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Renewable Energy Sources vs. an Air Quality Improvement in Urbanized Areas - the Metropolitan Area of Kraków Case

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The premise for the selection of the topic discussed in this article is the lack of research on the level of reduction of air pollutant emissions by the use of photovoltaic micro-installations in single-family buildings, both in Poland and other countries of Central and Eastern Europe. Therefore, the Authors made an attempt to estimate the scale of air pollution reduction (in particular CO_2) in the area of the urbanized Metropolitan area of Krakow, which is one of the most polluted regions in Poland. The installation of photovoltaic panels on single-family buildings, co-financed by the government *My Electricity Program*, is the investment cost in improving the air quality in this region, and thus increasing the well-being of its inhabitants.

Keywords: CO_2 emission, air pollution, PV micro-installations, renewable energy, Małopolska Voivodship

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INTRODUCTION

Reports of the European Environment Agency indicate Poland as a country in which significant exceedances of air quality standards are recorded. (Blazy, 2020; Poland Country Briefing, 2015). Compared to other European Union countries, Poland is the leader in greenhouse gas emissions (in particular carbon dioxide- according to WHO, **Figures 1**, **2**) (International Renewable Energy Agency (IRENA), 2019; Tucki et al., 2019), which directly affects, inter alia, to bad air condition. This problem is particularly visible in the southern part of the country. (Blazy et al., 2021). According to the report illustrating the air condition in Małopolska in 2020, the highest levels of pollution are mainly related to PM10 and benzo (a) pyrene.

This article raised the issue of possibilities of reducing air pollution using renewable energy sources in the form of photovoltaic micro-installations. Based on the published statistical data related to the implementation of the government program *My Electricity* in Poland in 2019 and 2020, research was carried out on the impact of the use of photovoltaic micro-installations in single-family buildings on the potential reduction of emissions of pollutants–greenhouse gases (carbon dioxide). The scope of analyses covers the area of the Małopolska Voivodship.

The measures taken successively since 2013 to improve air quality in Małopolska are gradually bringing improvement. (Rataj and Holewa-Rataj, 2020). Still, due to the dominant structure of the coal-based energy system and the form of electricity generation in the process of combustion of fossil fuels, the emission of greenhouse gases is a serious problem that requires constant modernization measures. (Shindell and Smith, 2019; Johnsson et al., 2019). According to WHO, (WHO, 2018) the air in the area of the Krakow agglomeration is one of the most polluted in Europe. Therefore (De Sousa, 2013), all measures aimed at its improvement are particularly important.

Moreover, it is necessary for the Polish economy to achieve CO_2 neutrality by 2050 as an integral element of the EU area, as defined by the Intergovernmental Panel on Climate Change (IPCC). The implementation of this intention should include both reduction and balanced management of emissions. (Eichner and Pethig, 2017; Day and Day, 2017; Zeppini and van den Bergh, 2020). In the Regional Action Plan for Climate and Energy developed for the Małopolskie Voivodeship (Marshal's Office of the Małopolska Region, 2019), activities have been identified that will contribute to:

- reduction of greenhouse gas emissions,
- improvement of air quality,
- low-emission transformation of the region by increasing the use of the local potential of renewable energy sources
- and reducing energy consumption and improving energy efficiency.

This document specifies the current (as of 2019) level of greenhouse gas emissions and sets out priority areas for action. The conducted assessment allowed for the identification of possible levels of reduction of greenhouse gas emissions by 2030.

FINANCIAL SUPPORT FOR CHANGING THE ENERGY SYSTEM STRUCTURE TO IMPROVE AIR QUALITY

Directions of Financing the Energy Production Growth From Renewable Sources

In line with the basic goals set out in the National Plan for Energy and Climate for 2021–2030, which should be achieved by 2030 - Poland aims to reduce greenhouse gas emissions, including CO_2, by 30% compared to 1990. (Ministry of State Assets, 2019). Pursuant to Regulation (EU) 2018/842, the reduction target for Poland in terms of greenhouse gas emissions in sectors not covered by the ETS was set at -7% in 2030 compared to 2005. In the National Plan for Energy and Climate, a forecast was adopted to increase the achievable power in PV installations to approx. 7.3 GW in 2030 and to approx. 16 GW in 2040. It is worth noting that in the National Plan for Energy and Climate, it is the use of solar energy through photovoltaic installations, it is expected to bring the highest effects (almost twice as high as compared to the use of wind energy on land or at sea) (Ministry of State Assets, 2019). Therefore, the government launched several subsidy programs aimed at the implementation of projects aimed at reducing the negative impact of pollution on the environment, through:

- development of renewable energy sources (Energy Plus Program (Energia Plus) - a pool of funds of PLN 4,000 million, District Heating Program (Ciepłownictwo Powiatowe) - a pilot project, with a pool of funds of PLN 500 million, Agroenergy Program (Agroenergia) - a pool of funds of PLN 200 million),
- increasing the use of geothermal resources in Poland (Polish Geotermia Plus Program (Polska Geotermia Plus) - a pool of funds of PLN 600 million)
- or acceleration of the development of the prosumer energy sector, which uses renewable energy sources (My Electricity Program (Mój prąd) - a pool of funds in the amount of PLN 1 billion).

A special place in the Polish so-called the energy mix is occupied by energy produced through the use of photovoltaic panels. (Gnatowska and Moryń-Kucharczyk, 2021). The government of the Republic of Poland gives priority to increasing the scale of energy production thanks to the Sun, popularizing and co-financing investments of individual households in photovoltaic panels. The main goal of the government's *My Electricity Program* is to increase energy production from photovoltaic micro-installations. This program is addressed to households, and the co-financing may amount to no more than 50% of the installation costs and max. 5,000 PLN. The installations with 2–10 kW of installed power may be covered by financial support. In accordance with the regulations in force in Poland (Act of 20th February 2015 on the Renewable Sources of Energy, 2015), a micro-installation is understood as an installation of a renewable energy source with a total installed electric power not exceeding 50 kW, connected to a power grid with a rated voltage lower than 110 kV or with an achievable combined heat output whit the total installed electrical power does not exceed 50 kW.

The Polish program of co-financing energy production for individual households is not an isolated one. Similar programs supporting the reduction of pollutant emissions are also operating in neighboring countries. An example is the Czech Ministry of Environment Program managed by the State Ecological Fund of the Czech Republic. It is focused on saving energy in residential buildings. Under this program, support is provided for reducing the energy consumption of buildings (comprehensive or partial insulation), building or purchasing houses with very low energy consumption, environmentally friendly and effective use of energy sources and renewable energy sources (RES). The main objective of the program is to improve the condition of the environment by reducing emissions of pollutants and greenhouse gases (especially CO_2 emissions). The program also aims to reduce costs and energy consumption, as well as stimulate the Czech economy with social benefits such as improving the quality of housing, improving the appearance of cities and municipalities and launching long-term development trends. (Nová zelená úsporám, 2021).

Photovoltaics as a Tool to Reduce the Use of Solid Fuels for Energy Production

Growing demand for electricity and successively introduced formal and legal regulations (European Commission, 2018; De Sousa, 2013) aimed at reducing emissions, including CO_2, by limiting the use of solid fuels, make it necessary to look for alternative energy sources (Brodziński et al., 2021; Dovì and Battaglini, 2015; Li et al., 2016). At the same time, a decrease in the prices of photovoltaic modules and, on the other hand, an increase in the costs of energy generated by burning coal and gas[1], increases the production of electricity from renewable sources, including solar energy. (Alsagri, 2020; Shahsavari et al., 2019; Millstein et al., 2017). Research shows that actions taken by different countries to support the energy transition have different effects. Many publications related to the issue of CO_2 emissions concern China (Wang et al., 2021; Ouyang and Lin, 2017) which is one of the largest CO_2 emitters in the world. Various models of ensuring the energy security of states are being considered (Lucas et al., 2016; Shadman et al., 2016; Ren and Sovacool, 2015; Augutis et al., 2014; Cherp and Jewell, 2014; Gracceva and Zeniewski, 2014; Francés et al., 2013) as well as different approaches to the treatment and reuse of pollutants (Baier et al., 2018; Chery et al., 2015). In Poland, the National Plan for Energy and Climate for 2021–2030 (Ministry of State Assets, 2019), provides, inter alia, reduction of the share of coal in electricity production to 56–60%, assuming a further downward trend until 2040. Currently, approx. 77% of electricity in Poland is generated from hard coal and lignite.

Scientific considerations in the articles focus on ecological effects in terms of microclimatic changes (Yue et al., 2021) or biodiversity (Uldrijan et al., 2021). Ecological effects of preferential vegetation composition developed on sites with photovoltaic power plants. *Ecological Engineering*). In terms similar to the one adopted in this article - the search for a system solution - the works concern, among others, African countries (Bendaoud, et al., 2020). The literature also presents the hypothetical impact of changing the energy system - from the traditional use of fossil fuels to solar energy - in the context of global climate change (Hu et al., 2016). Various options are considered for reducing the negative impact on the environment, including reducing low emissions. Research studies are carried out in relation to both renewable energy sources and thermal modernization of buildings. (Dzikuć and Adamczyk, 2015; Blazy et al., 2021). At the same time, most of the scientific works on similar topics concern countries in which the development of energy generation using photovoltaic cells is significant - mainly China, and in Europe, Germany or the Czech Republic (Roos (2021), in Poland, e.g., rural areas (Piwowar and Dzikuć, 2019), or the western part of the country. There are also studies presented in a similar approach, but calculated for an individual object Olczak et al., (2020). On the other hand, there are no scientific studies comprehensively covering the area of the Małopolskie Voivodeship in relation to the possibility of obtaining an ecological effect with the use of photovoltaic installations. So far, neither the calculations of the hypothetical maximum environmental effect for the region of the Małopolskie Voivodeship as a result of the implementation of the “My Electricity” program have been presented, nor have the effects of introducing this program been described in the form adopted in this article.

Photovoltaics can be a partial solution to problems related to both ensuring energy security of countries as part of the so-called energy mix (De Sousa, 2013), while being a clean source of energy (Jungbluth, et al., 2009), the use of which reduces the emission of pollutants into the atmosphere. The increased peak demand for electricity in the summer, noted especially in recent years in Poland, can be ensured thanks to the use of photovoltaic panels as an energy source (Sobik, 2019). Following the example of Czech (Raport ERU, 2018; Pálenský and Lupíšek, 2019; Sojkova et al., 2019; Šerešová et al., 2020; Tanil and Jurek, 2020) and German (Fraunhofer Institute for Solar Energy Systems ISE, 2018), that is, in areas with similar insolation conditions, it can be concluded that the potential for the development of photovoltaics in Poland is significant and still unused.

The ecological aspect of adopting solutions reducing the need to use solid fuels for the production of electricity is particularly important in areas with a high level of pollutants emitted into the atmosphere (Shaddick et al., 2018), both in terms of the effects on the health of residents (Brauer, et al., 2016; Yang et al., 2018) and long-term effects related to climate change. (Peel et al., 2013; Dasandi et al., 2021).

PURPOSE, MATERIALS, AND METHODS

The analyzed problem is a continuation of the research conducted by the team, presented in the article “Thermal Modernization Cost and the Potential Ecological Effect - Scenario Analysis for Thermal Modernization in Southern Poland” concerning the achievement of the potential ecological effect through thermal modernization of buildings. In the quoted article, the impact of thermal insulation of the building partition on the reduction of environmental pollution by reducing CO_2 emissions was determined, because the reduction of the so-called low emissions is a key problem in highly urbanized areas. This article can be considered as another part of the problem analysis as the team is reconsidering the possibility of achieving an ecological effect on the environment in the same region, but this time by increasing the scale of photovoltaic micro-installations, which have been funded by the government’s *My Electricity Program*. The team made the assumption that increasing individual energy production using photovoltaic panels will reduce the consumption of energy obtained from solid fuels, and thus reduce the emission of carbon dioxide to the atmosphere.

The aim of the research is:

- determination of the potential reduction of carbon dioxide emissions as a result of the implementation of photovoltaic micro-installations under the My Electricity Program,
- determining the share of this reduction in the annual emissions generated by the largest power plants and combined heat and power plants in Małopolska,

[1]In 2019, the prices of photovoltaic modules in Poland decreased by 29% compared to 2018, the price of coal increased by 15%, gas by 30%, and CO_2 emission rights by 170%. Available online: https://wysokienapiecie.pl/16645-raport-produkcja-energii-i-emisje-co2-w-2018-roku/, accessed on: 12 July 2021

TABLE 1 | Gross electricity production in Poland by fuel (TWh) (Piech et al., 2019).

	2005	2015	2025	2040
Lignite	54.8	52.8	49.7	10.3
Coal[a]	88.2	79.4	78.9	53.3
Gaseous fuels[b]	5.2	6.4	15.4	41.9
Heating oil	2.6	2.0	1.9	1.6
Nuclear energy	0.0	0.0	0.0	36.2
Biomass	1.4	9.0	10.4	14.0
Biogas	0.1	0.9	1.9	3.2
Water energy	2.2	1.8	2.6	3.3
With pumped water	1.6	0.6	0.5	1.3
Wind energy	0.1	10.9	21.3	39.7
Solar energy	0.0	0.1	3.1	14.9
other types of fuel[c]	0.7	1.0	1.1	2.2
Sum	156.9	164.9	186.6	221.6

[a]*Including coke oven gas and blast furnace gas.*
[b]*High-methane and nitrogen-rich natural gas, gas from demethanization of mines, gas accompanying crude oil.*
[c]*Industrial and municipal waste.*

- forecast of carbon dioxide emission reduction, assuming that photovoltaic micro-installations will be installed on all single-family buildings in Małopolska or on the surface of its building plot.

The research was conducted by applying a few research methods, i.e., secondary sources, the desk research method and the exploration method, critical and comparative analysis, inductive and deductive reasoning and some mathematical calculation (**Table 1**).

The methodology used to obtain the final data and conclusions was based on a three-step approach. First, estimation of the amount of pollutant emissions (CO_2) in the Małopolska Voivodship, generated, inter alia, by three coal-fired power stations and combined heat and power stations located in Kraków or in the Metropolitan area of Kraków. Secondly, searching for up-to-date documentation on the rules of government co-financing of energy production from photovoltaic micro-installations under the *My Electricity Program*, which made it possible to calculate the amount of co-financing in 2019 and 2020 and the amount of potential energy production from photovoltaic micro-installations by households in the Małopolska region. In the third step, the hypothetical amount of carbon dioxide emission reduction was estimated, assuming full use of single-family housing in the Małopolska Voivodship for photovoltaic micro-installations.

POTENTIAL ECOLOGICAL EFFECT AS A RESULT OF PHOTOVOLTAIC MICRO-INSTALLATIONS SUBSIDIZED FROM THE *MY ELECTRICITY PROGRAM*

Input Data

In Małopolska, the largest CO_2 emissions are generated from point sources from the industrial sector (**Table 2**).

Part of the air pollution in the Małopolska voivodeship is related to industrial pollution from various economic entities. In 2018, they emitted over 11.34 million MgCO2 in Małopolska, and in 2019 over 11.40 million MgCO2. The industrial plants that are the largest source of greenhouse gas emissions in the region include: Grupa Azoty S.A., PGE Energia Ciepła S.A. – Electrical Power and Heating Plant in Kraków, Tauron Wytwarzanie S.A. – Siersza Power Plant Branch in Trzebinia, CEZ Skawina S.A., ArcelorMittal Poland S.A., Tameh Polska Sp. z o.o. and Tauron Wydobycie S.A. Among those mentioned are 3 coal-fired power plants and combined power and heating plants located in Krakow or in the Kraków agglomeration. (Marshal's Office of the Małopolska Region, 2019; Marshal's Office of the Małopolska Voivodeship, 2020). **Table 3** presents estimates of their annual CO_2 emissions in 2018 and 2019.

In 2019, the government subsidy program *My Electricity Program* was announced in Poland, under which every natural person generating electricity for their own needs after concluding an agreement with the Distribution Network Operator may receive co-financing of expenses incurred for the renewable energy sources (RES) investment. The co-financing concerns the purchase and installation of photovoltaic micro-installations with an installed electrical capacity of 2 to 10 kWp.

This is a limitation resulting directly from the assumptions of the *My Electicity Program*. So far, 2 calls for proposals have been carried out under the programme. As a result, 24,585 grants were granted (as at July 10, 2021) in the amount of up to PLN 5,000 (**Table 4**). From July 1, 2021, another call for applications for a grant up to PLN 3,000 is launched. (My Electricity Program, 2021).

The published ranking lists show that the average power of the installation in both calls is 5.706 kWp, and the total power is 140,806,204 kWp. The total amount of subsidies for all investments is PLN 123,253,919.84.

The question arises to what extent the assembly of photovoltaic installations in single-family buildings can contribute to the reduction of pollutant emissions into the atmosphere in the Małopolska Voivodship. The implementation of a photovoltaic micro-installation allows to reduce the demand of residential buildings for electricity from the power grid, and thus, to a certain extent, the amount of energy produced by the power plant or combined heat and power plant. In order to determine the potential amount of CO_2 emission reduction as a result of the implementation of photovoltaic micro-installations under the *My Electricity Program*, the following were estimated: the annual amount of electricity produced by a photovoltaic micro-installation, the potential change in electricity production in the power plant for a year, and ultimately the potential ecological effect (understood as a reduction of CO_2 emissions in the power plant) obtained by installing photovoltaic micro-installations in single-family buildings in Małopolska.

In order to determine the potential ecological effect, it was assumed that the electricity produced by photovoltaic panels replaces the demand for energy from coal-fired power plants. This assumption allows to determine the maximum, hypothetical effect regarding the reduction of CO_2 emissions. It should be

TABLE 2 | Lists of pollutant emissions in Małopolska against the background of CO_2 emissions[3].

Surface emission				CO_2 emission		
PM10	PM 2,5	Bap	NO_2	Related to the production of heat for the housing sector	From point sources (industrial sector)	From the services and utilities sector
[Mg/year]						
20,085.74	19,601.29	10.49	5,601.03	6,838,127	10,721,731	813,491

TABLE 3 | Estimated amounts of carbon dioxide emissions by 3 power plants/combined heat and power plants in Małopolska in 2018 and 2019 – summary[4].

	Emissions of CO_2 (Mg)	
	2018	2019
PGE Energia Ciepła S.A. – Elektrociepłownia w Krakowie	1,587,600	1,482,000
Tauron Wytwarzanie S.A. – Oddział Elektrownia Siersza w Trzebini	1,134,000	1,140,000
CEZ Skawina S.A.	1,360,800	1,026,000
SUM	4,082,400	3,648,000

TABLE 4 | Volume of subsidies and achieved installation capacity in the government program called *My Electricity* in the Małopolska Voivodship[5].

Years (call)		2019	2020
Number of submitted applications according to ranking lists		3,211	21,468
Installation power (kWp)	Min	2.010	2.000
	Average	5.409	5.750
	Max	10.000	10.000
Total installation power (kWp)		17,369.449	123,436.755
Average grant amount (PLN)		4,981.82	4,996.15
Total grant amount of all investments (PLN)		15,996,614.44	107,257,305.4

emphasized, that achieving the assumed maximum effect through photovoltaic installations is currently not possible i.a. due to the limitations of the power grid related to the transferring excess energy and the lack of energy storage. However, this assumption makes it possible to verify the scale of the potential maximum effect and relate it to the financial costs incurred.

Results

Electricity Production Annually

The annual amount of electricity produced by a photovoltaic micro-installation can be determined according to the formula (Szymański, 2020):

$$E\ [kWh] = \frac{R\left[\frac{kWh}{m^2}\right] x\ P\ [kW]\ x\ PR}{Rstc\left[\frac{kW}{m^2}\right]}$$

E–electricity production, generated by a photovoltaic micro-installation. R–solar radiation on the surface of the modules. P–installation power. PR–performance ratio. Rstc–STC radiation intensity (radiation intensity under STC conditions = 1 [kW/m2])[2]

[2]Szymański., 2020. *Instalacje fotowoltaiczne*, GlobEnergis SP. Z O.O., Kraków, p. 324

The amount of energy produced by a photovoltaic installation depends i.a., : on the conditions of insolation (R), the power of the installation (P), the efficiency of the installation expressed in the form of a performance ratio (PR) and the radiation intensity in STC (Standard Test Conditions–standardized test conditions of the photovoltaic module).

In Poland, it is assumed that the value of annual solar radiation per horizontal area is from 950 to 1,100 kWh/m^2 per year. (Szymański, 2020). Its level depends, i.a., on its geographical location. In the southern part of the country, solar radiation rates are usually higher than in other areas of the Poland. In this article, it was assumed that the average annual solar radiation per horizontal area for the Małopolska Voivodeship is 1,028 kWh/m^2. (Szymański, 2020). In order to calculate the solar radiation on the surface of PV modules, this indicator should be adjusted by the radiation correction factor for the horizontal surface, which depends on the inclination and orientation of the installation. Due to the inability to determine the actual conditions for individual investments, the average value for all installations was assumed under optimal conditions, i.e. the angle of inclination 35°, deviation from the south 5° (correction factor = 1.14). (Szymański, 2020).

The performance ratio of PV installations based on very good components is about 80–88%. In the case of low-quality components, these values may be below 75%. (Szymański,

TABLE 5 | Potential annual production of electricity generated by subsidized photovoltaic microinstallations in Małopolska - calculation results.

Year (call)		2019	2020
E (kWh)	Total	16,488,040	117,172,982
	Average (per 1 installation)	5,135	5,458

TABLE 6 | Potential change in electricity production in the power plant for a year - the results of calculations.

Year (call)		2019		2020	
Unit		(kWh/year)	(GJ/year)	kWh/year)	GJ/year)
ΔE	Total	17,540,468	63,145.69	124,652,108	448,747.59
	Average	5,464	19.67	5,806	20.9

2020). For the purposes of this study, it was assumed that the new installations would meet modern quality requirements. For this reason, the performance ratio was assumed at 81%.

Data on the power of individual installations were obtained from the published ranking lists of the *My Electricity Program.*

As a result of the analysis, the potential average annual electricity production generated by subsidized photovoltaic micro-installations is 5,416 kWh. The total results of the calculations for each call are presented in **Table 5**.

Potential Electricity Production Change at a Power Station Per Year

The reduction in the annual electricity production in the power plant due to the use of photovoltaic installations in single-family buildings can be calculated on the basis of formula (Gużda and Szmolke, 2017):

$$\Delta E\left[\frac{kWh}{year}\right] = \frac{E}{\eta_{PSE}}$$

ΔE–change in electricity production in the power plant. E–production of electricity generated by a photovoltaic micro-installation. η_{PSE}–losses of electrical energy transmission in Polish Power Grids.

The calculations are legitimate by the hypothetical assumption of the possibility of transferring excess electricity to the electricity grid. The amount of change in electricity production in the power plant is influenced by the losses of electrical energy transmission in the Polish Power Grids. According to the data of the Polish Society and Distribution of Electricity (Polskie Towarzystwo i Rozdział Energii Elektrycznej), the rate of losses in the transmission network in 2016 was 5.65%. (Polish Society of Transmission and Distribution of Electricity, 2018). In view of the above, $\eta_{PSE} = 0.94$ was adopted. The results of the calculations are compiled in **Table 6**.

Estimated Size of the Potential Ecological Effect

The ecological effect measured as a reduction in CO_2 emissions generated by coal-fired power plants/combined heat and power plants can be determined on the basis of the formula (Gużda and Szmolke, 2017):

TABLE 7 | Potential ecological effect, obtained thanks to the installation of photovoltaic micro-installations in single-family buildings in Małopolska–calculation results.

Year (call)		2019	2020
ΔCO_2 (kg/year)	Total	5,906,647.3	41,975,849.5
	Average (per 1 building)	1,839.5	1,955.3

TABLE 8 | Comparison of potential reduction of CO_2 emissions generated by coal-fired power plants with the current annual CO_2 emissions generated by 3 power plants/combined heat and power plants in Małopolska.

Current CO_2 emissions (as of 2018) (Mg)	Potential total reduction of CO_2 emissions (Mg/year) with 24,679 buildings	Level of reduction (percentage)
4,082,400	47,882.4968	1.17(%)

$$\Delta CO_2\left[\frac{kg}{year}\right] = \Delta E\ x\ WECO_2$$

ΔCO_2 – reduction of carbon dioxide emissions into the atmosphere by coal-fired power plants/combined heat and power plants. ΔE–change in electricity production in the power plant. $WECO_2$ – carbon dioxide emissions in commercial power plants and combined heat and power plants.

The carbon dioxide emission rate in power plants and combined heat and power plants powered by hard coal in 2018 in Poland amounted to 93.54 kg/GJ. (National Center for Balancing and Management of Emissions, 2018).

The results of research on the potential ecological effect obtained as a result of the implementation of photovoltaic installations under the *My Electricity Program* are presented in **Table 7**. As a result, it was found that the use of a photovoltaic installation in 1 single-family building allows for a reduction of CO_2 emissions by the power plant at the level of 1,940.2 kg/year.

A comparison of the potential reduction of CO_2 emissions to the current emissions from the 3 analyzed power plants and combined heat and power plants in Małopolska allows us to conclude that the implementation of investments that have qualified for co-financing under the *My Electricity Program* may potentially contribute to the reduction of CO_2 emissions from power plants at the level of 1.17% (**Table 8**).

At the end of 2016, there were 563,700 single-family buildings in the Małopolska Voivodship. (Lewandowski et al., 2018). If all these facilities were equipped with a photovoltaic micro-installation, this would potentially reduce CO_2 emissions in power plants by about 26.79% (**Table 9**).

DISCUSSION AND CONCLUSION

The production of electricity in Poland is mostly based on fossil fuels, in particular solid fuels (hard coal and lignite). Its production is associated with an increased emission of air

TABLE 9 | Potential reduction of CO_2 emissions when installing a photovoltaic micro-installation in all single-family buildings in Małopolska.

Average reduction of CO_2 emissions achieved by installing a photovoltaic micro-installation in 1 single-family building (Mg/year)	1.9402
CO_2 emissions by the 3 largest combined heat and power plants in Malopolska – 2018 (Mg/year)	4,082,400
Number of single-family buildings in Małopolska	563,700
Potential reduction of CO_2 emissions when installing a photovoltaic micro-installation in all single-family buildings in Malopolska (Mg/year)	1,093,690.74 (26.79%)

pollutants. In this paper, the authors focused on the analysis of the potential impact of solutions related to the application of micro photovoltaic installations on the overall reduction of carbon dioxide emissions. The area that was selected for the study includes the Małopolska Voivodship. This location was chosen due to the fact that air quality standards are significantly exceeded in this area, especially in areas with a high density of single-family housing not connected to heating systems. In these areas very high emissions of pollutants and greenhouse gases are observed, resulting from burning fossil fuels in old-type furnaces. At the same time, these households are large consumers of electricity, which also comes from fossil fuels. Reducing the level of consumption of electricity from external power sources in single-family houses is becoming one of the important actions to reduce CO_2 emissions by large power plants and CHP plants. In Małopolska among the industrial plants that are the biggest emitters of greenhouse gases are 3 coal-fired power plants/combined heat and power plants located in the Krakow agglomeration. They are the main supplier of electricity in the region. The elements that make it difficult to reduce low emissions include: technical restrictions on the development of centralised heating systems, the dispersal of buildings and complicated and expensive connections to the grid.

The conditions predispose the analysed area for a large-scale application of solutions which will contribute to the reduction of pollutant emissions into the atmosphere. One of the solutions whose ecological effect is considered in this article is the installation of micro photovoltaic installations in single-family buildings. This activity may contribute to the reduction of carbon dioxide emissions generated by power plants in the region. The research carried out allowed to determine the potential level of greenhouse gas reduction, in particular CO_2 reduction, as a result of reducing electricity consumption by single family houses using micro photovoltaic installations. The starting point for the analysis was statistical data on the current implementation of the government programme *My Electricity Program*, which assumes financial support for the construction of individual photovoltaic installations in single-family buildings. For a single building, the legislator provided a maximum power of micro-installation financed by the *My Electricity Program* at the level of 10 kW.

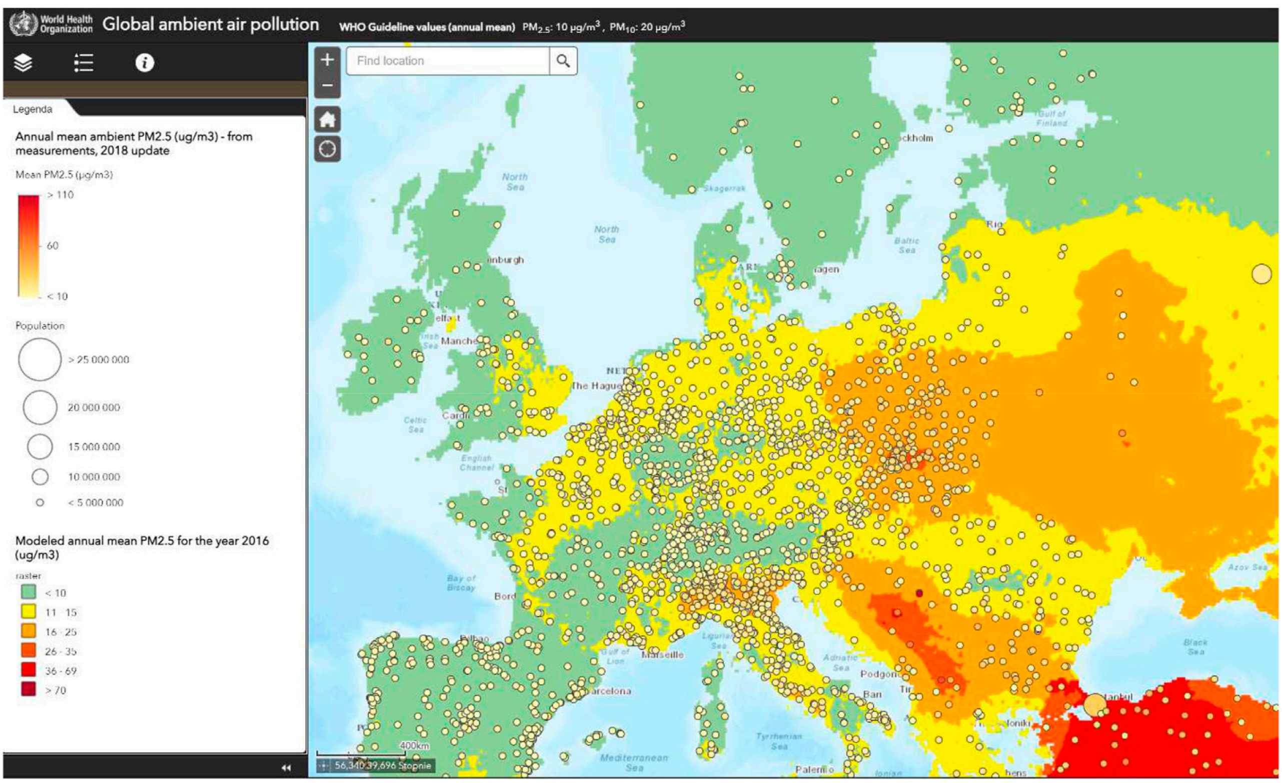

FIGURE 1 | WHO: Global ambient air pollution. Update 2018.

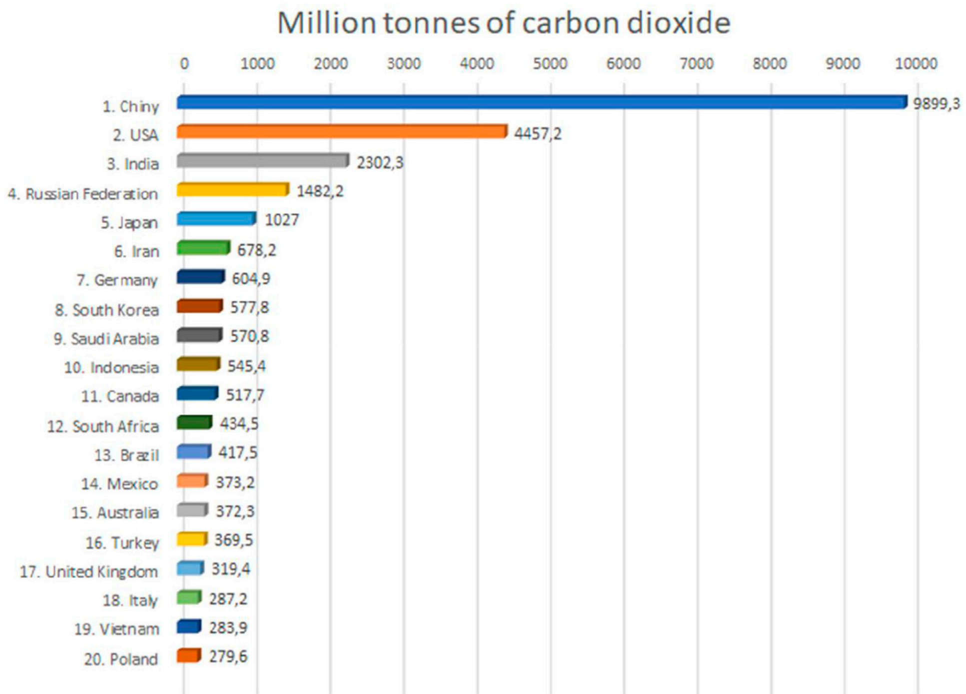

FIGURE 2 | Carbon dioxide emissions in 2021 - largest CO_2 emitters in the world. According to Statistical Review of World Energy 2021/70th edition. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-co2-emissions.pdf (accessed on: August 24, 2021).

The results of the study are presented in **Tables 4–9**. Particularly noteworthy are the results presented in **Table 4**. They indicate an increase in the interest of single-family house owners in obtaining subsidies for the installation of photovoltaic installations. Moreover, a mild upward trend in the average power of installed micro-installations is observed. In 2019, the average power of a photovoltaic installation for one single-family building was 5.135 kWh, which increased to 5.458 kWh in 2020. This may be due to the desire to shorten the payback period for the costs incurred by users of micro photovoltaic installations for its installation. The electricity surplus obtained during the summer period can be discharged into the general electricity grid. In return, during the winter period there is a chance to get a discount on the purchase of needed electricity from the grid. Pursuant to the Act on Renewable Energy Sources, an energy prosumer, who produces electricity in a micro-installation with a total installed capacity of no more than 10 kW, can collect 80% of each 1 kWh of energy supplied to the grid. (Act of 20th February 2015 on the Renewable Sources of Energy).

As indicated by the results of the conducted analyses (**Table 8**, **9**), the potential of single-family buildings in relation to the feasibility of photovoltaic installations makes it possible to reduce the existing CO_2 emissions in power plants and combined heat and power plants, which have been responsible for the supply of electricity so far. Photovoltaic installations, realised with the use of co-financing within the confines of *My Electricity Program* in the area of Małopolskie Voivodship, potentially allow to reduce CO_2 generated by the three power plants and combined heat and power plants under consideration by 1.17%. Potentially, the implementation of photovoltaic micro-installations on all 563,700 single-family buildings in the Małopolskie Voivodeship could reduce CO_2 emissions to the atmosphere by more than 26% of the current level (**Table 9**). This is a very favourable result from the point of view of the achievable environmental effect, but not sufficient to become independent from fossil fuels. The achievement of such a high result is unlikely due to existing constraints such as construction, location and legal restrictions, which prevent or hinder the implementation of photovoltaic panels on all existing buildings. There are also limitations related to the power grid and the lack of energy storages.

Moreover, the research results presented in this paper do not take into account the effect that micro photovoltaic installations have on the local microclimate or the effects of disturbances that these installations may generate (Galla and Wlas, 2021; Pijarski et al., 2018). At the same time, research results presented in the literature (Yue et al., 2021) suggest that the use of photovoltaic panels affects the local microclimate by raising the ambient temperature. These results apply to photovoltaic power plants, but for micro-installations such studies have not been presented so far.The demand for energy is constantly increasing. However, in order to counteract the negative effects of climate change, energy must come from sources with lower CO_2 emissions. The

Green Deal policy introduced in Europe makes the use of pro-environmental solutions mandatory. As shown in the article, actions on a mass scale bring measurable environmental benefits. The proposed potential solution relates to solving many other problems, such as creating the behaviour of RES energy consumers. However, the biggest challenge is not how to generate electricity from RES, but how to store it efficiently. The performance of photovoltaic installations is highly dependent on weather and insolation conditions. As a result, energy production often does not coincide with the expectations of its users. Moreover, existing constructional, location and legal limitations do not allow the implementation of photovoltaic panels on all existing facilities. At present, we do not have an effective and cheap technology that would solve this problem in a comprehensive way. On a micro scale, energy storage for photovoltaic micro-installations is proposed, which allows to achieve energy independence with certain parameters of the installation's expansion. For strategic reasons, in the current economic situation, a complete reduction of fossil fuel power plants in favour of photovoltaic installations is not possible, due to the lack of effective energy storage (Tadeusiewicz, 2020). It is particularly important at times of peak energy demand to maintain a constant power supply to the system.

Modern micro-installations based on renewable energy sources are not capable of storing large amounts of surplus energy. The solution could be large energy storage facilities, the construction of which generates considerable costs, and the use of forms of conversion to other energy carriers, such as hydrogen, result in a large loss of energy recovery. New technologies for storing energy in a non-polluting manner are currently being researched. This is a very dynamic field of science today.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

RB and RŁ: conception and design of the study; RP: organization of data base; RŁ and JB: analysis of data; RŁ, JB, RP and AC: writing the paper; RB: supervision.

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