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Quantifying the Air Pollution Mortality Impacts of Renewable Energy Farms across 150 U.S. Cities

Samir Chowdhury and Vihaan Mathur*

Youth Climate Action Team Inc, USA

Abstract

Through trend and meta-analysis, this study estimates the public health benefits of renewable energy implementation in the United States by quantifying the mortality impacts of different sizes and types of renewable energy farms. The authors investigated the mortality benefits spurred by the reduction of $PM_{2.5}$ and PM_{10} air pollution that occurs with the implementation of 100 MW and 500 MW wind energy, solar energy, and nuclear energy farms in 150 populous cities across the U.S. The authors utilized socio-environmental statistical relationships postulated from the Harvard Six Cities Study to calculate 900 mortality benefit data points. The study revealed that each type of renewable energy project, across sizes and energy types, reduces mortalities induced by air pollution, or "saves lives", with the three energy types reducing an average of 3.75 deaths annually across all cities. When considering the U.S. 2021 estimated value of a statistical life of $ 7,500,000 per life, these benefits equate to $ 28,125,000. These findings affirm the tangible public health value of renewable energy and the life-saving value proposition that comes with it. This study found that wind energy reduces the most mortality; however, a One-Way ANOVA test indicates there is no statistically significant difference between the deaths reduced by the three types of energy. There is a correlation between mortalities reduced and social factors such as poverty and race, and the authors recommend that decision makers create renewable energy policies that prioritize and center low income, communities of color.

Keywords: Climate change; Air pollution; $PM_{2.5}$; Environment; Environmental justice; Policy; Energy

Introduction

According to the World Health Organization, 4,200,000 deaths from air pollution occur worldwide every year and 99% of people breathe air that surpasses pollution guidelines [1]. The majority of air pollutants are made up of Particulate Matter (PM) which refers to microscopic solid particles and liquid droplets found in the air. $PM_{2.5}$ refers to Particulate Matter with a diameter of $_{2.5}$ micrometres or less [2]. These particles are emitted from power plants and can also be created through chemical reactions in the atmosphere. Due to their minuscule size, $PM_{2.5}$ particles can be inhaled deeply into human lungs and the bloodstream, and are harmful to overall health as well [3]. Numerous studies have determined the health effects of air pollution, with the Harvard Six Cities Study titled "An Association between Air Pollution and Mortality in Six U.S. Cities" in 1993 first finding a correlation between cities with higher air pollution levels and higher mortality levels.4 This study aims to quantify the relationship between changes in air pollution and resulting changes in mortality, specifically cardiovascular mortality and the human intake of air particles known as $PM_{2.5}$ [4]. The study found a clear association between changes in $PM_{2.5}$ concentration and cardiovascular mortality and paves the way for quantifying the strong public health incentives for renewable energy implementation.

In addition to this statistical relationship between air pollution and cardiovascular mortalities, short term health effects of exposure to air pollution include coughing, irritation in sensitive areas like the nose and eyes, breathing problems, chest pain, and worsening of symptoms caused by conditions like asthma [5]. The long term effects of air pollution are more difficult to observe due to the presence of confounding variables. However, air pollution can lead to long term respiratory and heart disorders and has been linked to an increased risk for cancer and cardiovascular mortality [5].

In light of this pertinent crisis, the leading solution to mitigate the effects of global warming stands to be the implementation of clean, renewable energy resources. According to global development expert Jeffrey Sachs, fossil fuels are the primary cause of the climate crisis and there must be a "heart transplant" where fossil fuels are replaced with alternatives [6]. According to the U.S. Energy Information Administration, about 67% of the energy produced in 2014 was in fossil fuels [7]. Additionally, fossil fuels are the largest contributor to air pollution in the world, releasing harmful aerosols and causing smog and acid rain [8]. According to a recent study by the University College London, fossil fuel $PM_{2.5}$ air pollution is responsible for 1 in 5 deaths worldwide [8]. This highlights the necessity for the increased implementation of renewable energy, to mitigate the emission of greenhouse gases, the public health effects of air pollution, and the overarching climate crisis.

The aforementioned health related consequences of the climate crisis emphasize its classification as not only an environmental issue but also a public health crisis. Clean, renewable energy solutions serve as the forefront solution to both the environmental and public health aspects of the climate crisis [9]. Compared to fossil fuels like coal which release about 800 tonnes of CO2 emissions per gigawatt hour, clean energy sources like wind and solar energy release only 4 and 5 tonnes, respectively.10 Additionally, death rates caused by air pollution and accidents for Coal are 26.4 deaths per terawatt hour compared to only 0.02 deaths caused

***Corresponding author:** Vihaan Mathur, Youth Climate Action Team Inc, USA, E-mail: contact@ycatinc.com

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by solar energy [10]. Thus, using clean energy can reduce the health consequences imposed by the greenhouse gas emissions from fossil fuel energy sources by a large margin [11].

Renewable energy isn't widely implemented in the U.S. and there are large gaps that emerge when analyzing public opinion on clean energy [12]. The U.S. Energy Information Administration found that in 2021 only 11% of the U.S. energy cumulative energy production was renewable energy while 70% was from fossil fuels [7]. Moreover, public opinion on clean energy also reveals hesitancy towards numerous types of energy. According to a Pew Research Center study on public opinion on renewables and other energy sources, 9% of U.S. adults say that they oppose solar energy, 14% oppose wind energy, and a staggering 54% oppose nuclear energy [13].

With the growing connections between climate change and public health, the aforementioned research gaps surrounding the minimal use of clean energy and the hesitancy regarding its implementation despite its benefits must be investigated. The purpose of this study is to further investigate the benefits of clean energy as a public health solution to $PM_{2.5}$ induced mortalities in the United States by quantifying these implications and determining which specific types of clean energy are the most effective in mitigating mortalities.

Methods

The methods implemented in this research study are based on the Harvard Six Cities Study using causal comparative research and meta-analysis. Using data from readily available sources and methodology from the Harvard Six Cities Study, this paper aims to quantify the mortality implications of photovoltaic (solar) energy, wind energy, and nuclear energy farms in 150 cities across the U.S. These three energy sources were chosen because they were the same energy types possessed the most hesitancy in public opinion determined by the aforementioned Pew Research Center study in 2020 [12].

The data was calculated using an Excel calculator where appropriate values could be inputted. For each of the 150 cities, implications of 100 MW and 500 MW renewable energy farms were calculated. These values were chosen because they are feasible energy project sizes in real world scenarios and for the purpose of consistency in the calculations. Calculations for each respective city began with calculating the total annual production of a renewable energy farm. The energy production value obtained is for solar farms, however, was applied and modeled to estimate the energy production of nuclear and wind farms as well. This value is dependent on the size of the farm (100 and 500 MW) and was calculated through the following equation [14].

Solar Irradiation describes the energy density of a solar farm and the value can be found in the National Solar Radiation Database (NSRD) [15]. The Derate Factor is a standardized value describing the efficiency of a solar farm which can also be found in the NSRD [15]. Monthly values for solar power were added together to yield the total annual production in kW hours/year (kWh/year) as illustrated below in Table 1.

$$\text{Total Monthly Production (MW hours/day)} = \text{Monthly solar irradiation (in MW hours^2/meters^2/day)} - \text{(Equation 1)}$$
$$\text{Days in a month }(\text{days}),\ \text{Size of farm }(\text{MW}),\ \text{Derate Factor}$$

Month	Solar Irradiation in Hrs/day equivalent with 1000 W/m2 (kWh/m2/day)	Days per month	DC Capacity in kW	DC to AC Derate Factor 2016	Average Monthly kWh produced (AC)
January	4.86	31	100000	0.795	11977470
February	5.84	28	100000	0.795	12999840
March	6.17	31	100000	0.795	15205965
April	5.76	30	100000	0.795	13737600
May	5.33	31	100000	0.795	13135785
June	4.53	30	100000	0.795	10804050
July	4.57	31	100000	0.795	11262765
August	4.74	31	100000	0.795	11681730
September	4.54	30	100000	0.795	10827900
October	5.24	31	100000	0.795	12913980
November	5.54	30	100000	0.795	13212900
December	4.91	31	100000	0.795	12100695
Total Annual Production=					149860680 KWh/year
Size of the array in KW=100000					

Table 1: Monthly solar irradiation and total annual production of a renewable energy farm

Then, the climate change effects of a renewable energy farm were determined. To calculate this, a comparison was made between the current energy compositions of a city (percentage energy output per energy source) versus a 100% renewable energy farm. The current electricity mix for each city was modeled by the national United States energy composition values released annually by the U.S. Energy Information Administration [7]. These energy composition values were then modified to be 100% coming from a single renewable energy source, for example, 100% solar energy or 100% nuclear energy as illustrated below in Table 2.

Old electricity mix		34.10%	31.80%	19.20%	0.90%	1.50%	5.70%	1.20%	5.20%	0.40%	0.00%	0.00%
New electricity mix		0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Impact Category	Unit	Coal Electricity 1KWh	Natural Gas Electricity 1KWh	Nuclear Electricity 1KWh	Oil Electricity 1KWh	Biomass Electricity 1KWh	Hydro Electricity 1KWh	Photovoltaic Electricity 1KWh	Wind Electricity 1KWh	Geothermal Electricity 1KWh	Wood Electricity 1KWh	Concentrated Solar Power Electricity 1KWh

Table 2: Depiction of modified old and new electricity mix values of various renewable energies

Three air pollution climate impact values were compared between the old and new electricity mix: 10-micrometer particulate matter formation (kg PM10 eq), terrestrial acidification (kg SO_2eq), and nitrogen oxides (NO_x) (kg of NO_x particles) [16]. These three climate impact values describe three different $PM_{2.5}$ particles, namely, general $PM_{2.5}$ particulate matter, SO_2, and NO_x. These particles are usually the most common particles found in the atmosphere. The values are measured per kWh use and are dependent on a certain energy source. For example, one kWh of coal electricity would release more kg NO_x than an equal amount of wind electricity. The values for the previous three impact categories were earlier determined by Brauer et al [16]. The completed energy comparison table is shown below for 100% solar energy (Table 3).

Old electricity mix	New electricity mix	Impact Category	Particulate matter formation	Terrestrial acidification	Nitrogen oxides (NO_x)
34.10%	0.00%	Unit	kg PM10 eq	kg $S0_2$ eq	Kg of NO_x
31.80%	0.00%	Coal Electricity 1KWh	0.002105	0.0086197	0.00345
19.20%	0.00%	Natural Gas Electricity 1KWh	0.001253	0.006003	0.000817
0.90%	0.00%	Nuclear Electricity 1KWh	0.0000762	0.0000819	0.0000308
1.50%	0.00%	Oil Electricity 1KWh	0.000958	0.0034363	0.000953
5.70%	0.00%	Biomass Electricity 1KWh	0.0002206	0.0007645	0.0001105
1.20%	0.00%	Hydro Electricity 1KWh	0.0000205	0.0000132	0.00000894
5.20%	0.00%	Photovoltaic Electricity 1KWh	0.0000793291	0.000206003	0.000114
0.40%	0.00%	Wind Electricity 1KWh	0.00003217	0.000047	0.0000271
0.00%	0.00%	Geothermal Electricity 1KWh	0.00004253810	0.000563443	0.000146
0.00%	0.00%	Wood Electricity 1KWh	0.0000818	0.0002635	0.0000784
		Concentrated Solar Power Electricity 1KWh	0.0000215	0.0000564	0.00000353
		Emissions/Litre hot water	0.0000106	0.0000438	0.0000271
		1 sqft Natural gas, high pressure (US)	0.0000116	0.0003669	0.0001588
		Current electricity mix	0.11%	0.49%	0
		New Electricity Mix	0.01%	0.02%	0

Table 3: Depiction of modified old and new electricity mix values of various renewable energies at three air pollution climate impact categories

For each city, the previous steps regarding energy composition were repeated with 100% nuclear and wind energy. The percentage values of climate change impact for each of the three categories were then converted into metric tons of emissions through the following equation. The annual energy production of the renewable energy farm was determined earlier through Equation 1. The emission in metric tons was calculated for the original electricity mix and the modified renewable energy mix and the difference was calculated as shown below in Table 4.

$$\text{Emissions in Metric Tons (MT)} = \frac{\text{(Annual Energy Production of Farm (kWh/y)} \times \text{Percentage value of climate change impact)}}{1000} - \text{(Equation 2)}$$

Impact category	Unit	Old annual emissions in metric tons	New annual emissions in metric tons	Difference in annual emissions in metric tons
Particulate matter formation	kg PM10 eq	171.9	11.9	-160.0

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Terrestrial acidification	kg $S0_2$ eq	736.470	30.872	-705.5978
Nitrogen Oxide emissions	Kg of NO_x	218.3	17.1	-201.2

Table 4: Calculations of old, new and difference in their annual emissions at different impact categories

With the difference in $PM_{2.5}$ emissions calculated, the change in $PM_{2.5}$ exposure concentration was then determined. This value was based on the difference in emissions as well as the population of a specific city, and another value known as the intake fraction [17]. The equation of tthe intake fraction is:

$$\text{Change in } PM_{2.5} \text{ exposure concentration } (\mu g/m^3) = \frac{(\text{Change in Emissions } (\mu g/\text{day}) \times \text{Intake Fraction})}{(\text{Breathing Rate } (m^3/\text{day}) \times \text{Population})} \text{ – (Equation 3)}$$

The intake fraction represents the quantity of air pollutant, $PM_{2.5}$, which actually makes its way to the lungs of humans and yields health consequences. The population of a specific city was found on the US census website, while the change in emissions was calculated earlier as shown in Table 4, and converted from metric tons per year to micrograms per day. Intake fraction values were drawn from the earlier determined dataset by Apte et al. and breathing rate was represented by the widely accepted value of 20 m3/day for humans [18]. The calculations were done for each of the three $PM_{2.5}$ values ($PM_{2.5}$, SO_2, and NO_x) and then were added together for the total change in $PM_{2.5}$ concentration in µg/m3 as shown in the following equation and in example calculations for Washington D.C (Table 5).

City	Washington DC
Population	693000
iF $PM_{2.5}$	0.00000675
iF $PM_{2.5}$_SO_2	0.000000675
iF $PM_{2.5}$_NO_x	0.000000107
CVD Mort	1680.7
Change in $PM_{2.5}$	-0.10677707518
Change in SO_2	-0.09418974217
Change in NO_x	-0.00425694992
Total Change in $PM_{2.5}$	-0.21

Table 5: Calculations of Washington D.C at three different $PM_{2.5}$ values

$$\Delta CPM_{2.5} \text{ Total} = \Delta CPM_{2.5} + \Delta CPM_{2.5}\_SO_2 + \Delta CPM_{2.5}\_NO_X \text{ – (Equation 4)}$$

The final step consisted of calculating the health benefits in terms of human deaths avoided by using renewable energy farms. The value used to calculate this number was the national cardiovascular mortality rate. This value is 0.00242632 cardiovascular deaths per person in the United States [19]. For each city, this number was multiplied by the population of the city to determine the value of cardiovascular mortality for that city. To determine avoided deaths, the statistical relationship between air pollution and cardiovascular mortality discovered by the Harvard Six Cities was used. The study determined that "an annual increase of 10 micrograms per cubic meter in the concentration of $PM_{2.5}$ increases overall cardiovascular mortality by 9%" with a 95% Confidence Interval [4]. Based on this, the following equation was used to determine the deaths avoided annually using the cardiovascular mortality value obtained above.

$$\text{Avoided Deaths(number of people)} = +\text{Cardiovascular Mortality (number of cardiovascular deaths)} \times (\text{Change in } PM_{2.5}\text{Concentration } (\mu g/m3)/10) \times 0.09 \text{ – (Equation 5)}$$

Since the change in $PM_{2.5}$ is negative for all renewable energy farms the value obtained from Equation 5 is negative. This value is changed to a positive value to describe the deaths avoided by the renewable energy farm. The calculations described above were done for each of the 150 most populous cities in the United States to yield the results of the study.

Results

The study illustrated that the benefits of clean energy as a public health solution to air pollution mortalities can clearly be quantified by the amount of air pollution caused deaths avoided or lived saved. For all of the 150 cities, the average lives saved annually for each type of renewable energy farm are summarized below in Table 6 and Figure 1. When taking these benefits into account, it is also pertinent to consider the U.S. 2020 estimated value of a statistical life of $ 7,500,000 to understand the value saved from another perspective.

Energy Farm Type/Size	Average Lives Saved
100 MW Solar	1.19
100 MW Wind	1.24
100 MW Nuclear	1.18
500 MW Solar	5.8
500 MW Wind	6.18
500 MW Nuclear	6.03
another	another
another	another

Table 6: Representation of average lives saved annually for each type of renewable energy

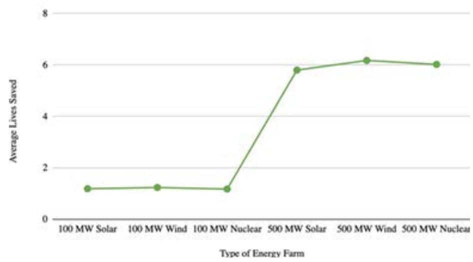

Figure 1: Average lives saved for each energy farm

As shown above, the annual mortality benefits are positive for every type of energy farm for which calculations were conducted, indicating these renewable energy farms avoid deaths that would be caused by air pollution. Therefore, the data supports the conclusion that renewable energy serves as a solution to air pollution induced cardiovascular mortality.

Further analysis included averaging the deaths avoided annually by all the different types of renewable energy farms, to create an "energy benefits" metric. This metric quantifies how much a given city would benefit from clean energy implementation. The top 10 cities that would benefit the most from these renewable energy projects according to this metric are as follows in Table 7. This metric also represents the top 10 cities that benefit the most from each individual energy type, as the top 10 cities benefiting from solar, wind and nuclear respectively are the same. The energy benefits for the top 10 cities that benefit the most are illustrated in the graph above. In the tables above, there doesn't appear to exist a correlation between the population size and the average amount of lives annually saved from a specific energy source. This is further shown below in Figure 2, a scatter plot.

City	Population	Energy Benefits	100 MW solar lives saved annually	500 MW solar lives saved annually	100 MW wind lives saved annually	500 MW wind lives saved annually	100 MW nuclear lives saved annually	500 MW nuclear lives saved annually
New York Northern NJ	20.3 million	16.44	5.38	26.9	5.6	27.98	5.46	27.3
Los Angeles	18.5 million	14.61	4.78	23.92	4.97	24.87	4.85	24.27
Rochester, NY MSA	1.07 million	14.19	4.65	23.23	4.83	24.15	4.71	23.57
Madison, WI MSA	6,80,000	13.21	4.32	21.59	4.47	22.34	4.42	22.11
San Francisco, CA	8,74,000	12.91	4.23	21.14	4.39	21.97	4.29	21.45
Seattle-Taco ma- Bremerton, WA CMSA	5,84,000	11.79	3.86	19.29	4.01	20.06	3.92	19.58
Washington- Baltimore MSA	7,02,000	9.48	3.1	15.52	3.23	16.14	3.15	15.75
Rochester, MN MSA	2,22,000	9.17	3	15.01	3.12	15.61	3.05	15.23
Boston, MA	6,89,000	8.77	2.87	14.35	2.98	14.92	2.91	14.56
Pittsburgh, PA MSA	2.35 million	7.4	2.42	12.12	2.52	12.6	2.46	12.3

Table 7: Representation of the top 10 cities which benefit from the most from renewable energy projects

The figure shows the population isn't correlated with the lives saved in a given city. Next, to compare the lives saved by each energy type (solar, wind, and nuclear), Figure 3 was created. It plots the average lives saved for each energy type regardless of the size of the farm with 5% error bars.

According to Figure 3, wind is the most effective energy type in mitigating air pollution mortalities. Although the average annual mortality reductions of all energy types are similar, wind energy had a slightly higher average than both solar and nuclear. Another way to analyze the difference between the means of different groups to see if they are statistically different is the use of a One-Way ANOVA test. This test examines if the difference between the means of three or more groups is statistically significant. A significance level of 0.1 was used and two tests were conducted, one with the 100 MW energy farm data and another with the 500 MW energy farm data. P-values of 0.892689 and 0.895369 were found for the 100 MW and 500 MW farms, respectively. Thus, the differences in lives saved annually between the wind, nuclear, and solar energy farms were not statistically significant (Figure 4).

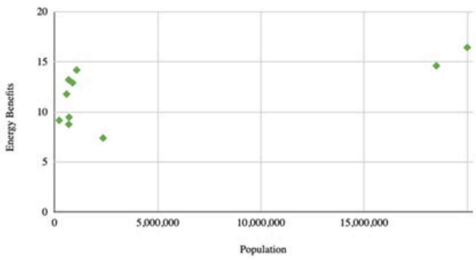

Figure 2: Population vs. energy benefits for Top 10 most benefitting cities

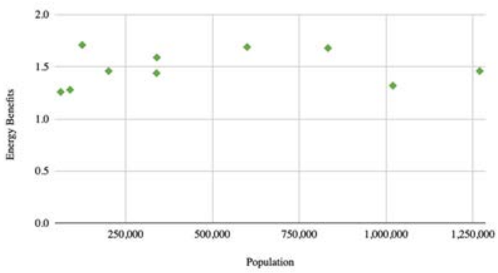

Figure 3: Population vs. energy benefits for Top 10 least benefitting cities

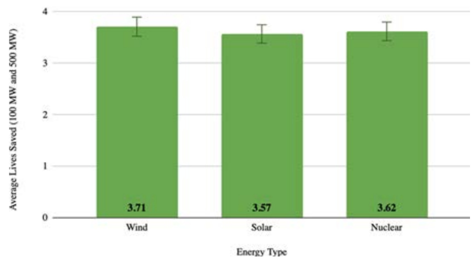

Figure 4: Energy type vs. average lived saves saved

Discussion

General policy recommendations

Broadly, the calculations conducted through this study strongly corroborate the tangible community impacts of clean energy implementation and its capacity to save human lives. Thus, it is apparent that the policymakers of today aggressively heighten their renewable energy goals and policies not only for the purpose of sustainability but for public health as well. It is clear that the climate crisis is a public health issue, and now it is clear that renewable energy serves as an effective solution to mitigate many of the public health implications of the changing climate.

Despite it being so in government today, the data reveals that the climate and energy crisis is a nonpartisan issue. It is a modern challenge that concerns the well-being of every individual. The data in this study gives decision makers the opportunity to reduce air pollution caused deaths within their communities and outline the quantitative evidence to support such decisions. As addressed next in this paper, there are communities that benefit most from clean energy policies. Decision makers should prioritize those communities the most when considering these recommendations (Tables 8 and 9) [20,21].

Poverty and race

A direct cross-comparison of Tables 7-9, reveals potential results in regards to the intersection of energy benefits, race, and poverty prevalence across the United States. When analyzing the cities ranked in the top 10 for energy benefits as seen in Table 7, there is overlap with the cities ranked in the top 10 for poverty rates as seen in Table 8.

Specifically, Rochester, New York is observed to be in both the top 10 cities for energy benefits as well as the top 10 cities for poverty rates. There is also an overlap with the cities ranked in the top 10 for Black population rates as seen in Table 9. Specifically, Baltimore, Maryland is observed to be in both the top 10 cities for energy benefits as well as the top 10 cities for the highest percentages of Black people. The overlap found by the cross-comparison of energy benefits, race, and poverty rates corroborates the result that cities in the United States that tend to benefit the most from clean energy implementation also tend to be those in poverty and those with high black populations. This aligns with prominent environmental justice and intersectional equity gaps often observed in larger cities across the country [22]. Cities with high poverty rights tend to have higher populations of people of color, specifically black people. It is logical that cities that have the highest rates of poverty coincide with poorer living conditions stemming from underinvestment and poor infrastructure, which also includes heightened air pollutant rates [23]. Thus, the likelihood of higher pollution as a result of poverty and underinvestment logically fuels the suggestion from the data that cities that benefit most from clean energy are also among the poorest [23].

	City
1	Detroit, MI
2	Cleveland, OH
3	Dayton, OH
4	Hartford, CT
5	Rochester, NY
6	Newark, NJ
7	Jackson, MS
8	Syracuse, NY
9	Birmingham, AL
10	Springfield, MA

Table 8: Poorest Cities in the United States

City	%
Detroit, Mich.	82.7
Jackson, Miss.	79.4
Miami Gardens, Fla.	76.3
Birmingham, Ala.	73.4
Baltimore, Md.	63.7
Memphis, Tenn.	63.3
New Orleans, La.	60.2
Flint, Mich.	56.6
Montgomery, Ala.	56.6
Savannah, Ga.	55.4

Table 9: Cities in the United States with the Highest Percentage of Black People

Though the data included in this study is based on a city to city basis, it is strongly believed that these recommendations would also prove fruitful on a local community basis. Specifically, POC and impoverished local counties and districts within larger cities should also be prioritized when making decisions on clean energy implementation at the city level. This is especially policy relevant and adds further importance to policymakers to prioritize low income communities and communities of color when proposing energy legislation and also include them as key stakeholders in the renewable energy policy creation process. This data supports the current efforts of the Biden Administration to prioritize underinvested, low income communities in their environmental justice and climate change policy plans. It also serves as an indicator for policymakers across the country to follow in line with the progressive environmental justice plan of the Biden Administration.

Conclusion

In summation, this research paper aims to expand upon the socioenvironmental relationships established by the Harvard Six Cities Study to quantify the benefits of clean energy as a public health solution to air pollution induced cardiovascular mortalities. This investigation revolved around 150 populous cities in the U.S. It tested the efficacy of solar energy, nuclear energy, and wind energy in each city to reduce mortalities caused by air pollution. Each type of energy reduced deaths caused by air pollution, illustrating the clear, tangible public health benefits of renewable energy. The data corroborates heightened renewable energy implementation and infrastructure across the U.S., with a focus on low income and colored communities who are often victims of disproportionate effects of climate change and, more broadly, communities who suffer greatly from air pollution mortalities.

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Competing Interest

The authors declare no competing interests.

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