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Population Density as a Factor for Distributed Energy Generation Development, Renewables Consumption and CO2 Emissions: Evidence from Poland and Argentina

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Abstract:

Purpose: *The purpose of this article is to identify and analyse the relationship between distributed renewable energy generation systems and population density which is related to spatial urbanization patterns that affect CO_2 emissions.*
Design/Methodology/Approach: *The authors analysed, using the example of two countries with similar population sizes but very different land use and urbanization patterns, as well as relatively ineffective spatial planning systems (Poland and Argentina) – whether there are the correlations between the indicators of: population density, renewable electricity production, renewable energy consumption, CO_2 emissions from transport, and CO_2 emissions from electricity consumption.*
Findings: *The results of this research underscore the multi-faceted impact of urbanization on energy and environmental indicators and highlight diverse relation-ships between population density and the consumption and production of renewable energy, as well as CO_2 emissions in Poland and Argentina. In Poland there is an inverse relationship between population density and the consumption and production of renewable energy, while in Argentina there is a mixed relationship.*
Practical Implications: *In the concluding part of the article, the authors formulate recommendations pointing primarily to the need to in-crease the effectiveness of integrated resource planning and land use management, especially within suburban zones, taking into account energy demand and consumption in transport and other municipal services.*
Originality/Value: *The originality of the article results from the use of quantitative methods and macro-level indicators to examine the relationship between the development of distributed energy systems and their impact on population density.*

Keywords: *Energy consumption, distributed energy resources (DER), distributed generation (DG), renewable energy sources (RES), CO_2 emissions, transport emissions, land use patterns, urban sprawl.*

JEL codes: *F63, F64, O18, O21, O44, O57, P11, P18, P41, P48, Q42, Q43, Q48, R14.*

Paper type: *Research article.*

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1. Introduction

1.1 Literature Overview – Relationships between Distributed Generation, Population Density and CO_2 Emissions

One of the considerations that strongly distinguishes traditional power generation, which is typical of large and centralized utility power sources from renewable power generation in DG systems is the strong dependence of the latter on land use patterns.

Due to the so-called low density of RES in physical space (van Zalk and Behrens, 2018; Dijkman and Benders, 2010) (arising from factors such as the specific intensity of solar radiation, wind intensity and frequency, river network layout, or the occurrence of geothermal water deposits), more favourable conditions for the development of DG systems exist in areas with lower building density (and consequently lower population density) (Zhang, Gang, Zhang and Yuan, 2023; Śleszyński, Nowak, Brelik, Mickiewicz and Oleszczyk, 2021; Moroni, Antoniucci and Bisello, 2016).

Renewable energy (its infrastructure and facilities) is highly terrain-intensive (Hernandez, Easter, Murphy-Mariscal, Maestre, Tavassoli, Allen, Barrows, Belnap, Ochoa-Hueso, Ravi, and Allen, 2014), and thus can also be conflicting (Kim, Park, Song, Hong, Jo and Lee 2022; Ketzer, 2020; Oakleaf, Kennedy, Baruch-Mordo and Kiesecker, 2017).

For this reason, the natural place predisposed to the development of distributed energy, using RES will therefore be primarily rural, agricultural, suburban areas (Poggi, Firmino and Amado, 2018; Planning…, 2023; Kereush and Perovych, 2017; Piwowar and Dzikuć, 2019). Such areas are technically more favourable for the development of distributed energy due to spatial conditions – locating physical infrastructure for obtaining energy from renewable sources is easier (and cheaper) there.

This is because suburban and rural areas do not require costly adaptation, as may be required in the case of highly urbanized areas in inner city zones (Marrone, Fiume, Laudani, Montella, Palermo, and Fulginei, 2023), where in already existing and compact development, there may be a lack of physically available space to locate technical infrastructure for renewable energy production, and the existing distribution infrastructure is designed to supply energy to end users from centralized sources, rather than periodically receiving over-production of energy from local and domestic sources.

The development of renewable distributed energy, especially if additionally supported by the public sector, can – indirectly – contribute to stimulating the growth of lower-density development and population areas. This, in turn, means that the development of these systems can – on the one hand – contribute to reducing the share of hydrocarbon fuels in the energy balance of the economy (resulting in a reduction in CO_2 emissions), but on the other hand potentially create new problems and challenges related to dispersed land development and the resulting anthropogenic environmental hazards.

The problem comes from the fact that the possibility for a single entity (household, business) to have its own source of cheap energy, and therefore independent of supply from the centralized network, can lead to the dispersion of development, especially residential in the suburban areas, particularly those that are beyond the reach of centralized power grids (this effect is particularly evident in the case of heat supply systems generated from centralized sources and distributed locally, but can also be seen in relation to the development of individual power systems).

The development of distributed energy, based on clean (i.e., emission-free) and RES, and thus environmentally friendly means of generation, can therefore generate a kind of "suburbanization impulse" (Trainor, McDonald and Fargione, 2016), and thus cause secondarily another kind of negative environmental effect in the form of urban sprawl, resulting in changes in the spatial behaviour of the population.

The urban sprawl (development of areas with relatively low population density), may be further accompanied by a secondary increase in energy demand (Li, Yang, Huang, Liu and Guo, 2023; Lasarte Navamuel, Rubiera Morollón and Moreno Cuartas, 2018; Cartone, Díaz-Dapena, Langarita, and Rubiera-Morollón, 2021), consumed primarily in transportation (Lefèvre, 2009; Marique, Dujardin, Teller and Reiter, 2013; Kaza, 2020).

2. Research Hypotheses

Considering the above remarks, on the interdependencies between urbanization patterns, distributed energy generation and CO_2 emissions, we formulated two research hypotheses:

H1: The potential for renewable energy production in DG systems is quite closely linked to land use patterns, i.e. in such a way that lower development density (manifested by lower population density) promotes the development of renewable, distributed energy sources.

H2: Low-spatial density of RES developed in the form of DG systems can contribute to the development of low-density settlement systems and population, causing negative spillover effects (externalities) in the form of suburbanization and deurbanization – the sprawl of development in suburban areas – which may ultimately lead to an increase in energy demand for transportation and other municipal services using grid infrastructure.

3. Materials and Methods

Studies of the relationship between distributed and decentralized renewable energy systems can be conducted in a variety of ways and depend in part on the availability of public statistics data. The authors of this paper have chosen for comparison two countries with similar historical dependence on fossil fuels and similar energy policy goals and directions aimed at supporting the development of RES and DG systems.

Table 1. *Argentina and Poland – general comparison: main similarities and differences (2023)*

Compared characteristics	**Country / state name**	
	Argentina	**Poland**
Basic geographical features	44,7 mln inhabitants	37,7 mln inhabitants
	territory of 2,780 mln km^2	territory: 0,312 mln km2
Population & urbanization	population denisty: 16 people/km^2; urbanization index: 92%	population denisty: 120,8 people/km^2; urbanization index: 59,68% (slowly ↓)
Energy resources	large variety of natural resources in general (energy resources in particular)	strong dependence on domestic coal and lignite resources as well as gas supplies from Russia for many decades
	significant gas and lithium reserves and strong renewable energy potential.	the potential of geothermal energy in some regions and local areas and the potentially high availability of biomass resources in rural areas
Energy policy	public energy policy mainly at the national level	public energy policy at the national as well as at local level

Source: *Own compilation.*

These countries have a similar size of resident population (Table 1), however differ fundamentally in their land-use structure and the shape of their settlement system. Poland is a country with a strongly polycentric settlement system, but also with a fairly significant percentage of its population living in rural areas. Argentina, on the other hand, which is almost ten times larger in area, has a strongly monocentric settlement system, an extensive share of agricultural land in the country's total area and a high degree of urbanization (concentration of population in cities).

These differences translate into a drastically different magnitude of the population density index in the two countries. Thus, it can be assumed that Poland as a whole is a territory with a very high degree of suburbanization, while Argentina, conversely, has a fairly compact (concentrated on a smaller area of the country) settlement pattern. These differences translate into completely different values of the population density index of the two countries.

Our intention was also to compare countries with different energy mixes. In this paper, we analyse data on the degree of urbanization, renewable energy consumption, renewable energy production, CO_2 emissions from personal transportation and CO_2 emissions from electricity (Table 2).

Table 2. *Data for statistical analysis*

Data	Indicator	Designation
Population density (independent variable)	Pop_dens	people per sq. km of land area
Renewable energy consumption (dependent variable)	Ren_cons	% of total energy consumption
Electricity production from renewable sources (dependent variable)	Ren_prod	% of total
CO_2 emissions from transport (dependent variable)	CO2_trans	% of total fuel combustion
CO_2 emissions from electricity (dependent variable)	CO2_elec	% of total fuel combustion

Source: *Own compilation.*

The study looked for correlations between the indicators mentioned in table 2. All data were sourced from the World Bank's database, and the time range was 1990-2020.

It should be emphasized that population density was treated in this article as a value derived from the phenomenon of concentration/dispersion of development at the scale of the entire settlement system, the relationship of which with the production and consumption of energy from renewable distributed energy systems was sought to demonstrate (however, in formulating the final conclusions, it should be borne in mind that Argentina's low population density index generally means a high concentration of development in that country, and Poland's much higher population density index generally means a lower concentration of development in that country).

Population density, which refers to the number of people living per unit area, is often used as a proxy to measure the stage of urbanization in a region. At a basic level, it is assumed that higher population density usually indicates more urbanized areas, while lower population density is often associated with rural or less developed regions.

In addition, an increase in population density in a region often signals a concentration of people in urban centres, due to better employment opportunities, access to education and health care, access to infrastructure and other amenities offered by cities. In this context, our intention was to analyse other variables such as renewable energy consumption (Ren_cons), electricity production from renewable sources (Ren_prod), CO_2 emission from transportation (CO2_trans) and electricity (CO2_elec) and compare them between the two countries studied.

It should also be mentioned that population density is often used by spatial planners and urban planners as an indirect indicator of infrastructure needs, particularly for such systems as collective public transportation, water supply, sewerage, electricity and network heat supply (remote) systems, as well as other public services. This means that population density can therefore be used as a useful indicator (measure) indicating indirectly the degree of concentration/sprawl of settlements.

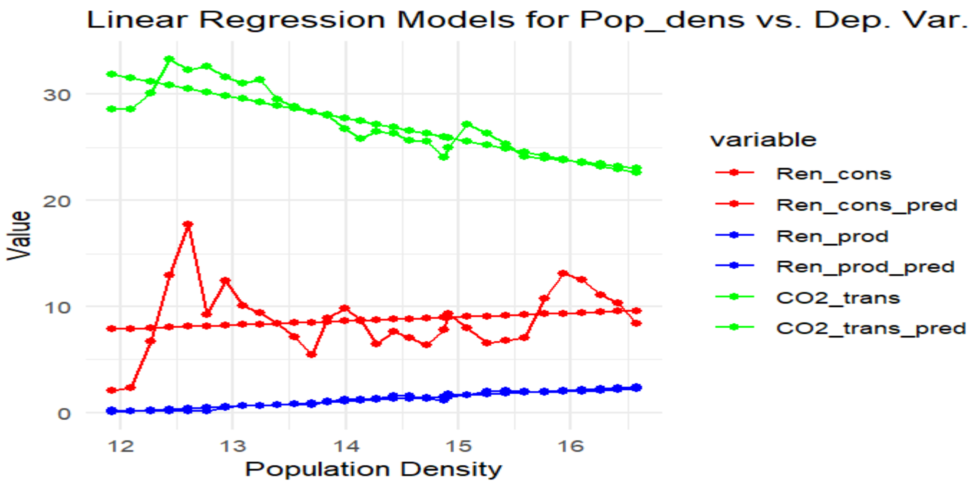
The constructed model, due to the quantitative approach at the macro level, is simplified in nature, but it allows to capture statistically significant relationships between the indicated independent variable (population density) and the dependent variables (production and consumption of renewable energy and CO_2 emissions), in the context of comparing with each other two countries with the aforementioned similarities and differences – which was the primary intention of the authors.

4. Research Results

4.1 Results of Data Analysis for Argentina

Since the data used for the study represents a high level of generality, the effect of the independent variable on the dependent variables was tested with a one-way ANOVA. The graphical form of the linear regressions models are shown in Figure 1 and the nonlinear regression model is shown in Figure 2.

Figure 1. *Linear regression for variables (ARG)*

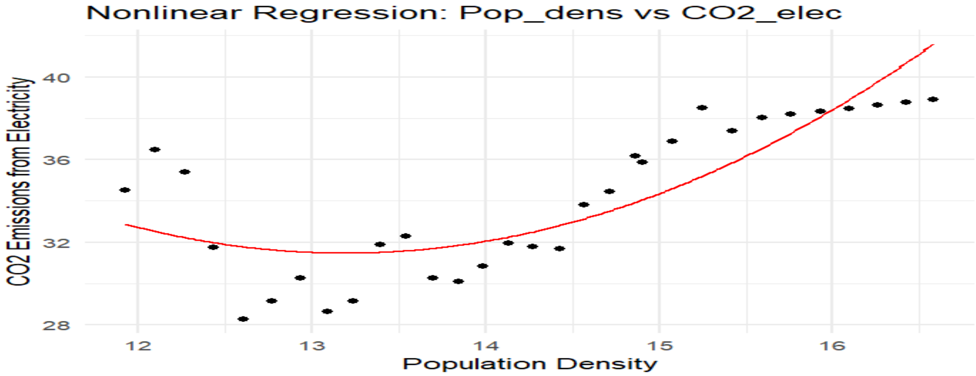


Source: *Own compilation.*

4.2 Results of Data Analysis for Poland

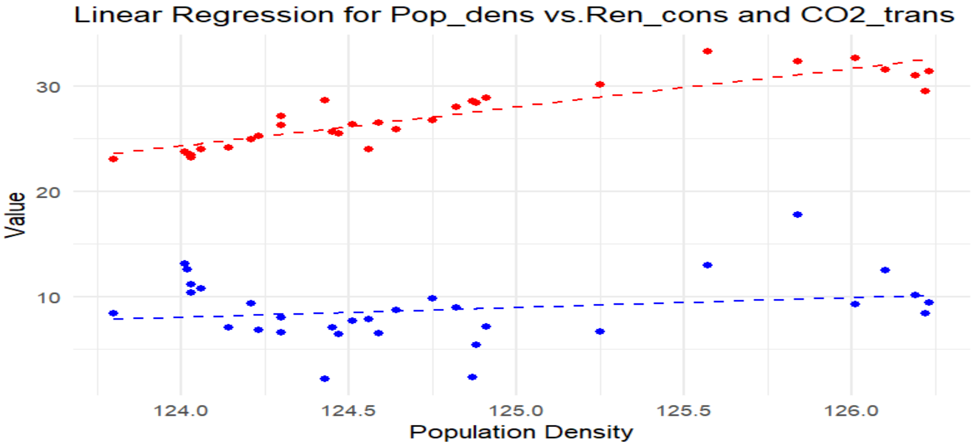
One-way ANOVA for Poland provided the following results. The graphical form of the linear regression models are shown in Figure 3 and nonlinear in Figure 4.

Figure 2. *Nonlinear regression for variables Pop_dens and CO2_elec*



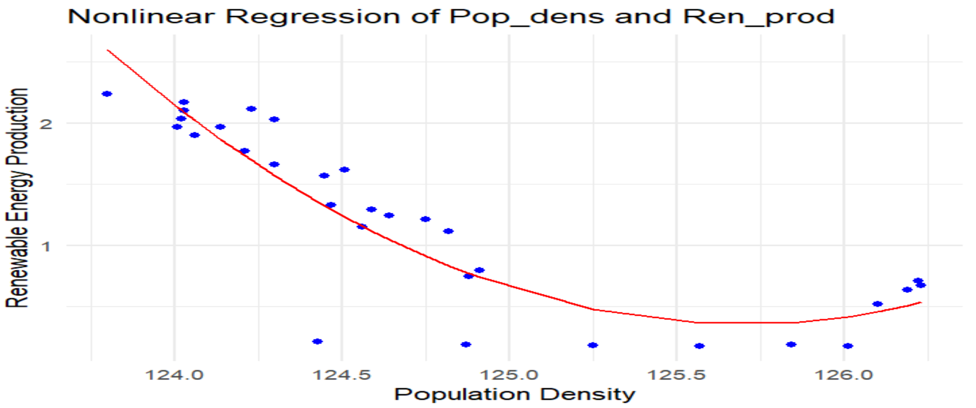
Source: *Own compilation.*

Figure 3. *Linear regression for variables (PL)*



Source: *Own compilation.*

Figure 4. *Nonlinear regression for variables Pop_dens and Ren_prod (PL)*



Source: *Own compilation.*

5. Discussion of Research Results, Conclusions and Recommendations

Research to date has focused primarily on identifying the relationship between a city's spatial structure and its impact on energy consumption and associated CO_2 emissions (Li, Zhou, Wang, and Hu, 2018; Cui, Cai, Bin and Wang, 2020; Shi, Xu, Li, Chen, Gong, Wu and Yu, 2020; Crippa, Guizzardi, Pisoni, Solazzo, Guion, Muntean, Florczyk, Schiavina, Melchiorri and Fuentes Hutfilter, 2021; Wang, Madden and Liu, 2017; Song, Feng, Wang, Fu, Jiang and Chen, 2019; Liu, Ou, Chen, Wang, Li, Jiao and Liu, 2019), particularly those related to transportation (Wang, Liu, Zhou, Hu and Ou, 2017; He, Meng, Wang and He, 2011; Liu, Ma and Chai, 2017).

In contrast, this article attempts to answer the question of whether the development of DG energy systems has the side effect of sprawling – dispersing spatial structures (primarily with regard to residential development) which, in turn, may secondarily increase energy consumption for transportation and other subsistence needs of the population related to municipal energy consumption, and subsequently cause an (unintended) increase in CO_2 (bearing in mind that still a significant part of the energy produced and consumed, both in Argentina and Poland, comes from fossil fuels).

In this paper, we performed a correlation and regression model analysis for the impact of urbanization, as measured by population density, and RES consumption, RES production, CO_2 emissions from transportation, and from energy generation. The results highlight the multifaceted impact of urbanization on energy and environmental indicators, and show different relationships between population density and RES consumption and production, as well as CO_2 emissions in Poland and Argentina.

Poland shows an inverse relationship between population density and renewable energy consumption and production, while Argentina shows a mixed relationship. Urbanization leads to increased production of renewable electricity, it also results in higher electricity-related CO_2 emissions. The reduction in transport-related CO_2 emissions can be attributed to efficient urban transportation systems and a possible shift to electric vehicles (in Poland, for example, there is an annual increase in the use of individual electric cars and electric or gas-powered public transportation vehicles).

In the context of Argentina, the linear regression analyses delineate a scenario where urban density positively correlates with renewable energy production, signifying that as cities become denser, their capacity or inclination to bolster renewable energy infrastructure increases.

This relationship underscores the potential of urban areas in Argentina to contribute significantly to the renewable energy landscape. Conversely, the analysis regarding

CO_2 emissions from transportation reveals a notable decrease in emissions as population density escalates, suggesting the presence of more efficient transportation systems or alternatives in denser urban configurations that mitigate CO_2 emissions.

Simultaneously, the study unveiled a non-linear relationship between population density and CO_2 emissions from electricity consumption in Argentina. This complexity hints at varying degrees of emissions increase with urban density, potentially reflecting differences in energy demand management, efficiency measures, and the energy mix across urban densities. Such a non-linear pattern underscores the challenge in linearly extrapolating the impacts of urban densification on electricity-related CO_2 emissions, necessitating a nuanced understanding of urban energy consumption behaviours.

In Poland, the regression models unearth a distinct narrative. The negative correlations between population density and renewable energy consumption. The reasons for this state of affairs can be attributed to the model of RES management, in which prosumers with individual houses (mainly located in peripheral areas of larger towns and cities) have RES micro-installations, while using the produced electricity for their own needs. The average self-consumption from RES in Poland is 30-40% of the electricity generated from backyard PV installations (Kurz and Nowak, 2023).

The regression analysis conducted for Poland revealed a non-linear relationship specifically between population density and renewable energy production. This indicates that the interaction between urban density and the capacity or efforts to produce renewable energy does not follow a straightforward path. Instead, it suggests a more complex relationship where certain thresholds or factors related to urban density could disproportionately influence renewable energy production.

Such a non-linear pattern points towards an intricate interplay between urban form, availability of space for renewable energy installations, local policy environments, and perhaps socio-economic conditions that collectively shape the renewable energy production landscape in densely populated areas.

This nuanced understanding underscores the complexity of urban systems where multiple variables interact in dynamic ways to influence outcomes. Consequently, this non-linear relationship emphasizes the necessity for policies and planning strategies that are adaptable and responsive to the specific characteristics of urban environments. For policymakers and urban planners, recognizing and accounting for these non-linear dynamics is crucial for designing interventions that effectively promote renewable energy production within the urban development context.

Furthermore, such non-linearity necessitates a more sophisticated analytical approach to urban and energy planning, suggesting that simple linear models may not always capture the full extent of the relationships between urban density and environmental or energy production metrics.

This calls for a more integrated, systems-thinking approach to urban planning and energy policy that considers the complex feedback loops and interactions inherent in urban systems.

Furthermore, Poland's transportation-related CO_2 emissions exhibit a decrease with increased urban density, aligning with the proposition that denser urban areas potentially facilitate more efficient transportation modalities, thereby reducing CO_2 emissions. This observation is consistent across both countries, reinforcing the notion that urban densification can serve as a lever for transportation efficiency and CO_2 mitigation.

The findings concerning the relationship between population density and CO_2 emissions from electricity in Poland present a compelling aspect of urban energy dynamics, indicating neither a linear nor a non-linear relationship is evident between these variables. Furthermore, the near absence of correlation between population density and CO_2 emissions from electricity consumption suggests a level of independence in the way urban density impacts electrical energy's carbon footprint.

It may imply that other factors, external to the direct influence of population concentration, play a more significant role in determining CO_2 emissions from electricity in urban areas. Such factors could include the energy mix, energy efficiency measures in buildings and infrastructure, and the presence of policies promoting sustainable energy consumption and production.

The lack of a discernible pattern between urban density and CO_2 emissions from electricity consumption challenges some of the conventional wisdom regarding the benefits of urban densification for reducing environmental footprints.

While denser cities are often thought to be more energy-efficient due to shorter distances and potentially lower per capita energy use for heating and transportation, this does not automatically translate into lower CO_2 emissions from electricity. This could be due to the complex interplay between energy demand, supply characteristics, and the carbon intensity of electricity generation, which may not straightforwardly correlate with population density metrics.

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