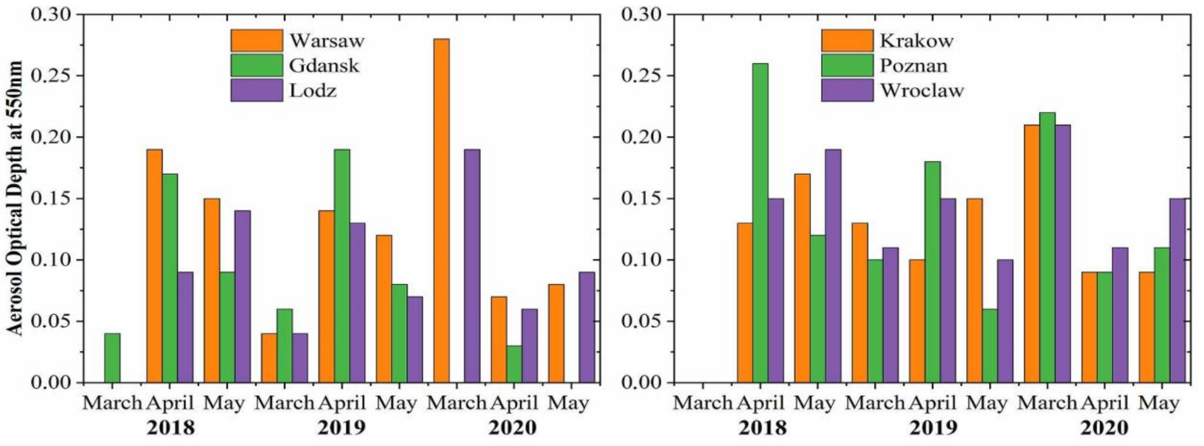


Source: Filonchyk et al., 2021

It is important to note that, in comparison to other parts of the world, the country's quantitative AOD change characteristics during the period prior to and during the pandemic range widely (from 0 to 0.62) over the majority of its territory, indicating a low aerosol loading and consequently lower atmospheric turbidity (Filonchyk & Peterson, 2020;Kanniah et al., 2020;Nichol et al., 2020). Images from March 2018, 2019, and 2020 may be compared to show that, in 2020, AOD levels increased to 0.3–0.62 throughout the majority of the country, compared to the prior years. However, compared to 2018 and 2019, a notable AOD decline of about −23% and −18% is seen in April and May. This could be connected to the imposition of quarantine laws, which are linked to a decline in economic activity, the closure of plants that use a lot of energy, the suspension of air and train traffic, and a reduction in power production. All of these things reduce anthropogenic emissions into the atmosphere, which in turn lowers aerosol loading (Alshayef et al., 2019). Restrictive measures implemented in other EU nations (Menut et al., 2020;Zoran et al., 2020)may have contributed to the decrease in air pollution during the partial shutdown period by reducing the transit of pollutants to neighbouring regions. However, the increased AOD foci that were seen in April and May of 2020 could be connected to certain agricultural activities, which are linked to emissions from burning biomass and peat as well as dust (Ahmed et al., 2020) as a result of people remaining at home.

In addition to the significant spatial-temporal variability in AOD fluctuations at the regional scale, a study of the variation of aerosol ratios in the nation's main cities was conducted (Fig. 2). The findings indicate that, for the years 2018, 2019, and 2020, respectively, AOD was lower in April and May in comparison to Warsaw (0.19, 0.14, 0.07 and 0.15, 0.12, 0.08), Gdansk (0.17, 0.19, 0.03 and 0.09, 0.08), Lodz (0.09, 0.13, 0.03 and 0.14, 0.07, 0.09), Krakow (0.13, 0.1, 0.09 and 0.17, 0.15, 0.09), Poznan (0.26, 0.18, 0.09 and 0.12, 0.06, 0.11), and Wroclaw (0.15, 0.15, 0.11 and 0.19, 0.1, 0.15). In March, practically all cities had no AOD data available, and in May, Gdansk and Poznan had none. These cities are distinguished by a high level of industrial activity and anthropogenic activities. In comparison to prior years, the data shown in Table 1 indicate an AOD drop in the range of −10% (Krakow) to −84.2% (Gdansk) in April and −8.3% (Poznan) to −47.1% (Krakow) in May. The complete halt of human activity intended to stop the spread of COVID-19 is responsible for the notable AOD decline in every location (JARYNOWSKI et al., 2020). In other parts of the world, where the AOD decreased during the partial lockdown, similar outcomes were seen.

Figure 2: The monthly mean AOD at 550 nm over six large cities in Poland during March–May 2018–2020.



Source: Filonchyk et al., 2021

Table 1: Relative percentage change in AOD at 550 nm during March–May 2018–2020. (where: 2020/2019 is ratio of 2020 vs 2019, 2020/2018 is ratio of 2020 vs 2018).

	2018/2020			**2019/2020**		
	March	**April**	**May**	**March**	**April**	**May**
Warsaw	–	−63.2	−46.7	60	−50	−33.3
Gdansk	–	−82.4	–	–	−84.2	–
Lodz	–	−33.3	−35.7	37.5	−53.8	28.6
Krakow	–	−30.8	−47.1	61.5	−10	−40
Poznan	–	−65.4	−8.3	120	−50	–

Wroclaw	–	−26.7	−21.1	90.9	−26.7	50

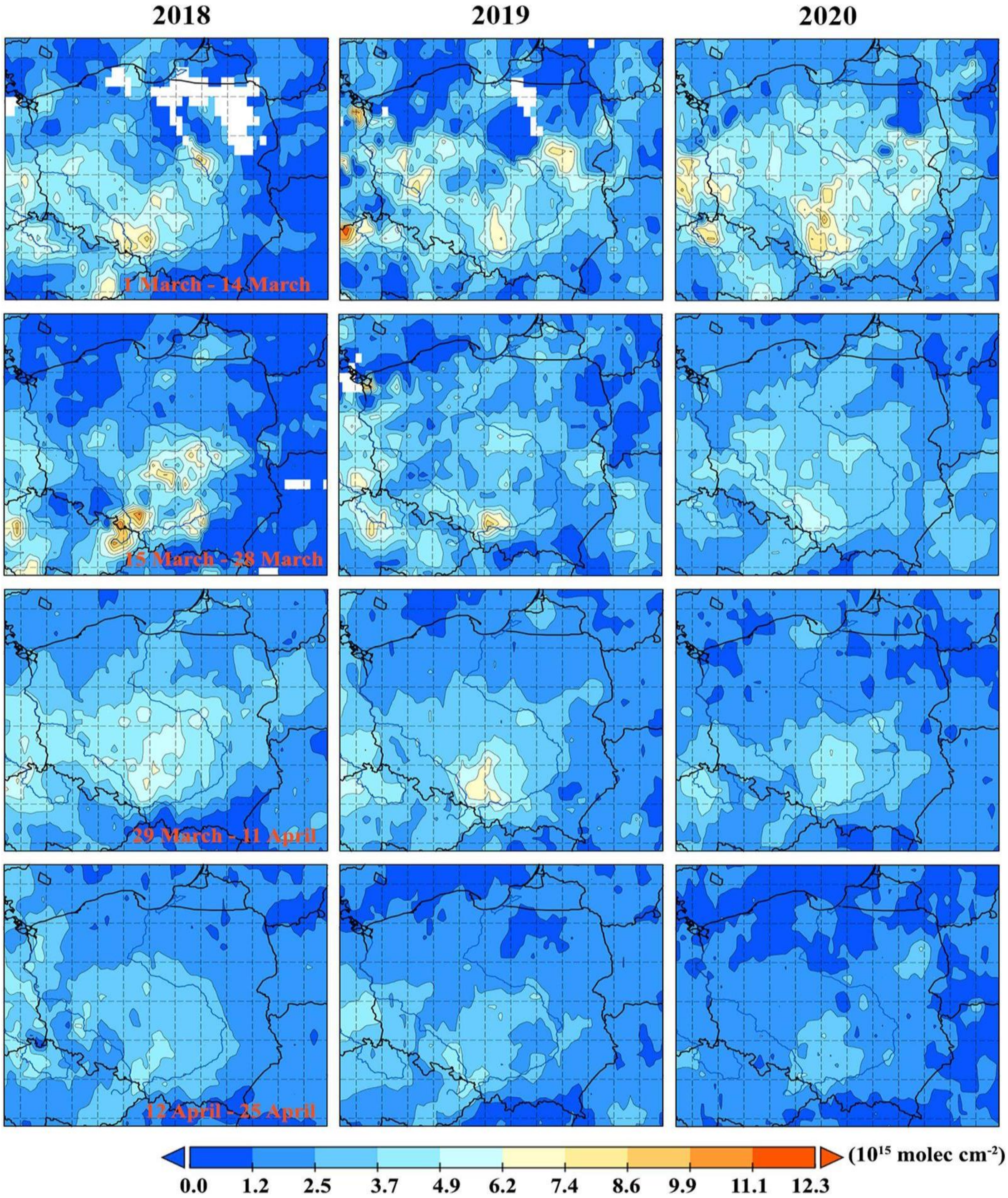
Source: Filonchyk et al., 2021

3.8 Detection and analysis of NO_2 using satellite technology.

Among the most dangerous components of smog are nitrogen oxides. In comparison to sulphur dioxide or carbon monoxide, they are far more dangerous. Particularly hazardous to human health is nitrogen dioxide (NO_2), which is most frequently produced when nitrogen oxide (NO) oxidises in the atmosphere (Kamarehie et al., 2017). In the cities with the highest volume of motor vehicle traffic, this gas is the primary cause of photochemical smog generation. Nitrogen dioxide is easily reacted with chemicals. Burning fossil fuels in motor vehicles, power plants, and manufacturing facilities is the primary human cause of NO_2 creation (Li et al., 2018). Large Polish cities (Krakow, Warsaw, and Wroclaw) have greater air concentrations of NO_2 than other cities in the nation; this is correlated with a high volume of motor vehicle traffic.

The tropospheric NO_2 column measured by the OMI satellite sensor is displayed in Figure 3. The statistics were averaged for a fortnight period in 2020, for the same fortnight period in 2018 and 2019, and before (Period 1: 1–14 March) and during (Period 2: 15–25 March, Period 3: 26 March - 11 April, and Period 4: 12 April - 25 April) lockdown measures. NO_2 is a measure of the overall activity associated with emissions across the nation's regions. In comparison to the same time in 2018 and 2019, the recorded tropospheric NO_2 exhibited a decline in levels throughout the whole territory of Poland starting in mid-March (time 2) and ending in April (Period 3 and Period 4) 2020.

Figure 3: Spatial distribution of tropospheric OMI NO_2 during four periods from 2018 to 2020.



Source: Filonchyk et al., 2021

Significant drops in NO_2 content were seen in several major Polish cities, including Gdansk, Poznan, Wroclaw, Lodz, Krakow, and Warsaw. It is mostly linked to a decrease in traffic and the number of motor vehicles on the nation's roadways. The General Directorate for National Roads and Motorways said at the end of March that there were 25–54% less motor vehicles on the road than there were during the same period in 2019.

In general, Period 1 NO_2 values in Poland were 15% and 13% higher than those in 2019 and 2018. Comparing time 2 to the same time in 2018 and 2019, there was a reduction in NO_2 of −25% and −19%, respectively, following the deployment of lockdown measures. In comparison to the preceding years, there was also a noticeable decrease for Periods 3 and 4 across the nation, of −16%, −18%, and −13%, −10%, respectively. (Menut et al., 2020) also observed similar results, reporting a −27% decrease in NO_2 content in March 2020 compared to the same time in 2019. Almost all of the nation's major cities saw greater tropospheric NO_2 concentrations in Period 1 compared to the same periods in 2019 and 2018. In the second period, there was an estimated decrease of −45.8%, −18%, and −16.2% in Krakow, Gdansk, and Lodz, and a minor decrease of −5.1% and −3.5% in Warsaw and Wroclaw, respectively.

Comparing Periods 3 and 4 to the same time in 2019, a notable decrease was seen in Poznan, Krakow, Wroclaw, and Gdansk of −100% and −60%, −35.6% and −13.2%, −30% and −13%, −25.8% and −18.8% (see Table 2). This is a result of the partial lockdown's traffic restrictions. As previously noted, the primary cause of these large decreases is the decline in motor vehicle traffic. Every period saw the same degree of anthropogenic activity as the years before. Data on thermal hotspots and active fires taken from the Visible Infrared Imaging Radiometer Suite (VIIRS) were utilised as evidence for this claim. Hotspots are identified by VIIRS, and information regarding burning on very small areas of land is provided by a spatial resolution of 375 m (Schroeder et al., 2014). According to the data, there were essentially the same number of fire locations nationwide in March and April over the previous three years. The number of fireplaces was 1546 in 2018, 1486 in 2019, and 1788 in 2020. This demonstrates that human activity remained constant during the lockdown, and it also demonstrates that those who chose to remain at home could still engage in agricultural activities, which is probably what caused the rise in fire spots.

Table 2:Relative percentage change in OMI NO_2 during 2018–2020. (where: 2020/2019 is the ratio of 2020 vs 2019, 2020/2018 is the ratio of 2020 vs 2018).

Cities	**2020 vs 2019**				**2020 vs 2018**			
	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 1**	**Period 2**	**Period 3**	**Period 4**
Warsaw	5.8	−5.1	9.2	−110.5	−30.8	−62.2	2.1	−78.9
Gdansk	−76.5	−18	−25.8	−18.8	−82.4	−13	−35.5	−18.8
Lodz	50.6	−16.2	−4.8	−25	19	−161.3	−45.2	−7.1
Krakow	−8.3	−45.8	−35.6	−13.2	6.7	−10.4	−37.8	−7.4
Poznan	26.4	39.5	−100	−60	26.4	11.6	−186.7	−153.3
Wroclaw	−2.8	−3.5	−30	−13	3.9	12.3	−70	−4.3

Source: Filonchyk et al., 2021

3.9 Concentrations of air contaminants at ground level

The study involved the use of 28 automated air quality monitoring stations to measure the quantities of various pollutants, including $PM_{2.5}$, PM10, NO_2, and SO_2. It is important to remember, too, that many stations only keep an eye on a portion of these contaminants. As a result, in five cities, the concentrations of $PM_{2.5}$, PM10, NO_2, and SO_2 are tracked at 11 stations, 23 stations, and 12 stations, respectively. The results of the investigation might be used to assess how various sources contributed to the overall drop or rise in pollution during the COVID-19 shutdown. The daily mean concentrations of $PM_{2.5}$, PM10, NO_2, and SO_2 in Wroclaw, Lodz, Krakow, Warsaw, and Gdansk are displayed in Table 3. A comparison between the same period in 2019 and 2018 and the period from March to May 2020 was also conducted.

Table 3: Average daily concentration of $PM_{2.5}$, PM_{10}, NO_2 and SO_2 (µg/m3) in Wroclaw, Lodz, Krakow, Warsaw and Gdansk during March–May 2018–2020.

Cities	l	**2018**			**2019**			**2020**			**Relative % Change**					
											2020 vs 2018			**2020 vs 2019**		
		March	**April**	**May**	**March**	**April**	**May**	**March**	**April**	**May**	**March**	**April**	**May**	**March**	**April**	**May**
Wroclaw	PM2.5	37.9	19.7	15.3	18.8	21.3	13.3	20.9	16	10.5	−45	−18.9	−31.2	11.1	−24.7	−21.1
	PM10	43.1	31	23.3	28	33.5	19.2	26.7	26.8	14.1	−37.9	−13.5	−39.6	−4.3	−20.1	−26.9

	NO2	32.6	26.9	24.6	24.1	26	23.3	24.1	23.4	22	−25.9	−12.8	−10.6	0.3	−9.9	−5.3
	SO2	4.9	2.6	2.4	3.9	5.2	2.7	5.1	5.8	3.2	4.3	127.3	33.7	29.8	11.1	18.5
Lodz	PM2.5	32.9	16.6	12.2	18.5	19.2	12.9	20.8	14.2	10.2	−36.9	−14.7	−16.3	12.5	−26.4	−20.7
	PM10	47.5	33.1	26.9	29.6	40.5	22.7	35.9	34.6	20.8	−24.5	4.6	−22.7	21	−14.5	−8.5
	NO2	32.6	26.9	24.6	20.7	31.9	22.3	25.4	24.2	20.4	−22	−10.1	−17	22.6	−24.2	−8.5
	SO2	9.6	3.8	2.3	5.2	3.8	2.6	4.6	3.9	2.7	−52.4	2.1	17.6	−13	3.7	1.2
Krakow	PM2.5	52.7	24.4	19.1	26.7	24.4	15.7	27.3	21.7	14.4	−48.2	−11.2	−24.8	2.3	−11.1	−8.7
	PM10	69.8	41	29.9	38.6	36.3	23.3	36.7	33.2	21	−47.3	−19	−29.8	−4.8	−8.6	−9.9
	NO2	47.4	44.	38	40.6	40.	35	34.8	31.	28	−26.	−2	−2	−1	−20	−20

			4			2	.1		9		6	8.2	6.3	4.2	.7	.2
	SO2	11.3	4.8	5.1	7.2	5.6	3.7	5.3	5	3.6	−53.5	3.4	−28.8	−26.7	−11.2	−1.4
Warsaw	PM2.5	35.7	20	13.3	19.8	21	14	24.5	16.7	12.3	−31.5	−16.4	−7.8	23.4	−20.4	−12.4
	PM10	47.5	35.6	29.3	28.4	36.2	21.9	33.3	31.9	19.7	−29.9	−10.4	−32.9	17.2	−11.8	−9.9
	NO2	37.7	37.7	30.2	33.3	29.6	30.6	28.3	27.1	24.6	−25.1	−28.2	−18.7	−15.2	−8.6	−19.6
	SO2	–	–	–	3.7	2.4	0.9	4.3	3	2.7	–	–	–	16	27.7	190.8
Gdansk	PM2.5	21.9	16.9	13.7	–	–	–	24.4	12.5	9.4	11.4	−25.6	−31.4	–	–	–
	PM10	25.5	22	18.8	14.2	28.2	18.7	23.4	18.6	12.8	−8.4	−15.2	−31.5	64.2	−33.9	−31.5
	NO2	19.9	17.1	13.8	12.8	17.1	12.2	16.3	11.7	8.4	−18.4	−31.7	−38.7	27.3	−31.7	−30.8

	SO2	3.9	4.5	2.7	2.3	2.5	1.9	4.4	3.7	2.6	12.8	−18.3	−4.5	86.4	49.6	37.6

Source: Filonchyk et al., 2021

Pollutant concentrations in 2020 were generally lower than in 2018, however in contrast to 2019, certain cities saw a rise in pollutants in 2020, particularly in March (Table 3), when lockdown measures had not yet been completely implemented. All pollutants, with the exception of SO_2, were significantly reduced in April and May compared to prior years. In comparison to 2018 and 2019, the largest decreases in $PM_{2.5}$ were seen in Wroclaw in April (−18.9% and −24.7%) and May (−31.2% and −21.1%); Lodz in April (−14.7% and −26.4%) and May (−16.3% and −20.7%). However, other cities also saw notable drops in $PM_{2.5}$ concentrations in April compared to the same month in 2019 of −20.4% (Warsaw) and −11.1% (Krakow).

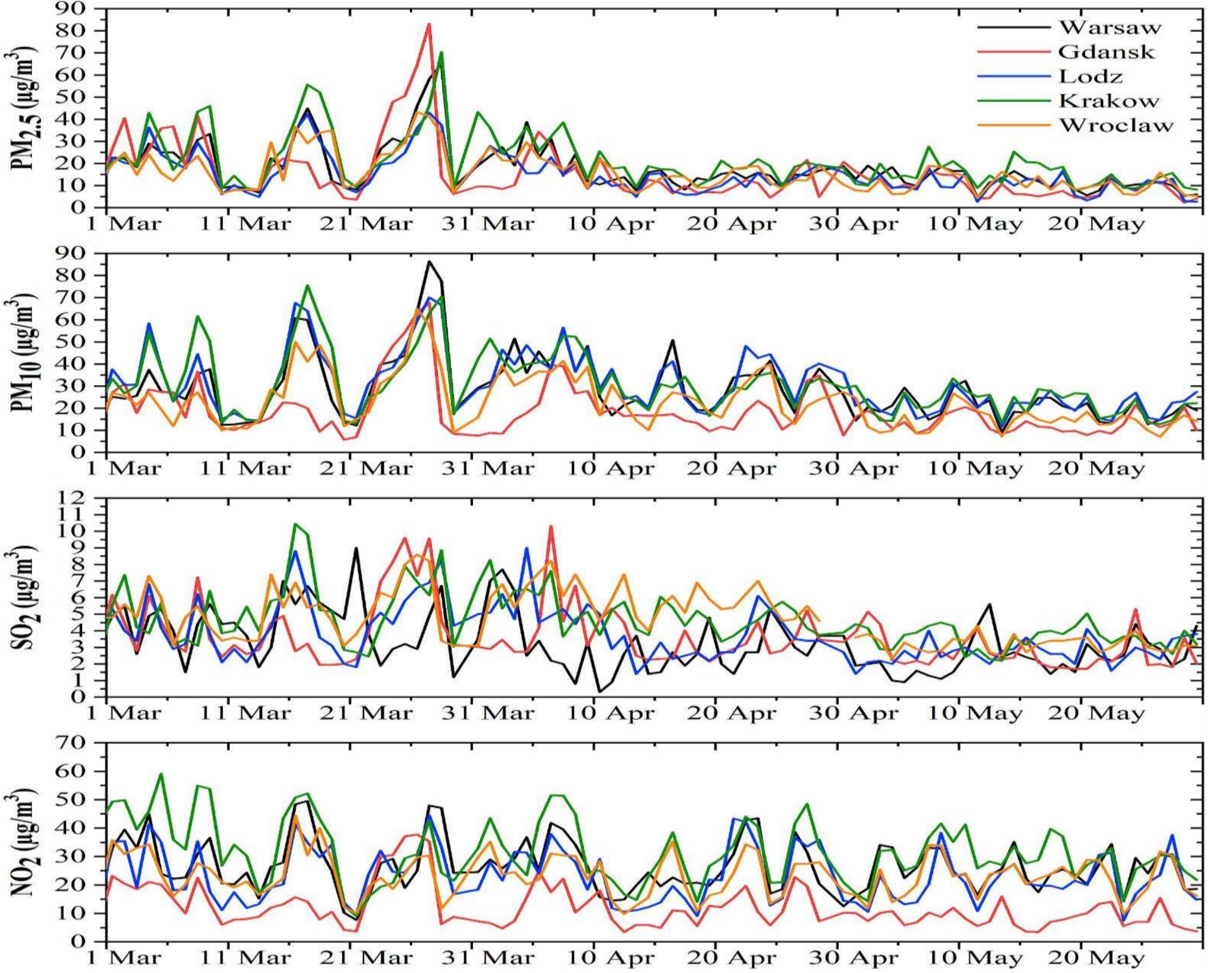
Even while $PM_{2.5}$ concentrations were significantly lower in many places, they were still higher than the WHO's recommended levels (10 µg/m3). The levels of PM10 were also higher than the WHO's recommended threshold of 20 µg/m3. In contrast to other years, there was a notable decrease in April and May across all cities. Specifically, compared to 2019, PM10 concentrations in Gdansk decreased by −33.9% and −31.5% in April and March, and in Wroclaw by −20.1% and −26.9%. In comparison to 2019, there was an even bigger decrease in NO_2 levels, which in April and May were lowest in Gdansk by −31.7% and −30.8% and lowest in Krakow by −20.7% and −20.2%. The tropospheric NO_2 concentration data from the OMI satellite (Fig. 3) and the surface NO_2 concentration data are mostly equivalent.

As previously stated, the primary cause of the decline in $PM_{2.5}$, PM10, and NO_2 levels was a notable drop in both domestic and international traffic, which in turn reduced the use of coal and crude oil, all of which had a major impact on air quality. Coronavirus halted the growth of international industry and transportation and shuttered educational institutions, museums, theatres, and shopping centres (JARYNOWSKI et al., 2020). Household power consumption rose as more individuals stayed at home, while total power consumption decreased by 20% from 2019 due to the production halts in several industry sectors. It is noteworthy that coal and crude oil were Poland's primary sources of raw materials for the generation of electricity in 2018. 32.8

million tonnes of oil and 50.5 million tonnes of coal equivalent were used by the nation (BP, 2019). PSE-Operator reports that during the epidemic, coal's share of the electricity output was down by 24 percent. However, it is important to note that the decrease in pollutants will only last temporarily. Electric power plant chimneys will begin to spew smoke after the epidemic is over.

Nearly all of the country's sulphur dioxide emissions come from stationary sources, where active fuel burning—mostly coal—is the primary source of emissions. Only around 2.6% of the country's emissions are attributed to SO_2 emissions during production, which are linked to the processing of crude oil, coke, and sulfuric acid manufacturing. Due to the low sulphur content of the liquid gasoline they use, motor vehicles typically only contribute 0.0005% of the nation's sulphur dioxide emissions. The concentration of SO_2 in the air rose relative to other pollutants, possibly as a result of certain manufacturing facilities carrying on with operations even during the quarantine. In comparison to March, April, and May of 2019, the biggest increases were observed in Gdansk (86.4%, 49.6%, and 37.6%), and Warsaw (16%, 27.7%, and 190.8%, respectively. However, there was a decrease in SO_2 concentrations in Krakow, which is linked to a decline in industrial activity. It is important to note that it is airborne, widely soluble in water, and spends around two weeks in the atmosphere. Because a cloud containing gas may be carried geographically, suggesting that pollution sources and areas may differ, SO_2 pollution is therefore of regional relevance.

Figure 4: shows daily change of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 concentrations before and during a partial lockdown. Starting from the late March, sharp reduction of $PM_{2.5}$, PM_{10} and SO_2 concentrations was registered in all the cities under study.



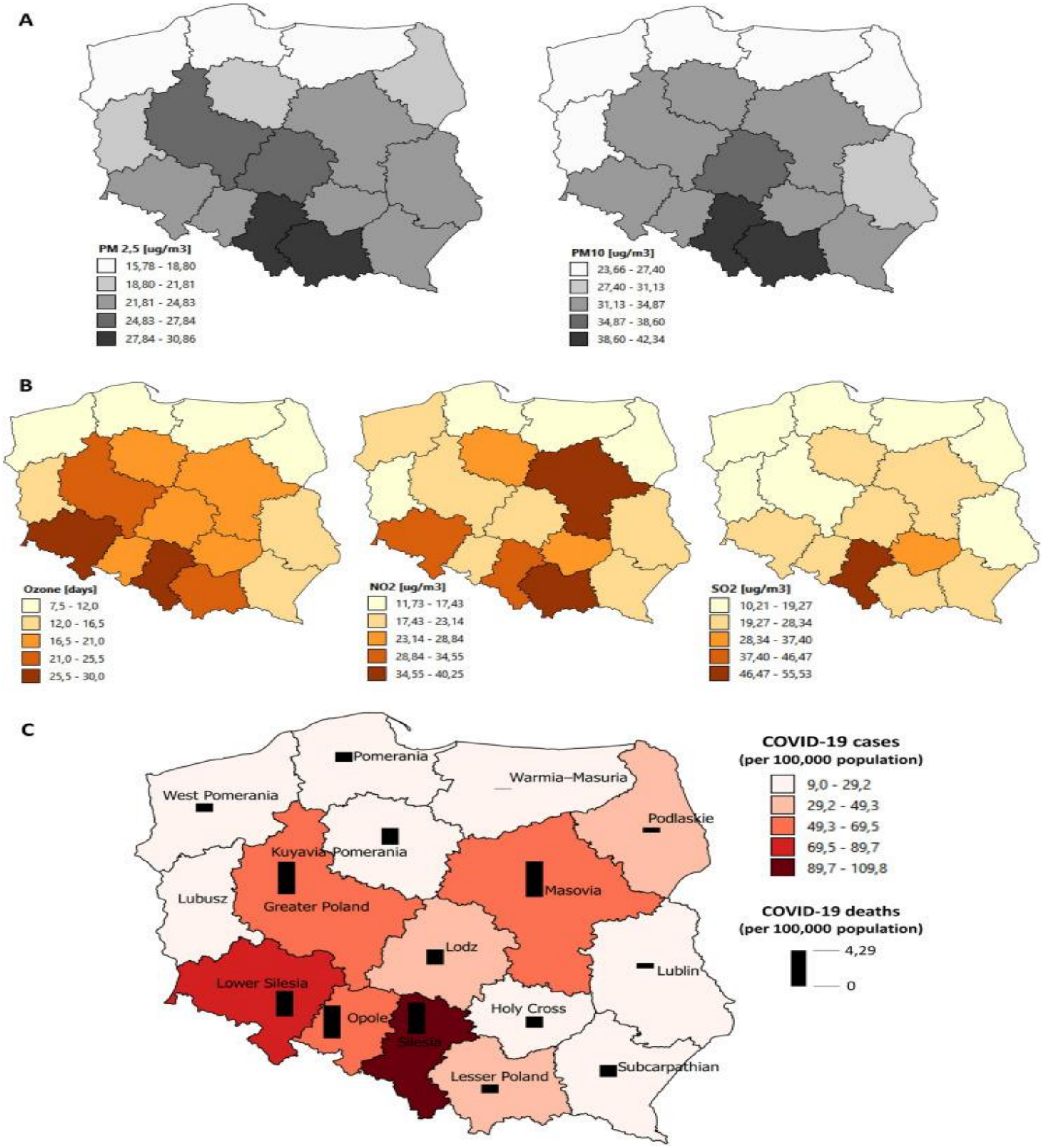
Source: (Filonchyk et al., 2021)

It is important to note that while NO_2 concentrations were lower than in prior years, the reduction in pollutant concentrations both before and during shutdown was not as great as that of other pollutants. However, as the picture illustrates, every pollutant exhibits a distinct weekly fluctuation, with maxima that align with the weekends. This might be connected to the rise in motor vehicle traffic brought on by people actively relocating from cities to the countryside to relax. These findings highlight the possibility that stringent regulations meant to stop the spread of COVID-19 might be linked to a substantial decrease in pollution emissions.

3.10 Influence of air quality on covid-19 morbidity and mortality rates

The global pandemic of coronavirus illness (COVID-19) is impacting people differently. The world's most polluted regions registered one of the greatest numbers of instances. Cardiovascular, respiratory, and diabetes are risk factors for severe COVID-19. It is well recognised that prolonged exposure to air pollution may exacerbate the same condition. The purpose of the study was to ascertain if average long-term exposure to air pollution is linked to a higher incidence of COVID-19 cases and fatalities in Poland. Between March 4, 2020, and May 15, 2020, the total number of COVID-19 cases and fatalities for every voivodeship (the primary administrative level of jurisdictions) in Poland were tallied. Long-term exposure to the primary air pollutants—$PM_{2.5}$, PM10, NO_2, SO_2, and O_3—at the voivodeship level was determined using official data released by the Chief Inspectorate of Environmental Protection. The data was averaged from 2013 to 2018. COVID-19 cases (per 100,000 population) and yearly average concentrations of $PM_{2.5}$ (R2 = 0.367, p = 0.016), PM10 (R2 = 0.415, p = 0.009), SO_2 (R2 = 0.489, p = 0.003), and O_3 (R2 = 0.537, p = 0.0018) were shown to be statistically significantly correlated. Additionally, yearly average concentrations of $PM_{2.5}$ (R2 = 0.290, p = 0.038), NO_2 (R2 = 0.319, p = 0.028), and O_3 (R2 = 0.452, p = 0.006) were linked to COVID-19 fatalities (per 100,000 population). Extended periods of exposure to air pollution, including $PM_{2.5}$, PM10, SO_2, NO_2, and O_3, appear to be critical factors in the occurrence and death of COVID-19. Prolonged exposure to air pollution may impair the prognosis of individuals with SARS-CoV-2 infections, increase susceptibility to the virus, and intensify the infection. The study offers broad and potentially universal tendencies. Data on comorbidities, socioeconomic factors, long-term exposure to air pollution, and COVID-19 cases and deaths at lower administrative levels of jurisdiction (community or at least district level) must all be considered in detailed analyses of the phenomenon specific to a given region.(Semczuk-Kaczmarek et al., 2021)

Figure 5: Summary of the average concentration of air pollution, COVID-19 cases, and death in voivodeships in Poland (A concentration of $PM_{2.5}$; PM_{10}; B concentrations of O_3, NO_2, SO_2; C, COVID-19 cases and death per 100,000 population)



Source: (Semczuk-Kaczmarek et al., 2021)

3.11 The impact of covid-19 restrictions on air pollution levels in urban areas with high volumes of vehicle traffic in Poland

People have changed what they do because of the SARS-CoV-2 epidemic in the first half of 2020. For example, people are keeping at least 1.5 m between each other, public places like high schools, offices, and other schools are closed, and people are staying away from public meetings. As a result, the whole world is locked down.New studies from the past two years (Bar et al., 2021;Venter et al., 2020;Skirienė & Stasiškienė, 2021;Girdhar et al., 2020;Filonchyk et al., 2021) stress that the world level of air pollution has gone down because the coronavirus spread slowed down the economy. The air quality got a lot better when people stopped doing things that pollute it, mostly by lowering the amounts of nitrogen dioxide (NO_2) and particulate matter (PM; particles smaller than 2.5 μm). Nitrogen fumes, which are found in smog in cities, are known to be harmful to people. Any fossil fuel can be burned in cars, power plants, and factories, and NO_2 is released into the air (Li et al., 2018). NO_2, a substance that is made when nitrogen oxide (NO) breaks down in the air, is the main thing that causes photochemical smog in places with a lot of car traffic (Kamarehie et al.2017). More coal is used for heating in Polish towns than in Western European countries. Because of this, the release of NO_2 when coal burns should also be considered (Rogulski & Badyda, 2021). Ultrafine PM, which is made up of solid particles and liquid drops (aerosols), is released into the air by incomplete combustion processes at high temperatures, stack emission, and car emissions that don't come from the exhaust. NO_x and PM are both very small, so they can get deep into the lungs and do damage. Because of this, they are both very bad for people.By looking at air quality from space,(Bauwens et al., 2020) found that NO_2 pollution dropped by an average of 40% in Chinese towns and by 20–38% in the USA and Western Europe (Italy, Spain, France, and Germany) during the 2020 lockdown compared to the previous year.

(Girdhar et al., 2020) found that the average amounts of PM10 and PM2.5 dropped by 14% and 30%, respectively, in 44 towns in Northern China. The writers said that the lockdown had caused a drop in air pollution, which had saved a few percent of human lives by lowering the death rate from air pollution from 7.6 percent to 3.4% (*The Dramatic Impact of the Coronavirus Outbreak on Air Quality: Has It Saved as Much as It Has Killed so Far?*, 2020) (Isaifan, 2020). A study in China tracked the rate of smog growth over 60 years, from 1950–1955, to 2010–2015. The data showed that because of the national lockdown that started on January 23, 2020, and ended in March when production slowly got better, NO2 levels dropped by 70% in places where people were doing a lot of human-made activities (Fan et al., 2020). As Girdhar et al. (2021) pointed out, this short-term slowdown of human-made activities, mostly industries, gave China a chance to become more airtight. A study from the Barcelona Institute for Global Health (ISGlobal, www.isglobal.org) says that the amount of air pollution that about 84% of Europeans are exposed to is higher than what the World Health Organisation recommends. In Europe, the city of Madrid had the most early deaths caused by NO2 pollution, while Antwerp, Belgium had the second most. Third place went to Turin, Italy, and fourth place went to Paris. Warsaw has been mentioned as having the most deaths from NO2 in Poland. But when it comes to PM10 and PM2.5 pollution, Polish towns do much worse in the ISGlobal list. Brescia, Italy, is the most dirty city, and it was there that the most deaths from fine PM2.5 were reported. Warsaw came in at number 20, and Cracow was number 28.Many studies show that the lockdown in 2020 because of the SARS-CoV-2 pandemic made the air quality much better around the world. For example, in Europe (Filonchyk et al., 2021;Gama et al., 2021;Higham et al., 2020;Wiśniewski et al., 2021;Ródenas et al., 2022;Baldasano, 2020;Jakovljević et al., 2020;Bar et al., 2021;Mikulski et al., 2021), the USA (Bar et al. 2021), and Canada (Mashayekhi et al., 2021;Kutralam-Muniasamy et al., 2020;Xu et al., 2020;Bauwens et al., 2020) This short-term change in air quality is good for people's health because it lowers the risk of lung and other diseases. This saves a lot of lives, since about 7 million people die each year because of air pollution. Also, the lockdown in 2020 seemed to have made the air quality better on a local level, especially in towns that were pretty much shut down during the first coronavirus wave, with empty streets, traffic limits, and so on. Other European countries, including some that are close to Poland, have declared a state of emergency or put their countries on lockdown with stay-at-home orders in order to stop the spread of SARS-CoV-2. On March 16, 2020, lockdowns were put in place across the whole of the Czech and Slovak Republics and Lithuania. Universities, schools, and shops that weren't necessary were closed, as well as all event sites. It became harder to cross state lines. Because of the SARS-CoV-2 pandemic, Germany put limits in place on March 22, 2020, and the governments of the German federal states told people to stay home. In Ukraine, the emergency was announced on March 20, 2020. In Belarus, a national quarantine effort didn't start until March 30, 2020. People coming into Belarus from pandemic-affected countries had to put themselves in self-quarantine for 14 days starting on March 25. On April 4, the government stated that schools would have two extra weeks of spring break. In this study, we tried the idea that a local drop in the number of vehicles (usually passenger cars) on the road leads to a big drop in air pollution in cities. During the national lockdown and pandemic limits that lasted for almost two years, we were able to do this study to find out how lowering emissions from local traffic can lower the pollution levels in the air. The most important thing is the local air quality because it has the biggest and most direct effect on people's health, especially in the city's most crowded places.We picked two big cities in Poland, Warsaw and Cracow, which are in the middle of Europe, to test our theory. Three types of pollution (NO_x, PM_{10}, and $PM_{2.5}$) were measured at two air pollution tracking points and their step-by-step concentrations were looked at for 2020, when there was a lockdown, and for 2019, before the pandemic. Our study was also extended to 2021, a year when many limits were in place because of the pandemic. The data came from air pollution tracking stations in the middle of Warsaw and Cracow. These stations mostly watch out for road pollution. It was thought that NO_x levels showed emissions from moving vehicles' exhaust, and PM levels showed emissions that weren't from vehicles' exhaust. Some of the busiest cities in Poland are Warsaw and Cracow. However, compared to the previous years (2017–2019), 2020 has seen the biggest drop (~9%).

3.12 Sources and Methods

Warsaw is the capital city of Poland. It is in the middle of the country in Mazovia and is home to about 1.8 million people, which is a population density of about 3,470 people per km^2. Cracow is in southern Poland, on the Vistula River, where the Carpathian Mountains and the Polish Uplands meet. The city has about 767,000 people living in it, which means that there are about 2,370 people living in every square kilometre G.((n.d.). *Główny Urząd Statystyczny*.) Traffic pollution is the largest source of air pollution in the central parts of Warsaw. Low-stack emissions, like those from home heating systems, have a smaller effect in the winter. In Warsaw, apartments have central heating systems that are mostly part of a big heat and power plant that is covered with electrostatic screens to stop coarse particulate matter from getting into the air. Domestic heating (furnaces or staves) is a major source of PM in Cracow during the winter. This is because local and distant emissions come from individual heating systems that use coal and wood, and because of local environmental conditions like air temperature inversions or katabatic flows that make even small emissions contribute to higher PM concentrations (Ścibor et al. 2020). During the summer (June–August), most of the air pollution comes from cars and trucks.

3.13 Transportation volume's influence on air pollution

Poland's air pollution is affected by the amount of transportation because it is one of the main sources of pollution. A study by the European Environment Agency says that about 20% of Poland's overall greenhouse gas emissions come from the transport sector. The main reason for this is that the country's energy sector uses a lot of coal, which makes particulate matter and nitrogen oxides (NOx) emissions, mostly from heavy-duty cars.

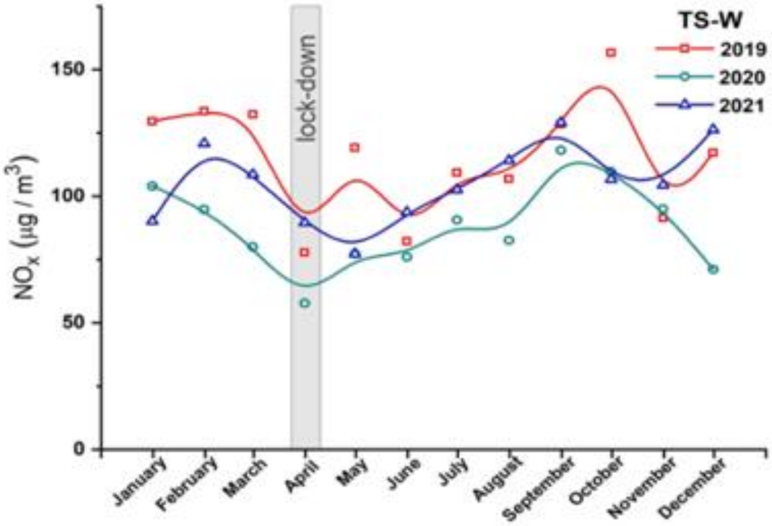
Poland's transport flow is affected by many things, such as economic growth, population growth, and the spread of cities. The need for transport goes up as the business of the country grows, which can cause air pollution to rise. Also, more people are using personal vehicles, especially cars, which are worse for the environment because they release more pollution than public transportation.

To deal with Poland's transportation-related air pollution, the government has taken a number of steps, such as encouraging people to use public transportation and encouraging the growth of other ways to get around, like walking and biking. The European Union has also given money to projects that try to lower emissions from the transport sector. (*Air Quality in Europe 2022*, n.d.).

3.14 The effect of lockdown measures on pollution emissions

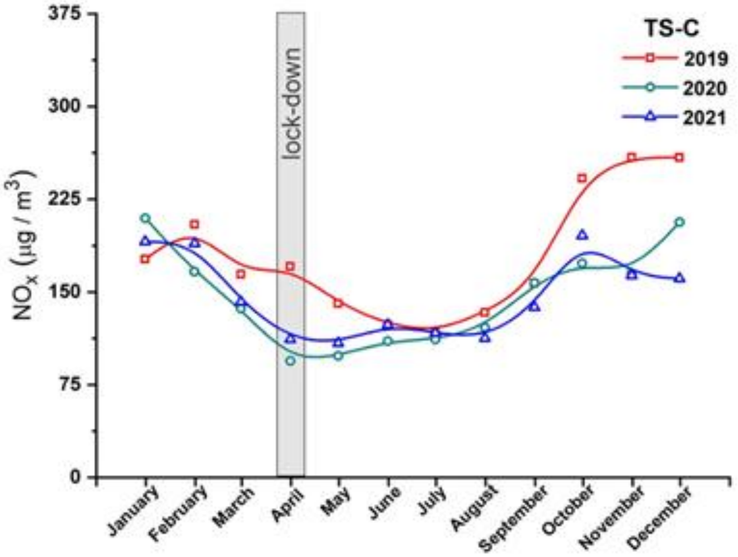
Three pollutants NO_x, PM_{10}, and $PM_{2.5}$ were measured at traffic pollution tracking stations. Two of them, NO_x and $PM_{2.5}$, were found to be good indicators of local air pollution levels that are affected by actions related to traffic in cities. Because private and public services were limited during the full lockdown, the levels of both toxins dropped by a large amount. Most research (Tian et al., 2021; Gama et al., 2021; Chen et al., 2021) found a link between the flow of transport and NO_x pollution in the air. Our research showed that NO_x levels in a certain area are most affected by emissions from cars and trucks. During the lockdown, the NO_x levels in both of the towns that were studied Warsaw and Cracow went down. But it looked like the drop was bigger in Cracow (by about 45%) than in Warsaw (by about 26%). It's possible that the reason why the NO_x content dropped less in Warsaw was because it dropped so much in April 2019 (Figure 6). As people started to move and do their daily tasks again after the lockdown, NOx air pollution rose in both towns. In Cracow, the NOx level kept going up until December 2020 (Figure 7), and in July and August 2020, the levels were the same as they were in the same months of 2019. In Warsaw, the amount of NOx rose until October 2020, but then it went down in November and December 2020 (Figure 6). This drop might be because of the second wave of coronavirus in Poland and the fact that the government put more restrictions in place during those months.

Figure 6: Average monthly concentrations of NO_x in 2021, 2020, and 2019. Data from air pollution traffic monitoring station (TS-W), Warsaw, Poland. B-spline curve (basis spline function) was applied for the smoothness of experimental.



Source: (Górka-Kostrubiec & Dudzisz, 2022)

Figure 7: Average monthly concentrations of NO$_x$ in 2021, 2020, and 2019. Data from air pollution traffic monitoring station (TS-C), Cracow, Poland. B-spline curve (basis spline function) was applied for the smoothness of experimental data.



Source: (Górka-Kostrubiec & Dudzisz, 2022)

PM$_{2.5}$ levels can show how polluted the air is in a certain area due to fumes that don't come from burning fuel. This kind of fine particle is made when vehicles move, like when brake pads and discs, ground, and tyres rub against each other. This is the part of the environment that has the most harmful effects on health, causing heart diseases, lung diseases, and more. When compared to 2019, PM$_{2.5}$ levels dropped by 38% and 13% in Warsaw and Cracow during the lockdown in April 2020. However, these concentrations during the lockdown were not the lowest in all of 2020. They slowly dropped over the next few months, hitting their lowest point in the summer (July–August). This could mean that sources that are most active in the winter add a small amount to PM$_{2.5}$ levels.

During the lockdown, the European Space Agency's satellites saw a big change in the amount of NOx in the atmosphere around the world Using computer simulations,(Menut et al., 2020) found that during the 2020 lockdown, the levels of NO$_2$ and PM would drop by 30–50% in all Western European countries. Between 27 and 25% less NO$_2$ was in the air in European towns on average . In many towns in Italy, especially in Lombardy and Veneto, as well as in Turin and Bologna, NO$_x$ pollution went down by a large amount. During the lockdown in 2020, the average amount of NO$_2$ in the troposphere over Milan and Venice was 38% lower than it was during the same time in 2019. It was also seen that the NO_2 column dropped by about 30% during the tight lockdown in Spain and France compared to the same time in 2019. In Germany and Belgium, there was a drop of about 20%, which may be because shutdown rules are not as strict there. When compared to the same time last year, NO_2 levels dropped by about 35% at the traffic site in Zagreb, Croatia, during the COVID-19 lockdown. During the lockdown, the levels of $PM_{2.5}$, PM_{10}, and NO_2 in the air dropped in five Polish towns. Data from air quality monitoring stations in different parts of the city, like urban, suburban, rural, and industrial zones, showed that the levels of pollution were 11.1% to 26.4% lower than they were in 2018, 2019, and 2020, respectively. In April, the amount of $PM_{2.5}$ in the air in Warsaw dropped by 20% and in Cracow it dropped by 11.1% compared to the same time last year. In April, the amount of PM10 in the air dropped by 11.8% in Warsaw and 8.6% in Cracow. The amount of NO_2 in the air dropped even more in April. Compared to 2019, the levels dropped 8.6% in Warsaw and 20.7% in Cracow. Our research showed that during the full lockdown in April 2020, NO_x and PM2.5 levels dropped much more significantly in both towns than what reported. This is because we looked at pollution levels in the area that came from sites that mostly measure pollution from cars. Ten to twelve percent less NO_x was in the air at urban (no traffic) air pollution monitoring stations in April 2020 than it was in April 2019 in Warsaw and seven to eight percent less in Cracow.(*Coronavirus Lockdown Leading to Drop in Pollution Across Europe*, n.d.)

The weather, including wind speed and direction, humidity, and temperature, may also affect the air quality in the area where traffic sources are present. However, during the lockdown, the levels of pollutants did not show this trend. This suggests that the drop in pollution levels may be mostly due to lockdowns and people not being able to move around as much. When data on pollution concentrations were compared to the usual amount of rainfall, no connections were found that could explain how pollutants could be washing down from the air. For example, in Cracow, the average amount of rain fell less in March and April 2020 than in the same months in 2019, but the levels of NO_x, PM_{10}, and $PM_{2.5}$ were the highest. We say that the speed of the wind might be the most important thing that helps get rid of pollution (breathing of the city). The average wind speed in Warsaw is more than 1 m/s faster than in Cracow, which is less than 2.1 m/s. According to some reports, this may be one reason why the air quality in Cracow was worse than in Warsaw during the lockdown.

3.15 Poland's district heating challenges

The number of people living in the world passed eight billion on November 15, 2022, and it's expected to hit nine billion by 2037(*Day of 8 billion | United Nations*, n.d.). The number of homes is expected to rise from 1.9 billion in 2010 to 3.2 billion in 2050, according to (*Energy Technology Perspectives 2012*, n.d.). This is because the population is growing. Residential buildings use 40% and business buildings use 26% of all the energy used by homes in the US and Europe, respectively (*Energy Technology Perspectives 2012*, n.d.). Carbon dioxide (CO_2) emissions are at 38% in the US and 36% in Europe. This is a matter of course since things are going this way. It's also true that the fast growth of cities has some bad effects, like the formation of urban heat islands (Mirzaei, 2015; Mirzaei et al., 2015). So, the numbers show why we need a world goal to cut CO_2 emissions in half by 2050, with a focus on the Pathway to Net Zero in 2050. To reach this goal, emissions must drop by 8% every year *(Energy Transition Outlook, n.d.)*. The outlook *(Energy Transition Outlook, n.d.)* also says that the supply shock caused by Russia's invasion of Ukraine and the demand shock caused by the pandemic will not have much of an effect on the fast and broad shift in the long term, even though they caused a brief slowdown. Fit for 55 package and RePowerUE ("RePowerEU: A Plan to Rapidly Reduce Dependence on Russian Fossil Fuels and Fast Forward the Green Transition. 2022.") are the most important documents in the European Union for changing energy use and lowering CO_2 emissions. In Poland, the Polish Energy Policy until 2040 (PEP2040) (*Energy Policy of Poland Until 2040 (EPP2040) - Ministry of Climate and Environment - Gov.pl Website*, n.d.) and the National Energy and Climate Plan (KPEiK)(*Krajowy Plan Na Rzecz Energii I Klimatu Na Lata 2021-2030 - Ministerstwo Klimatu I Środowiska - Portal Gov.pl*, n.d.) are the most important documents for changing energy use and lowering CO_2 emissions.

As two-thirds of the world's energy and seventy-five percent of its CO_2 emissions come from cities (Reda et al., 2021), it is clear that they are very important for stopping climate change. Changing district heating (DH) networks is important for changing individual heating because they provide a lot of heating and cooling services in many cities around the world. In places like Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Poland, Russia, Sweden, and northern China, for example, DH meets more than half of the heat needs. There is a summary of district heating and cooling around the world as well as more in-depth studies of the situation in Europe

(Werner, 2017). These include talks about the market, technical, supply, environmental, political, and future backgrounds. In (Mazhar et al., 2018; Talebi et al., 2016; Buffa et al., 2021) you can read about the main features and classifications of DH based on location, size, heat density, and user, as well as the latest developments and problems with the current methods. There was a thorough look at how heating and cooling systems were put in place in the US in(Lake et al., 2017). What's going on now and the problems the UK is facing with DH can be found in (Millar et al., 2019). In a study of the Polish heat market, including its current state and important problems for its future growth was carried out.

Decarbonising the district heating sector is very important for promoting the switch to carbon neutrality in places where district heating is a big part of the energy grid. The DH sector has a lot of room to become less carbon-based, especially when it comes to heat sources. In (Yang et al., 2015), a new cogeneration system is pushed. This system can help study heating technology, which can then improve ways to save energy and lower CO_2 levels. (Lundberg & Fridahl, 2022) talks about the current state of policies in the US, UK, and EU member states for getting rid of carbon dioxide, with a focus on crops that collect and store carbon. The paper (Mathiesen et al., 2019) suggests legal steps and important turning points on the way to a full heat transition. This is done to speed up the implementation of the plan for decarbonising the heating and cooling sector in Europe. (Ricci et al., 2022) has a case study from Italy about how the efficient DH works from the point of view of decarbonisation. Smart technologies can be used to cut down on the harmful pollution from DH devices. In (Grzegórska et al., 2021), smart asset management for DH systems around the Baltic Sea was talked about. In (Kinelski et al., 2021), modelling results for Metropolis GZM in Poland were shared.

The district heating system is pretty adaptable, and it can use a number of different energy-conversion methods to make heat. In (Salman et al., 2021), the role and market potential of new technologies and technology pairing to help thermal businesses make more money and the growth of green energy sources were looked at again. The best way to plan for future district heating systems has been looked at in (Jiang et al., 2022). The authors of (Averfalk & Werner, 2017) give important suggestions for how to plan and build the fourth generation (4GDH) systems. They also give a critical study of the problems that make it hard to lower temperatures and the reasons why present third generation (3GDH) systems have too high of return temperatures. In (Buffa et al., 2019), a study of 40 DH networks that work in Europe was given. The point of the paper was to look at the definitions again and come up with a clear one for fifth generation heating and cooling networks. The research found that every year for the past ten years, three fifth generation district heating (5GDH) and cooling devices have come on the market. In this area, Germany and Switzerland are the best. A study (Lund et al., 2017) compared three different DH temperature level ideas: low temperature (55/25 °C), very low temperature with electric enhancement (45/25 °C), and very low temperature with heat pump enhancement (35/20 °C). The study looked at network losses, production efficiency, and building requirements based on conditions in Denmark. According to a study (Sorknæs et al., 2020), switching from third generation (3GDH) to fourth generation (4GDH) systems can help the energy industry work together better, lower grid losses, and make it easier to include renewable energy sources (RES). The effects on the economy and energy were talked about in terms of Aalborg, Denmark. Based on the findings of the studies, the authors of (Metzger et al., 2021) emphasised the importance of new cogeneration (CHP) solutions for ensuring the supply of electricity and heat, as well as the need to manage network congestion by making use of the flexibility that comes from connecting sectors and making plans for network expansion. The piece gives a thorough look at Germany's plans to stop using coal by 2038.

The most interesting renewable energy sources (RES) are those used for heating, especially in low-temperature district heating networks (Neirotti et al., 2019; (Pellegrini & Bianchini, 2018). One way to improve heating and make it more efficient is to use power to heat, which means turning electricity from wind farms into heat. Based on 34 studies and an overview from the 1950s, (Gjorgievski et al., 2021) lists the many benefits of this method. When solar heat (Reiter et al., 2016), heat pumps (David et al., 2017), nuclear plants (Teräsvirta et al., 2020), or geothermal energy (Sáez Blázquez et al., 2018;Romanov & Leiss, 2022)are used in DH, big changes in technology are bound to happen (Djørup et al., 2020).

Statistics that have been made public (“Electricity and Heat Statistics”) show how fast and in what way the heating sector in Europe is changing. Until 2021, heat production from fossil fuels kept going down. From 2000 to 2021, it dropped by 40.5% to 125 TWh (451 PJ), and from 2022 to 2023, it dropped by 5.6% to 118 TWh (426 PJ). The biggest drop ever was seen in 2020, when it reached 117 TWh (422 PJ). The amount of crude oil and oil products used to make heat followed a similar pattern. From 2000 to 2021, they went down by 67.2%, reaching a record low of 21 TWh (74 PJ) in 2020. In 2022, they went up by 35.2% compared to 2021. Prices for natural gas went up by 14.3% between 2000 and 2021. They peaked in 2005. In 2022, the price of natural gas and industrial gases fell by 11.9% compared to the year before. The steady rise of renewable energy continued until 2021. However, there was a small drop of 6.5% in 2022 compared to 2021. Renewable heat production rose by as much as 408.7% between 2000 and 2021. It is clear that this is the way the district heating business needs to change.

The main point of the paper is to give an outline of the current state of district heating in Poland and its possible future growth, with a focus on existing trends around the world and the European situation. Besides the opening, the paper is put together like this: The second part talks about district heating systems and gives a brief background and outline of how DH has changed over time in Poland. It also talks about DH sources and generations. In the third part, we talk about the Heating State in Poland by looking at the organisation of heating companies and the prices of heat. The fourth part talks about Poland's growth goals as a member of the EU. The last part of the paper, section five, is the findings.

3.16 Heating systems for districts

3.16.1 Major polish cities with district heating

At first, heating systems in Warsaw, Poland, were only meant for individual houses. To heat a house this way, the first one was built in 1841 at Jan Mitkiewicz Square (*Sto Lat, Sto Lat Już Grzeje, Grzeje Nam. . .*, n.d.). The Warsaw University of Technology and the Infant Jesus hospital building on Lindley Street were both built at the start of the 20th century. They each had their own combined heat and power plants and heating systems (Krzysztof Wojdyga, 2016). A modernist housing estate for workers in Żoliborz was built in the 1920s and 1930s. It had a central boiler house that heated the blocks of flats. When Poland's capital was being rebuilt after World War II, there was a heating boom. The Warsaw heating network is the biggest of its kind in the European Union right now. It has about 1800 km of networks that heat 19,000 buildings in Warsaw, which is 80% of the capital's needs. The heating system in Warsaw gets its heat from four different sources, and its ring-shaped design makes sure that the city always has heat (*Veolia – Energia Dla Warszawy*, n.d.).

Before the war Apartments in Cracow, Poland, were mostly warm by fires. There were sometimes boiler houses for single homes or small living developments. A company called the Municipal Heating Company (MC) was formed from these ideas in 1953. The business took over running these boiler houses. There were 12 of them, and the network that spread the heat was only 30 km long. Over the next few years, MC took over the running of more local heating plants. In 1962, it changed its name to the Municipal Heat Energy Company (MPEC) (idel.pl, 2022). During the early 1960s, the Lenin Steelworks were the main source of heat in Cracow. In 1970, a new large heat and power plant opened. Then, in the mid-1980s, the heating system in Cracow was changed again by something called the first ring-connection of the northern and western mains. In 1995, a computer tracking, and surveillance system was created, built, and put into use that was the only one of its kind in the Polish DH industry. The next year, one of Poland's most important landmarks, the Wawel Royal Castle, was linked to MPEC. At the start of the 2000s, MPEC was able to shut down all of its coal-fired boiler plants. This means that the company no longer uses solid fuels to make heat. From 2014 to 2020, MPEC worked on three district heating projects to make better use of energy from high-efficiency cogeneration. These projects included building a DH network with heat substations and connections so that new buildings and existing buildings could use another heat source (idel.pl, 2022).

In Lublin, Poland, the heating business began in the late 1950s and early 1960s, when the Department of Heat Management was created at the Municipal Board of Residential Buildings. Then, it took over running and improving Lublin's heating system under the name of the Municipal Heat Energy Company. Lublin Heat Energy Company (LPEC) is the name that has been used since 1974. When the heating system in Lublin was centralised in the 1970s, local and regional boiler houses were shut down and as many facilities as possible were linked to the city network. In the 1980s, the business tried to make the so-called "ring heating system," which brought together all the different types of heat. A company called LPEC (*Strona Główna*, n.d.) was one of the first to automate the transfer, delivery, and conversion of heat energy. Nearly 75% of homes in Lublin get their heat from LPEC right now, keeping about 250,000 people warm. Right now, the company is in charge of more than 2,000 heat substations and 460 km of district heating networks.

In Szczecin, Poland, the Municipal Heat Management Company was founded in 1962 on the foundation of coal-fired boiler houses in the area. As many as 160 of them were spread out all over the city. Around the middle of the 1970s, a business was set up to oversee all of Szczecin Voivodeship's networks. That's why the company was named Voivodeship Heat Energy Company (WPEC). In 1997, heating systems were given to the communes. This is when the recent history of the company Szczecin District Heating (SEC) (*Szczecinska Energetyka Cieplna Sp. Z o.o. Company Profile - Poland | Financials & Key Executives | EMIS*, n.d.) starts. The Thermal Waste Treatment Plant was added to the system in 2016. It now runs over 366 km of district heating networks and over 3.8 thousand heat substations, keeping about 18.9 thousand people warm.

In Opole, Poland, heating first came on in the 1970s. Opolszczyzna District Heating (ECO), which is one of the most active heating companies in Poland, was started and grew here (*Energetyka Cieplna Opolszczyzny SA*, n.d.). Starting ECO was a first in its field way of organising things: using the heating assets of the communes in the Opolskie Voivodeship to build a company. ECO currently runs 27 DH systems in 5 voivodeships in a variety of cities of different sizes. They are also working on a number of projects to make the heat production process less harmful to the environment, such as building a geothermal heating plant in Kutno, running a high-efficiency gas cogeneration system in Jelenia Góra, and building a PV farm in Opole, with the goal of reaching zero carbon by 2050 (*ECO Na Drodze Transformacji*, 2023).

The Polish district heating industry moved into a new era at the end of the 1990s and the start of the 2000s. A lot of companies are getting money from foreign investors who bring new skills and ideas for making current heating systems that use less energy. There are also new chances because of the ability to get EU funds for updating networks and building new heat sources. Poland has one of the largest heating networks, along with the Baltic countries. System heat is used by half of the people. At the same time, heating companies and heat makers have to deal with new problems: protecting the environment and making sure that RES are used in the right amount of energy output. This is a problem that our country will have to deal with for the next few years!

3.16.2 The sources of district heating

One very important thing about district heating is that it can use a lot of different heat sources. A district heating network can use a lot of different centralised and decentralised sources to work reliably and be flexible, all thanks to simple control methods. The most popular ways to make heat have been ranked in(Wei et al., 2010), taking into account economic, energy, and environmental issues. In this study, the authors used a fuzzy comprehensive evaluation method to put these technologies in order of how often they are used: oil boilers, water source heat pumps, coal boilers, ground source heat pumps, solar energy heat pumps, and combined heat and power (CHP). Decarbonisation means that green and trash sources are the most valuable (Zvingilaite & Balyk, 2014), especially since they can be used in a heat grid that works at low temperatures (Lund et al., 2014). You can get waste heat from farming or industrial processes (Persson & Werner, 2012; Fang et al., 2015;(Yang et al., 2018), or you can burn the waste, which is known as Energy from waste (EfW) (Eriksson et al., 2007; Persson & Münster, 2016;Udomsri et al., 2011). Bioenergy comes from biofuels like biogas and wood pellets and chips. It is a developed technology that can be used on a bigger scale in a district heating network (Djuric Ilic et al., 2014; Djuric Ilic et al., 2014; Karschin & Geldermann, 2015;Saad et al., 2019). Bioenergy is often used as a fuel in combination with fossil fuels or instead of fossil fuels in combined heat and power plants. Solar thermal energy is made by turning the sun's rays into heat. It is a very hopeful alternative energy source that can be used to make either heat or electricity. It is possible to use this technology in both big and small settings (Carpaneto et al., 2015; Lindenberger et al., 2000; Marx et al., 2014; Kumar et al., 2019). More and more people are interested in how heat pumps can help power the DH network. Different types of heat pumps get their low-temperature heat from different sources, such as geothermal water (Yamankaradeniz, 2016; Sekret & Nitkiewicz, 2014), seawater (Calise et al., 2022; Østergaard & Andersen, 2018;Zheng et al., 2016), or air absorption (Shirani et al., 2021;Carroll et al., 2020;Kensby et al., 2017).

It is possible to store energy in thermal storages during times when demand is low. During times of high demand, they can be used as heat sources. Energy storages are meant to be built into DH so that unpredictable changes in the energy flow from RSEs don't have an effect (Tarragona et al., 2021). Large hot water tanks are the most common type of heat storage (Dahash et al., 2019), especially when it comes to centralised storage (Nuytten et al., 2013). The energy storage method is thought to be between 20 and 60 percent efficient (Jungbauer et al., 2009). According to

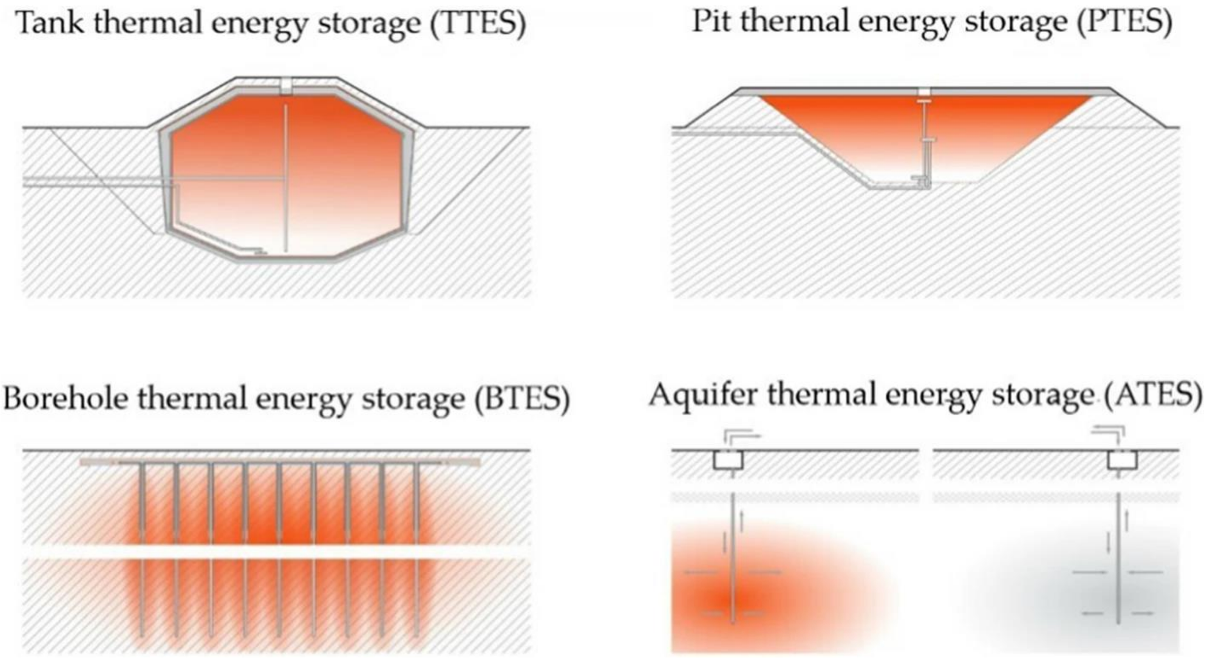
(*Optimal Design and Energy Management of a Renewable Energy Plant with Seasonal Energy Storage | E3S Web of Conferences*, n.d.), shows the main idea behind each type.

Table 4: Lists and describes different types of energy storage.

Type	**Reservoir**	**Reservoir in a soil excavation**	**Ground battery**	**Battery in an aquifer**
English name and abbreviation used	Tank thermal energy storage (TTES)	Pit thermal energy storage (PTES)	Borehole thermal energy storage (BTES)	Aquifer thermal energy storage (ATES)
Storage potential kWh/m^3	60–80	30–80	15–30	30–40
Characteristics	Ground or semi-underground water reservoir	A water reservoir formed in a pit dug in the ground filled with water or water and gravel	Storage of heat in the ground by supplying and receiving heat through boreholes	Heat storage in aquifers, access via two wells

Source: (Talarek et al., 2023)

Figure 8:Seasonal Thermal Energy Storage, 2015



Source: (Talarek et al., 2023)

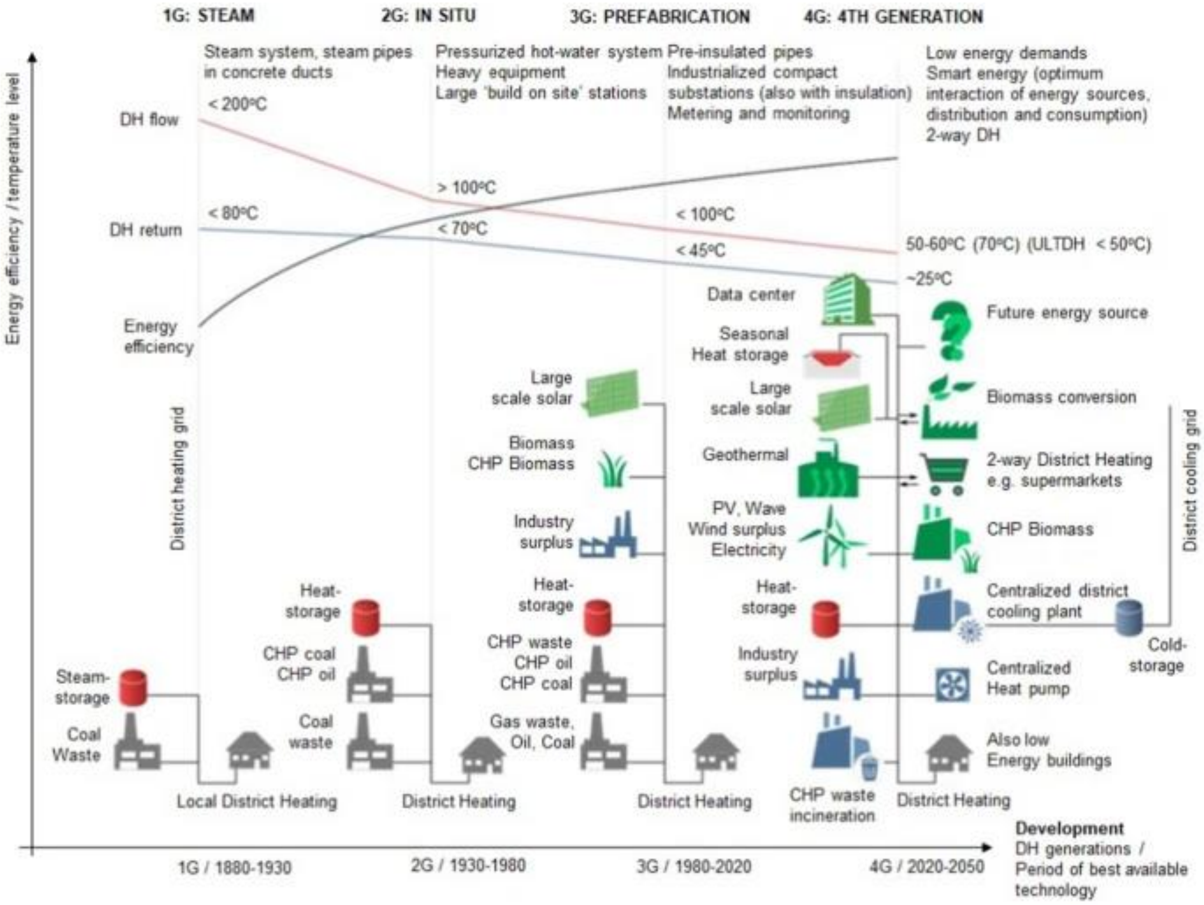
Recently, there has been a rise in the use of big TES devices for DH in Poland. Since 2002, the power company (PEC) in Siedlce has used the first TES device. In Poland, the biggest TES was built at the Combined Heat and Power Plant (CHP) Siekierki in Warsaw. It has been running since 2009. The next four were set up between 2011 and 2015: CHP Cracow, Białystok, Ostrołęka, and Bielsko-Biała. This tank is the tallest in Poland. The TES system has been in use at CHP Toruń since 2017. You can read about the technical details of big TES systems that were built in Poland. The article (Dyczko et al., 2021) looked at thermal and mechanical energy storage options and talked about the best ways to use energy storage technology. It also talked about the possibility of using these solutions in Poland.

3.16.3 Generations of district heating

The first heating networks, also known as "first generation networks," were built in the US and Western Europe at the end of the 1800s. They used steam that was hotter than 150 °C to carry heat. In the second generation of DH systems, hot water under pressure that was over 130 °C was sent through steel lines that were not well insulated and ran in concrete pathways. This method has been used since the 1930s and was very popular until the 1970s, especially in Poland and other socialist countries. Both of these methods had a lot of transmission loss. In Scandinavia in the 1970s, the third generation of heating systems was created. The water temperature was dropped below 100 °C, and pipes that were already insulated and buried in the ground were used. The great majority of networks around the world are based on this technology right now, with source temperatures of 70–120 °C and return temperatures of 40–70 °C. Compared to the last two generations, transmission losses are much smaller and building networks costs less.

Now that the third generation is over, it's time for the fourth generation in the heating sector. The water temperature drops below 70 °C, and the infrastructure for gas, energy, sewage, and city heating are all combined into one system. The main heat and power plant, for example, is becoming less important as this generation goes on. It is now filled by RES installations like wind farms, solar collectors, and geothermal sources. Waste heat from factories is also added to the grid. Low-temperature district heating networks are being built in Germany, Denmark, Sweden, and Finland, among other places (*CIEPŁO DO ZMIANY*, 2020). For low-temperature networks to work, they need new infrastructure, like energy storage and IT systems that can control how many energy sources work. Heat should also come from places that have a good energy potential. The user and his needs will be taken into account when designing the heating system. This will allow energy solutions to be made for places like shopping malls, public utility buildings, and certain areas. Like roads and streets, district heating has been an investment for a long time. By the middle of the century, the networks that are being built now will be ready to use. Because of this, it is a good idea to spend money on new methods.

Figure 9: Directions of development of heating systems

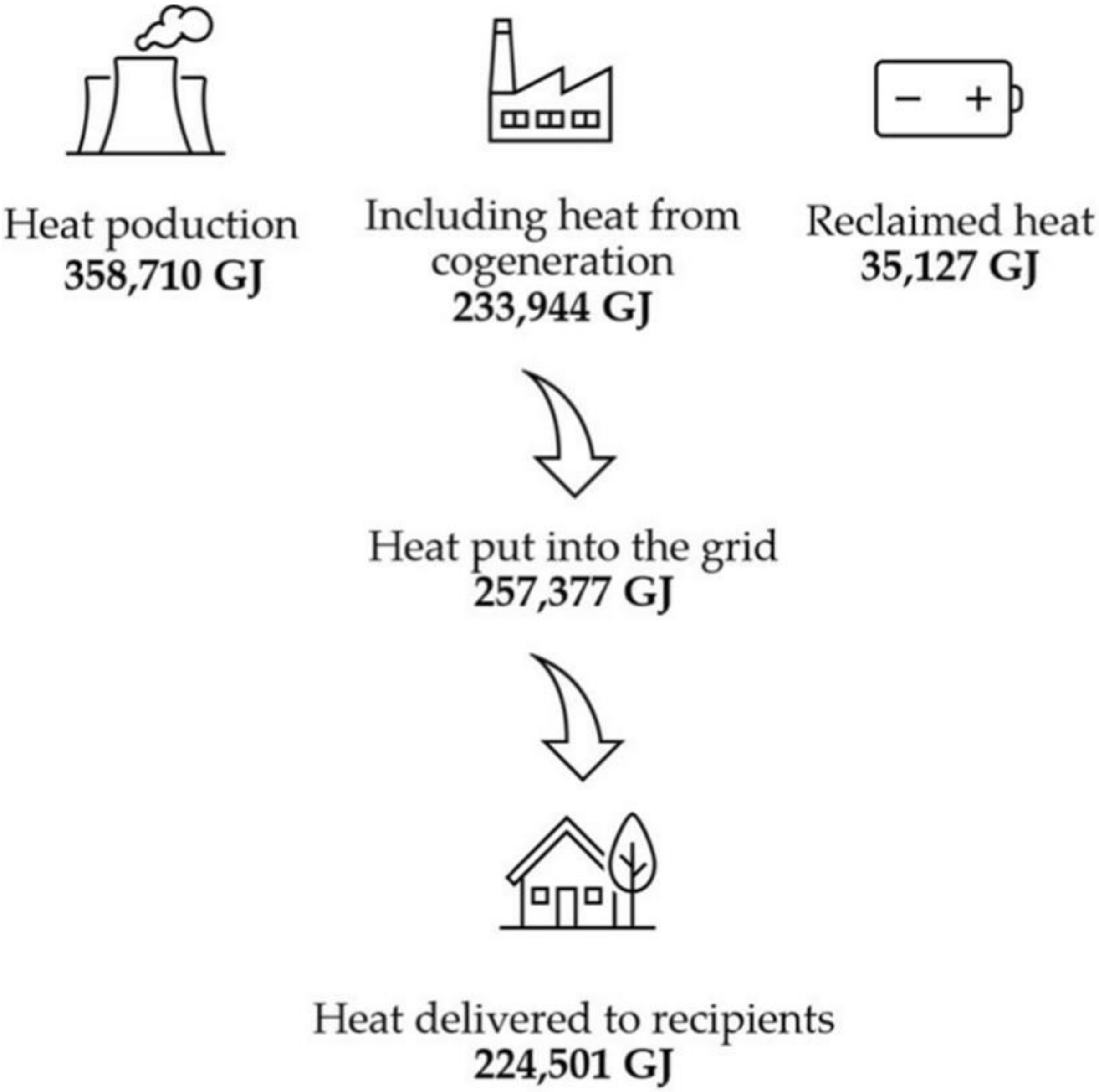


Source: (Talarek et al., 2023)

3.16.4 State of heating in Poland

The yearly report from the Energy Regulatory Office (URE) (Office, n.d.) says that as of the end of 2020, there were 387 licensed energy companies in Poland that provided heat. Companies with a total capacity of 53,271 MW in their power plants and transport networks that are 22,123 km long showed how promising these companies could be. Only 8.4% of the businesses that were asked did not have a network. However, 65.8% did have networks longer than 10 km, and one-third of those were over 50 km long. Company licensees sold 95,753,511 MWh of heat in 2020. In Figure 10 (Talarek et al., 2023), data on the production of licenced heat and the amount of heat sent to the network from receivers are shown.

Figure 10: Basic parameters of heat supplied to the network in Poland



Source: (Talarek et al., 2023)

These energy companies, which are not licensed, are asked to provide an extra 5 MW of power. It is thought that these businesses sell 50,000 TJ of heat to their clients. Also, 500,000 TJ of heat is made by homes and local heating plants to meet the temperature needs of people who live in multi-unit buildings. Also, we can't forget about the business that makes more than 200,000 TJ of heat.

The European Union's climate and energy policy and Poland's Energy Policy until 2040 have very high goals. As a result, the process of switching to different fuels for heating is moving very slowly. This is especially true now that Russia's military attack in Ukraine has caused an energy crisis.

The data published by the Energy Regulatory Office shows that:

- Most of the fuels used for heat sources will still be coal, making up about 69% of all fuels used in 2020, up from 71% in 2019 and 72.5% in 2018 and 74% in 2017.
- The sector had more cash on hand in 2020, while the total amount of debt went down.
- Between 2002 and 2020, the rate of replacing fixed assets went up by a lot. This value went up by 37.5%, which is more than the rate at which fixed assets lose value and shows a lot of spending.
- In 2020, more than 90% of all heating companies polled were involved with making heat. They made more than 394,000 TJ of heat, which includes heat that was recovered through scientific operations. This is 1.6% less than the previous year's production.
- In 2020, 65.2% of all heat production came from cogeneration. Of the 370 heat production businesses that took part in the study, 128 (34.6%) also used cogeneration to make heat.
- The average price of heat as a single component in 2020 was PLN 55.95/GJ, which was 7.7% more than the price in 2019 (PLN 51.93/GJ) and 13.1% more than the price in 2018 (PLN 49.46/GJ).
- In 2020, licenced heating companies sold about 344,000 TJ of heat, which was 0.3% less than in 2019 (including heat that was sold to other businesses);
- In 2020, the average price of heat sold from all authorised sources was PLN 44.33/GJ, which was 8.2% more than in 2019 (PLN 40.97/GJ). In 2019, the average price of heat produced by licenced sources without cogeneration was PLN 51.87/GJ, and the average price of heat produced by licenced sources with cogeneration was PLN 41.32/GJ.

3.16.5 An overview of polish heating companies structure

According to information released by the President of the URE in (Energetyki, n.d.2020), as of December 31, 2020, 387 companies had licences to do activities related to producing, transporting, distributing, and trading heat. This meant that a total of 797 companies could do a certain type of activity related to providing heat to consumers. As was said, the Energy Regulatory Office did the first study on the heating industry in 2002. Poland's licensed heating companies have dropped by more than half since then. This was mostly due to a change in the Energy Law, which also affected the size of the controlled heating market. Based on the information in Table 5 about the installed thermal power, it can be seen that the total amount of thermal power installed by suppliers has gone down by 25% since the first study in 2002, reaching 53,271 MW. In the past few years, the stabilisation has been seen. In 2020, heating companies with licences had networks that went over 22,123 km. This amount included low-parameter networks, which are outdoor receiving systems, and heating networks that connect heat sources to heat nodes. Only 8.5% of the businesses that were polled did not have networks. However, 67.9% had networks longer than 10 km and 31.4% had networks longer than 50 km.

Table 5: The number of licensed enterprises, installed and ordered capacity and network lengths in 2002, 2019 and 2020

Tasks	**2002**	**2019**	**2020**	**Relative change 2020/02 (%)**	**Relative change 2020/19 (%)**
Number of licensed heating companies	894	396	387	− 56.71	–2.27
Number of enterprises participating in the survey	849	404	399	− 53.00	− 1.23
Installed capacity (MW)	70,954	53,561	53,271	− 24.92	− 0.54

Power ordered (MW)	38,937	34,408	34,665	− 10.97	+ 0.75
Network length (km)[a]	17,312	21,701	22,123	+ 27.79	+ 1.94
Employment in full-time jobs	60,239	29,037	28,737	− 52.30	− 1.03
Total heat sales (TJ)	469,355	344,712	343,691	− 26.77	− 0.30
Heat transferred to the grid (TJ)	336,043	258,909	257,377	− 23.41	− 0.59

Source: (Talarek et al., 2023)

Since 2004, the length of the network also includes low-parameter networks says that starting in 2022, there will be big changes to how heating companies are regulated by the law. Figure 10 shows that the trend of changing the structure has an effect on how the ownership of different businesses changes.

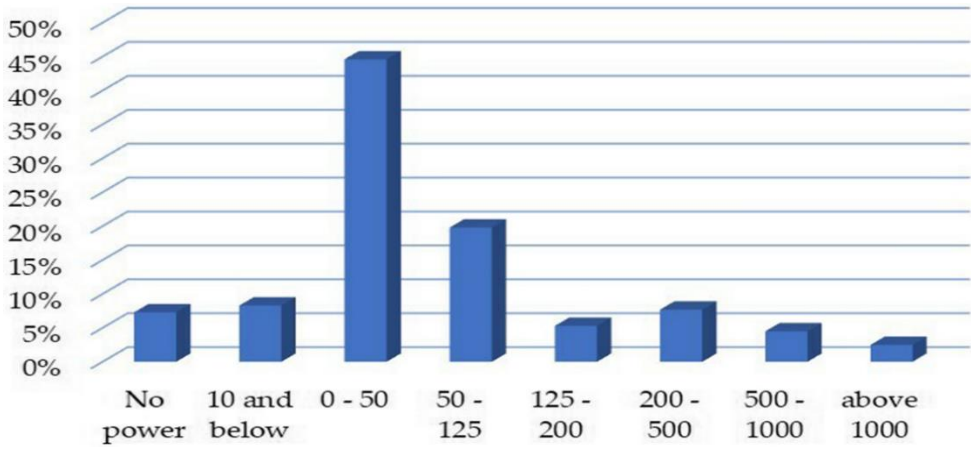
Table 6: Changes in the structures of legal forms of heating companies in the years 2002–2022

Share (%)	**Local government units (%)**	**Joint-stock companies (%)**	**Limited liability companies (%)**	**Housing companies (%)**	**State-owned enterprises (%)**	**Other companies (%)**
2022	9	26.1	54.4	2.7	3.4	4.4
2020	0.8	18	77.4	77.4	0	2.8

Source: (Talarek et al., 2023)

Businesses made heat from a range of different-sized sources in 2020, with 44.6% of businesses using small sources up to 50 MW. Ten of them were able to produce more than 1000 MW of power each. Figure 11 shows how businesses are set up.

Figure 11: Structure of heating companies by MW installed capacity in heat sources in 2020

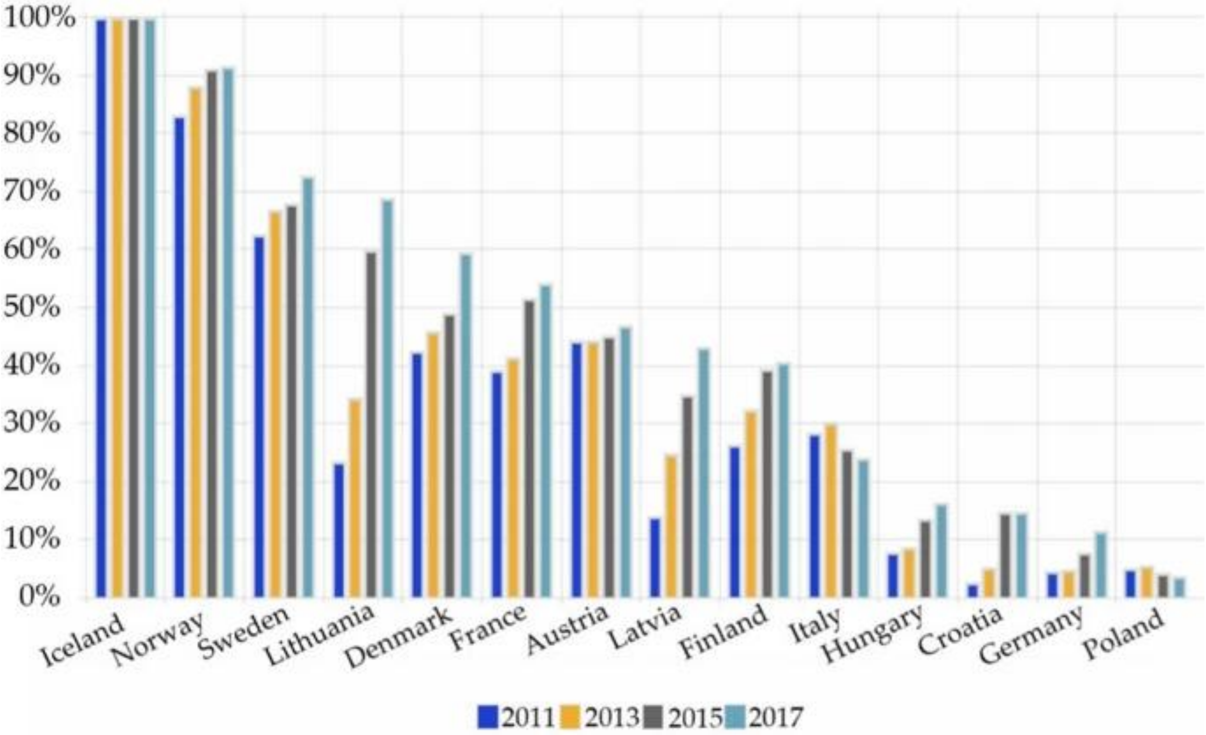


Source: (Talarek et al., 2023)

3.17 Pathways for development and the role of renewable energy in heat engineering

Figure 12 shows the amount of green energy used for district heating in some EU Member States that was talked about in (Talarek et al., 2023). The information we have suggests that heating companies in Poland have a much harder time following the rules of the instructions than companies in other countries. In order to happen, this change takes a lot of time and money.

Figure 12: Share of renewable energy in district heating



Source: (Talarek et al., 2023)

As a result of the European Union's policies in 2025 and 2030, the Chamber of Commerce of Polish District Heating set the very right and correct goals for changing technology in the energy sector. These goals are:

- generating energy from sources that don't release pollution.
- storing energy
- developing decentralised ways to get energy from renewable sources.
- Getting the heating industry to use electricity.
- promoting technologies and solutions that are more environmentally friendly and efficient.
- Integration of the heating and electricity industries more closely.
- Use trash to make energy.
- Modern low-temperature heating systems getting better.
- The energy grid getting better and more adaptable to climate change.

- Change your system by using smart digital tools that protect your data.

However, the Institute for Renewable Energy says that big cities have to gradually switch to zero-emission energy sources and rely on importing low-emission energy carriers, at least until zero-emission (green) hydrogen becomes popular or until all of the electricity they make comes from renewable sources. From this point of view, the next 20 years will still see high costs of making heat, which means that customers will have to pay high prices for heat. Smaller towns have a different look because they can get more power from other sources, like renewable energy.

In the climatic conditions of Poland, from 1 km^2 allocated to the production of energy from RES can be obtained respectively:

- 1440 TJ from solar thermal energy (solar collectors, efficiency 40%);
- 360 TJ from solar photovoltaic energy (efficiency 10%);
- up to 150 TJ from wind energy (with a high density of windmills of 20 MW / km^2);
- up to 15 TJ from biomass (with the most efficient energy crops).

4. Model analysis

The primary practical result of this thesis will be facilitated through the utilisation of a regression model. Panel data is commonly employed in situations where there is a requirement to examine indicators from both a time-series and cross-sectional standpoint. The first analysis focuses on the development of specific indicators over time, while the second observes multiple subjects/indicators simultaneously. Panel data, also known as longitudinal data, provides researchers with the opportunity to investigate a wider range of issues compared to time-series and cross-sectional data. The observed data points are derived from the interplay between the variable N and the variable time (T). The increased number of data points in this analysis leads to a higher number of degrees of freedom and a decreased likelihood of collinearity among the explanatory variables.

The selection of this type of analysis is justified by the various potential factors contributing to pollutants in Poland. The indicators employed to elucidate the dependent variable will differ, in terms of viewpoint, among economic, environmental, and geographical parameters. The objective of the forthcoming panel data analysis is to offer a comprehensive comprehension of the primary determinants impacting air quality through a comparative examination of air pollution levels during the Covid-19 period and its pre-pandemic era.

4.1 Introduction of the model

The functions shown in the econometric models were constructed to evaluate the dependence of pollutants from each province in Poland on economic and environmental indicators. Each indicator consists of a set of 10 observations spanning the years 2013 to 2022. The time period was selected based on its accessibility and its relevance in relation to the EU's efforts to enhance air quality in the environment.

The production functions will be generated using the previously provided data. All functions will be computed using a single equation model that is independent of the other. The initial production function of Technology Adoption will be established. The explained variable in this study will be pollutants (Y1t), specifically PM2.5, PM10, NO2, SO2, O3, and NOx. The explanatory variables for this variable will include GDP Per Capita (X2t), Number of transport vehicles (X3t), Household consumption (X4t), Energy consumption (X5t), Industrial emissions

(X6t) and Investment in pollution control measures (X7t). The inclusion of the unit vector (X1t) in our model is necessary to derive the intercept.

In order to streamline the model, it is imperative to establish a linear relationship between the variables. The equation of the economic model is presented as

$$\beta 11 y1t = \gamma 11\ x1t + \gamma 12\ x2t + \gamma 13\ x3t + \gamma 14\ x4t + \gamma 15\ x5t + u1t$$

Where,

γ – the parameter represents an exogenous variable that is estimated in order to explain the association between endogenous and exogenous variables.

Y1t – Pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, and NOx)

X2t – GDP Per Capita

X3t – Number of vehicles (all motor vehicles)

X4t – Household consumption

X5t – Energy consumption

X6t – Industrial emissions

X7t – Investment in pollution control measures

4.2. Assumptions

The provinces are connected to all of the previously mentioned indicators, whether from an environmental or economic standpoint. Determining the importance of each indicator with regard to the pollutants produced by the sector as well as the emissions from households, transportation, and industry is the primary objective, though. To accomplish this, it is crucial to make assumptions based on each indicator's historical developments regarding the cause-and-effect relationships between each independent variable and the dependent. Prior to conducting a comprehensive analysis of potential cause-and-effect relationships based on available data, statements known as assumptions are made. Making "what if" scenarios out of hypothetical circumstances is how an assumption sets the stage for taking action.

The assumptions are as follows:

- As was previously mentioned, all Polish provinces are used as the basis for the air quality index (AQI), and the higher emissions are calculated to determine whether the value falls within WHO limits.
- A nation's total economic activity or prosperity can be gauged by looking at its GDP per capita. Pollutant levels tend to rise in tandem with the GDP, which is steadily rising.
- Emissions from cars have a direct effect on air quality, as can vehicle ownership, the number of vehicles on the road, and how they are used. Poland's Air Quality Index (AQI) is rising due to rising pollution levels from PM2.5, PM10, NO2, SO2, O3, and NOx.
- Air pollution may be significantly influenced by industrial production, which is measured. Industrial province's output, which is a consequence of variations in air pollution and impacts the AQI.

4.3 Parameters estimation

The Ordinary Least Squares (OLS) method is used to estimate the parameters of the two models. By reducing the sum of squares of residuals, the software (Microsoft Office Excel 2016) facilitates parameter calculation (which is the basis for OLS). A specific parameter that describes how a one unit change in each of the independent variables is likely to affect the dependent variable can be attributed to the development of each of the previously mentioned secondary data. Three additional values are added to each coefficient obtained using the OLS method in order to confirm its significance. Because the standard error is always positive, the accuracy of the coefficient estimation can be understood. An estimate is more accurate when the standard error is smaller. In this instance, the t statistic value and the p-value can be used to determine whether the variables are significant within the model or to reject the null hypothesis. For this purpose, the p-value will be compared to the selected α (alpha), which denotes the likelihood of rejecting the null hypothesis in the event that it is true. Below is a display of the entire regression statistics in addition to the output pertaining to the regression coefficients. The number of observations, the adjusted R^2, the standard error for the entire model, and the coefficient of determination (R^2) are among the regression statistics.

The first model seeks to evaluate the effects of primarily economic indicators on the Air Quality Index (AQI) from Poland's provinces. The AQI includes $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, and NOx pollutants. Industrial, household, and vehicle pollution are also included. This section's primary objective is to enhance knowledge of cause-and-effect relationships and their significance in light of the ten observations that were gathered for each of the indicators.

4.3.1 Parameters estimation and statistical verification of the model

The regression model output from Microsoft Excel 2016 will be shown in two sections: the first part will deal with the estimation of the coefficients and their significance, while the second part will assess the overall model's significance and number of observations. Table 3 shows that the regression model has an R^2 of 95.78%. In percentage form, the R^2 indicates how well the exogenous variables explain the endogenous one. Due to the high R^2 value of this model, the remaining 5 variables for the EU-28 between 2013 and 2022 account for nearly 91% of the variance in Air quality index (AQI). When estimates are derived from samples, as is not the case here, the adjusted R^2 can be helpful. Only the degree to which independent variables have a significant impact on the dependent variable is indicated by the adjusted R^2. Around 1.011 thousand tonnes of CO2 equivalent are represented by the standard error, which shows the values' dispersion within the set.

Table 7: Output from OLS method for the model

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	17.99219538	12.7177461	1.41473145	0.230058733
GDP Per Capita	0.000265868	0.000356819	0.74510727	0.497605662
All Motor Vehicles	-0.003126573	0.006889583	-0.45381163	0.045349626
Household consumption	0.002075232	0.008947103	0.231944522	0.048279642
Energy Consumption	0.000247017	0.000412775	0.598429975	0.058179097
Industrial Emissions	0.069550633	0.056367818	1.233871299	0.02847923
Investment in pollution control measures	0.056385371	0.046258376	1.080039186	0.142048367

Regression Statistics	
Multiple R	0.978685139
R Square	0.957824602
Adjusted R Square	0.905105354
Standard Error	1.011428712
Observations	10

Source: Microsoft Excel 2016. Author's computation

4.4 Correlation analysis

Analysing the model's coefficients to verify or deny the previously demonstrated assumptions constitutes the economic verification. All coefficients have significance, but their respective contributions to the dependent variable are not entirely supported by their significance. This section, as its name implies, examines the intensity and direction of the coefficients in order to confirm that the model consistently applies economic theory.

4.4.1 Economic verification of the regression model

According to the **AQI** coefficient, if all other variables remain constant, an increase of one unit in AQI corresponds to an average increase of **17.99 PPM** (Parts per million) in the dependent variable. This implies that a small rise in air pollution levels may be linked to greater economic prosperity, as measured by GDP per capita.

P-value Interpretation The significance level of 0.05 is not met by the p-value of 0.230. As a result, the influence of AQI on the result might not be deemed noteworthy in this particular situation.

According to the coefficient of **GDP per capita**, (assuming all other variables remain constant) an increase of one unit in GDP per capita corresponds to an average increase of **0.00027 USD** (US Dollars) in the dependent variable. This suggests that owing to improvements in vehicle technology or more stringent emission regulations, a slight improvement in air quality may result from an increase in the number of motor vehicles.

P-value Interpretation The significance level of 0.05 is not met by the p-value of 0.498. As a result, it's possible that the effect of GDP per capita on the result in this particular case is not significant.

According to the coefficient of **All Motor Vehicles**, the dependent variable will typically decrease by **0.0031 units** for every unit increase in the number of motor vehicles (assuming all other variables remain constant). This implies that an increase in the number of passenger cars could be a factor in the slight decline in air quality.
P-value Interpretation The significance level of 0.05 is exceeded by the p-value of 0.045. Thus, there is a substantial negative correlation between the number of motor vehicles and the outcome variable.

The dependent variable will typically increase by **0.0021 units** for every unit increase in the **number of passenger cars**, according to the coefficient of Number of Passenger Cars (assuming other variables are held constant). This implies that an increase in the number of passenger cars could be a factor in the slight decline in air quality.
P-value Interpretation The significance level of 0.05 is exceeded by the p-value of 0.048. Consequently, the quantity of passenger cars significantly increases the outcome variable.

According to the coefficient of **energy consumption**, the dependent variable will typically increase by **0.00025TJ** (Terajoule) for every unit increase in energy consumption (assuming all other variables remain constant). This suggests that increased energy use, potentially from home or commercial uses, could be a small factor in the marginal rise in air pollution.
P-value Interpretation The significance level of 0.05 is not met by the p-value of 0.058. Thus, in this particular context, the influence of energy consumption on the resultant may not be deemed noteworthy.

According to the coefficient of **industrial emissions**, the dependent variable will typically increase by **0.0695Mt** (Million tonnes) for every unit increase in industrial emissions (assuming all other variables remain constant). This suggests that industrial emissions have a considerable effect on air quality, with higher emissions being linked to noticeably higher pollution levels.
P-value Interpretation The significance level of 0.05 is exceeded by the p-value of 0.028. This relationship is statistically significant at the 0.05 level. Industrial emissions therefore significantly improve the outcome variable.

4.4.2 Economic verification of the correlation model

Correlation coefficients based on observations made between 2013 and 2022.

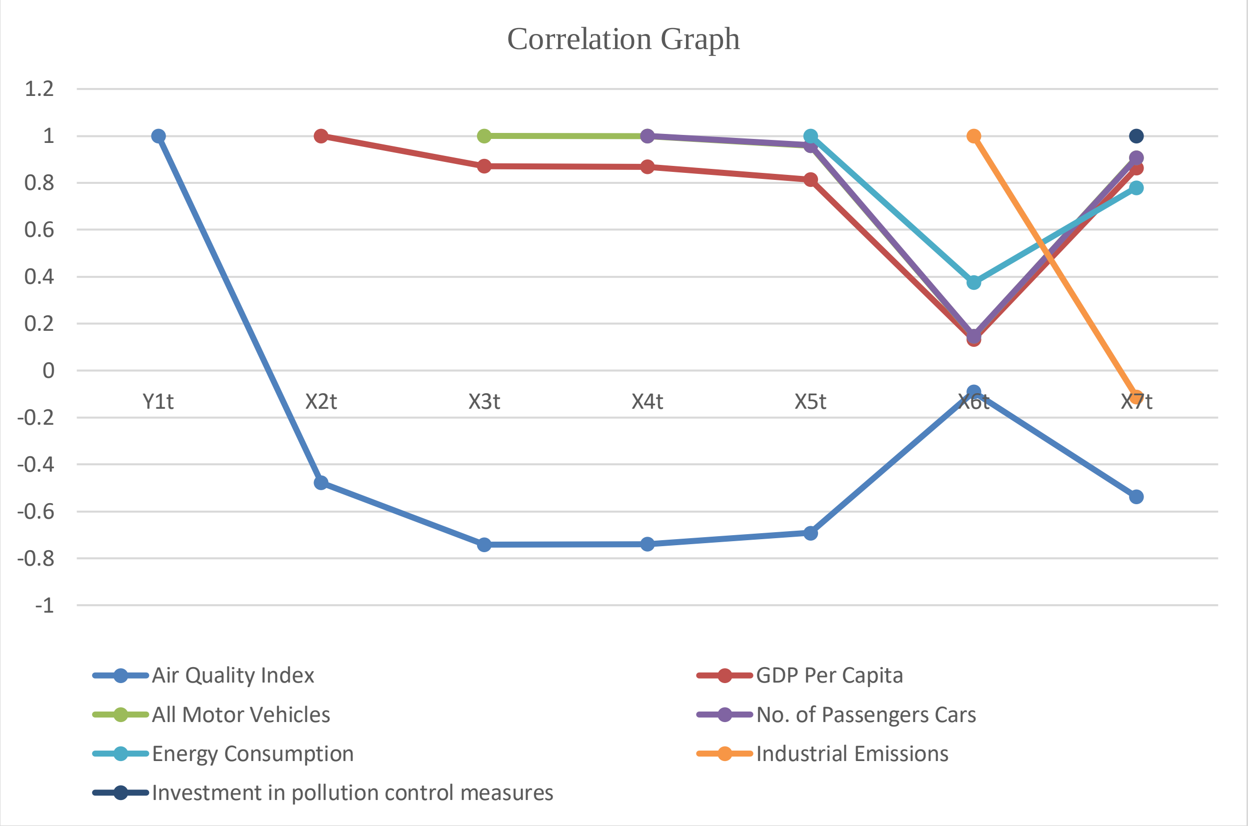
For n = 10, the 5% critical value (two tailed) is 0.6319.

Table 8: Output from OLS method for the correlation model

	Y1t	***X2t***	***X3t***	***X4t***	***X5t***	***X6t***	***X7t***
Air Quality Index	1	-0.47859	-0.742	-0.73931	-0.69199	-0.09048	-0.53758
GDP Per Capita		1	**0.871684**	**0.868298**	**0.814262**	0.132449	0.863727
All Motor Vehicles			1	**0.999858**	**0.95865**	0.146395	0.907862
No. of Passengers Cars				1	**0.959718**	0.14799	0.907167
Energy Consumption					1	0.37466	0.780547
Industrial Emissions						1	-0.11234
Investment in pollution control measures							1

Source: Microsoft Excel 2016. Author’s computation

Figure 13: Output from OLS method for the correlation model



Source: Microsoft Excel 2016. Author's computation

Multicollinearity between our explanatory variables is present, with values greater than 0.8. Household profile and Age profile, Household profile and Education profile, Age profile and Education profile, Income profile and Occupation profile are the explanatory variables that exhibit multicollinearity.

- The correlation coefficient between GDP Per Capita (x2t) and All Motor Vehicles (x3t) is **0.8716.**
- The Number of Passenger Cars (x4t) and GDP per capita (x2t) have a strong correlation of **0.8682**.
- The correlation between the Number of Passenger Cars (x4t) and All Motor Vehicles (x3t) is **0.9998.**
- GDP Per Capita (x2t) and Energy Consumption (x5t) are closely correlated; the latter is **0.8142.**

- The correlation between Energy Consumption (x5t) and All Motor Vehicles (x3t) is **0.9586.**
- There is a strong correlation between the Number of Passenger Cars (x4t) and the Energy Consumption (x5t), which is **0.9597.**
- There is no correlation between Industrial Emissions (x6t) and Energy Consumption (x5t), which is **0.37466.**

5. Evaluation of results and recommendations

5.1 Air Quality Index (AQI)

The coefficient of the Air Quality Index (AQI) indicates a possible positive correlation between levels of air pollution and economic well-being, as quantified by GDP per capita. Nevertheless, the statistical significance of the findings remains inconclusive as indicated by the elevated p-value of 0.230.

Suggestion: Additional research is required to ascertain the precise influence of AQI on the dependent variable.

5.2 The coefficient of GDP per capita

The coefficient suggests a modest correlation between GDP per capita and air quality, potentially attributable to advancements in vehicle technology or emission regulations. However, the statistical significance of the results is lacking (p-value = 0.498).

Suggestion: It is advisable to further investigate supplementary variables that could potentially impact the correlation between GDP per capita and air quality.

5.3 The coefficient for all motor vehicles

The presence of a negative coefficient suggests that there is a negative relationship between the quantity of motor vehicles and the quality of air. The observed relationship exhibits statistical significance, as indicated by a p-value of 0.045.

Suggestion: Implementing policy measures focused on decreasing vehicle emissions and encouraging the use of alternative transportation methods could effectively alleviate air pollution.

5.4 Coefficient for the Number of Passenger Cars

Like the preceding variable, there exists a correlation between an escalation in the number of passenger cars and a deterioration in air quality, which is statistically significant (p-value = 0.048).

Suggestion: Enact strategies to effectively handle traffic congestion and promote the use of environmentally friendly transportation alternatives.

5.5 Coefficient of energy consumption

The coefficient indicates a slight rise in air pollution as energy consumption increases, although it does not reach statistical significance (p-value = 0.058).

Suggestion: Investigate energy-efficient technologies and promote the utilisation of renewable energy sources as a means to mitigate environmental consequences.

5.6 Coefficient of Industrial Emissions

The impact of industrial emissions on air pollution levels is found to be statistically significant, as evidenced by a low p-value of 0.028.

Suggestion: Enhance regulatory frameworks and provide incentives for adopting cleaner production techniques as a means to address and alleviate industrial pollution.

The economic verification of the correlation model involves addressing the issue of multicollinearity.

The presence of multicollinearity is evident among multiple explanatory variables, suggesting a duplication of information they offer. To enhance the stability and interpretation of the model, it is advisable to tackle multicollinearity by employing variable selection, transformation, or regularisation techniques.

5.7 Coefficients of correlation

Significant associations can be observed between GDP Per Capita and a range of transportation-related factors, underscoring their interconnectedness.

Suggestion: It is advisable to prioritise the implementation of integrated urban planning strategies that take into account the interplay between economic development and environmental sustainability in order to effectively address the negative impacts on air quality.

6. General Suggestion and Discussion

- Perform additional investigations to examine supplementary variables and interactions that could potentially impact the dynamics of air quality.
- To enhance air quality and public health outcomes, it is recommended to implement targeted policies and interventions that focus on reducing vehicular emissions, improving industrial practices, and promoting sustainable energy solutions.
- Establish industrial rules and regulations and encourage cooperation between the government, industry, and environmental agencies to effectively address emissions.
- Encourage the use of public transport and other options, such as walking or cycling.
- To reduce air pollution in Poland, the report suggests making and following rules and policies that are based on facts. For strategies that put public health and environmental sustainability first, the government, businesses, universities, and citizens must work together.
- Research Directions for the Future: It is important to do research and monitoring to look at trends in air quality, find new pollutants, and rethink how to control pollution. Future studies should look into how to manage air quality, slow down climate change, and reach sustainable development goals in order to help make more environmentally friendly policies and actions.

7. Conclusion

To sum up, the regression model's economic verification has illuminated a number of variables affecting air quality and their possible financial effects. Though the statistical significance of the correlations varies, the coefficient analysis shows interesting relationships between economic indicators and air pollution levels.

Though more research is necessary due to the lack of statistical significance, the positive correlation between GDP per capita and the Air Quality Index (AQI) raises the possibility of a connection between economic prosperity and air pollution. In a similar vein, the weak correlation and negligible p-value found between GDP per capita and air quality highlight the necessity of examining more variables in order to fully comprehend the relationship between the two.

However, the negative coefficients linked to motor vehicles especially passenger cars highlight the adverse effect that vehicle emissions have on air quality, and their statistical significance indicates the pressing need for policy changes. Air pollution may be mitigated by policies that support alternative modes of transportation and lower vehicle emissions.

In addition, the marginal increase in air pollution linked to energy use emphasises how critical it is to investigate energy-efficient technologies and renewable energy sources. The coefficient pertaining to industrial emissions suggests that there is a noteworthy influence on air quality, underscoring the necessity of stricter regulations and more environmentally friendly production methods to tackle industrial pollution.

Furthermore, the existence of multicollinearity among explanatory variables demands that model interpretation and refinement be done with great care. Strategies like variable selection, transformation, or regularisation can improve the model's interpretability and stability, which will increase the model's accuracy in forecasting air quality results.

In conclusion, the results highlight the intricate relationship that exists between environmental sustainability and economic development, which highlights the need for integrated urban planning techniques. Societies can work towards striking a healthy balance between environmental preservation and economic growth by addressing the detrimental effects on air quality through focused policies and interventions.

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