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# Air pollution and life expectancy in Europe: Does investment in renewable energy matter?

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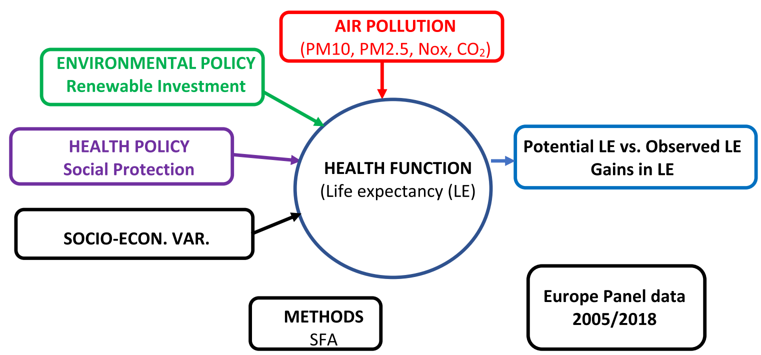
## HIGHLIGHTS

- The relationship between air pollution and potential life expectancy (LE) is analysed.
- A novel stochastic health frontier model is used.
- Panel data of 29 European countries is observed over the period 2005/2018.
- Investment in renewables has increased potential LE in the period analysed.
- Potential LE is negatively associated with NOx, PM2.5 and PM10 concentrations.

## GRAPHICAL ABSTRACT

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## ABSTRACT

This study examines the relationship between health and air pollution using a novel approach that allows differentiation between potential and observed health. It also permits an analysis of those factors that may contribute towards reducing any differences between the latter concepts. To this end, a panel data from 29 European countries for the periods 2005 and 2018 is used. Results indicate that the main pollutants affecting European countries, namely NOx, PM10 and PM2.5 have a negative impact on life expectancy at birth, while investment in renewable energies has a positive effect. Several conclusions can be drawn from these results. Firstly, if the aim is to minimize the detrimental effects of the global production of goods and services on air quality, a greater investment in renewable energies as compared to other more polluting ones, is called for. In turn, this would contribute to an improvement in the general health of citizens and the planet thereby increasing overall potential life expectancy. Secondly, NOx gases seem to be the ones that most affect the population's mean potential life expectancy. Results indicate that with regard to particulate matters, those with a diameter of less than 2.5 μm, are the ones that have the greatest impact on the health of European citizens, more so than larger particles (with a diameter between 10 and 2.5 μm).



## 1. Introduction

According to The EEA (European Environment Agency (2020)), particulate matters, nitrogen dioxide and ground-level ozone, are recognised as the three pollutants that most significantly affect human

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health. Around 90% of European citizens are exposed to pollutants at concentrations higher than the air quality levels deemed harmful to health. Air pollution can cause disease and shorten lives (Lelieveld et al., 2020; Landrigan et al., 2018). Long-term and peak exposures to these pollutants range in severity of impact, from impairing the respiratory system to premature death (Brunekreef and Holgate, 2002). Although during the past decades some of these emissions have decreased in European countries, air pollutant concentrations still surpass EU target value thresholds (EEA (European Environment Agency), 2020) and therefore air quality problems persist. Nowadays, reducing air pollution remains an important issue, meriting research to establish its concrete effect on health. The latter is a crucial determinant in the formulation of long-term policies involving multiple sectors, such as transport, housing, energy production and industry.

Both private and public investment in renewable energy plays a fundamental role in preserving the environment and the quality of the atmosphere. As such, investment in renewable energies is a key element of those measures aimed at achieving a sustainable energy transition within the European Union (EU) policy framework. This transition is sustained by the commitment of companies to investing in a cleaner and more sustainable industry, with investment in renewable energies seeing an increase over recent decades. This being the case, the present study analyses the potential effect of said investments on the health of European citizens.

An analysis is also conducted of the health effects generated by the pollutants identified as those that most affect life expectancy in European countries. In the first place, two types of particulate matter are considered: particles with a diameter between 10 and 2.5 μm; and particles with a diameter less than 2.5 μm whose harmful effect on health (especially for the smallest particles) has been extensively studied (see for example, Jiang et al. (2020); Khomenko et al. (2020); Vu et al. (2021); Li et al. (2020); Chen et al. (2019); Baloch et al. (2020); Yi et al. (2020); Janke (2014); Luechinger (2014); Chen et al. (2013); Ebenstein et al. (2016); Heyes and Zhu (2019); Zhang et al. (2018)).

Secondly, nitrogen oxides (NOx) are analysed. In addition to their harmful effects on health (Mauzerall et al., 2005; Boningari and Smirniotis, 2016; Chen et al., 2021), these gases have harmful effects on the environment. NOx act as precursors to the formation of tropospheric ozone that potentially affects climate change (Jia et al., 2021), thus aggravating the aforementioned consequences for health and the environment. Finally, carbon dioxide ($CO_2$) which contributes to air pollution in its role in the greenhouse effect and therefore, in the climate change, is analysed. Moreover, emerging evidence supports the possibility that $CO_2$ (at concentrations <5000 ppm) poses direct risks to human health (Jacobson et al., 2019).

When facing a study of the relationship between air pollution and health, the difficulties that this aim entails should be taken into account: economic growth implies the production of goods and services, which as a sign of economic progress, is usually associated with access to better health care. However, many industrial activities emit pollutants in populated areas with citizens living in zones where exceedances of air quality standards occur. This issue motivates a more in-depth analysis of the relationship between health and air pollution, which constitutes the central objective of this research.

In the literature, the study of the relationship between air pollution and health has been carried out at both a micro and macro level. At the micro level, it is necessary to consider different factors such as the concentration or type of pollutants present. Furthermore, biological variability and susceptibility to the effects of pollutants must be reviewed carefully. Recently, various key studies have appeared that address this topic from a macro perspective. The latter studies focus upon the average effect of air pollution on the population of a group of countries. For example, Tarín-Carrasco et al. (2021), analyse the premature deaths in Europe arising from different diseases associated with PM2.5 exposure, both for present and future periods. The results indicate that the annual excess mortality rate from fine particulate matter in Europe is likely to increase by 73% in 2050. On the other hand, Jorgenson et al. (2021) analyse the relationship between life expectancy and PM2.5 for 136 countries over the period 1990–2017 using time-series cross-sectional regression models. They find a negative relationship between these two variables and also reveal that the higher the level of income inequality, the stronger this relationship.

The present study follows a macro approach, in order to shed more light as to the effects of air pollution on the European population. For this purpose, panel data from 29 European countries is used for the period 2005–2018. The use of a data panel allows taking into account the peculiarities of each country, permitting more reliable results than would be the case for a cross-section sample.

## 2. Materials and methods

### 2.1. Data

Data were obtained from Eurostat and the BP Statistical Review of World Energy 2019 for $CO_2$ emission data.[1] Eurostat produces European statistics in partnership with National Statistical Institutes and other national authorities of the EU Member States. For the aims of this study both health output and input data are required.

Regarding the output variable, this paper uses life expectancy (LE) at birth -“more broadly health” as Shaw et al. (2005) point out- as a proxy of the population's health. Over recent years, the evolution of life expectancy has followed a steady upward trend (Fig. 1) reflecting, among other factors, the constant innovation in medical procedures that undeniably improves health results. The objective of this study is to also ascertain the effect of other factors (in particular air quality) on life expectancy.

Regarding inputs, socioeconomic, health policy and environmental factors are examined. As far as socioeconomic factors are concerned, income per capita (GDPc) in constant 2015 euros is considered. Higher income is usually associated with better jobs, access to better health care, and higher levels of education and information Woolf et al., 2007; Terza et al., 2008). In this sense, it is expected that individuals with higher incomes have a greater concern for their health, with a tendancy towards avoiding unhealthy behaviours as well as incurring investment in health.[2] Moreover, a higher income allows people to live in areas with less air pollution and more conditioned and safe houses (Jorgenson et al., 2021; Hill et al., 2019; Jorgenson et al., 2020; Ard, 2015; Ard, 2016; Huang et al., 2019; Mikati et al., 2018). Thus, several studies corroborate the positive relationship between greater access to resources and better health (Lantz et al., 2007); (Lantz and Pritchard, 2010; Marmot et al., 1978; Moss and Krieger, 1995; Rose, 2001; Wilkinson and Marmot, 2003).

With respect to environmental factors, air quality is viewed as a key determinant of a population's health. In this context, first particulate matters are taken into account. They come in different sizes, a characteristic which proves most important when determining their toxicity. Therefore, two variables have been included in the model (in tonnes): PM10_2.5 (diameter between 10 and 2.5 μm)[3]; and PM2.5 (diameter less than 2.5 μm) respectively. Also NOx gases (in tonnes) are considered. These gases are emitted mainly in combustion processes related with traffic (especially motor vehicles and diesel engines) and transport in general. They are also present in high temperature industrial and electrical generation plants. Finally, $CO_2$ emissions (in tonnes) are considered. Figs. 2, 3 and 4 show that, for the sample analysed, these

[1] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[2] Education is not included given that it is highly related to income, potentially causing multicollinearity problems to arise when the two variables are included together (Galea and Ahern (2005); Moore et al. (2007)).

[3] Where PM10_2.5 = PM10-PM2.5

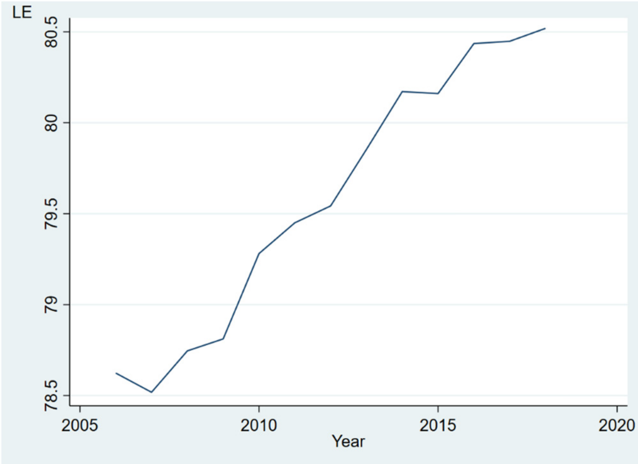


**Fig. 1.** Evolution of life expectancy (LE in years).

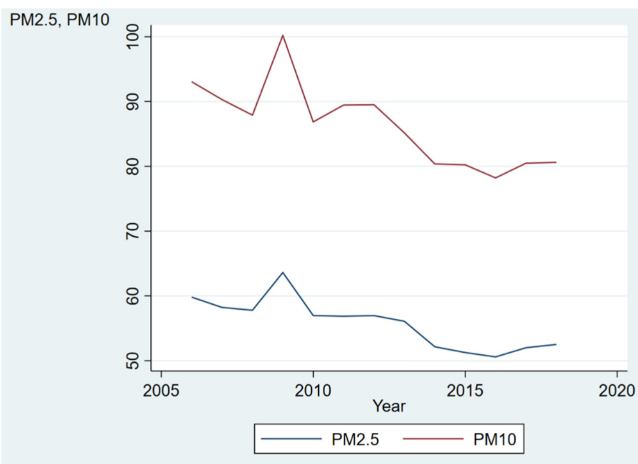


**Fig. 2.** Evolution of PM10 and PM2.5 (in thousands of tonnes).

pollutants have decreased in the period considered, especially with regard to NOx gases and $CO_2$ emissions.

The use of renewable energy sources is seen as a key element in energy policy, reducing the dependence on fuel imported from other countries and reducing emissions from fossil fuel sources. As such,


**Fig. 3.** Evolution of NOx gases (in thousands of tonnes).


**Fig. 4.** Evolution of $CO_2$ emissions (in millions of tonnes).

renewable energies contribute towards reducing the negative health effects of pollutant emissions into the atmosphere. Therefore, in order to analyse how investment in renewable energy has been able to affect LE, the variable Share_renew (the share of energy from renewable sources) is included. Eurostat offers a harmonized calculation of the share of energy from renewable sources since Member States are committed to using the exact same method for calculating the desired values. This prevents any irregularities from varying parameters and rules used in different calculation methods.[4] Fig. 5 shows an important increase in renewable energy investments during the period and for the sample considered (with a more marked increase at the beginning of the period).

As far as healthcare is concerned, it is expected that the healthcare system and related policies will have a direct effect on health results. The ratio of general practitioners by population denominated (Doctor_pop) is included as a proxy of a country's healthcare system. Moreover, the model includes the variable Social_Protection that indicates expenditure on social protection policies (as a % of GDP) which is provided to those households and individuals affected by a specific set of social risks and needs. This variable, together with the variable Share_renew, will also be included in Eq. (2) as it explains how both social and environmental policies have helped different European countries to become closer to their maximum potential life expectancy.

Finally, two more socio-economic variables have been incorporated into the model: Population density (Den_pop) as a proxy for the urbanization of a country (measured as the number of inhabitants per $km^2$); and a measure of inequality (Poverty), which indicates the percentage of persons considered to be at risk of poverty after social transfers, that is to say, people who have an equivalised disposable income below the risk-of-poverty threshold, which is set at 60% of the national median equivalised disposable income.[5]

Finally, the analysis is restricted to those countries with complete data reported for the relevant variables of study. Concretely, an unbalanced panel data of 29 EU countries during the period 2005–2018 is analysed. Table 1 shows the descriptive statistics, revealing an average life expectancy of 79.67 years for the sample.[6]

[4] https://ec.europa.eu/eurostat/web/energy/data/shares

[5] Other types of inequality measures such as the GINI index have been tested, but they have not been significant. Furthermore, following Jorgenson et al. (2021), an attempt has been made to cross the inequality variable with the variables that measure air quality. However, since the current model includes 4 air quality variables, it becomes too complex and does not converge.

[6] The year 2005 is used to obtain the lags in the variables.


**Fig. 5.** Share renewable energies evolution.

### 2.2. The model

In order to study the effect of air pollution on health, this paper models a health production function for EU member countries that represents the maximum (potential) level of health that a country can obtain given the factors available to it. The health function can be specified using a stochastic frontier approach expressed as follows:

$$\ln LE_{it} = \beta_0 + \beta_1 X_{it-1} + \Sigma\delta_i D_i + \Sigma\varphi_t T_t + v_{it} - u_{it} \quad (1)$$

where $LE_{it}$ represents the country *i*'s life expectancy observed in the year t. Vector X represents country characteristics related to socioeconomic, environmental or healthcare factors.

As Chen and Chen (2021) pointed out, many issues exist in quantifying the relationship between health and air pollution, due to the potential endogeneity problems. In order to tackle this issue, all variables have been lagged one year (predetermined variables). Hence, life expectancy in a given year should not affect variables in a preceding year (Shaw et al., 2005). Also, time dummies ($T_t$) are included to capture the effect of unobserved variables which, when evolving over time, affect all countries equally. Eq. (1) is estimated using panel data methodology (fixed-effects model). To do this, country dummies $D_i$ in Eq. (1) are included. These country dummies capture unobserved fundamental differences between countries. Note that this is very relevant for the aim of the study: health production is highly complex and as such, it is unlikely that an econometric model will fully encompass all the elements that affect it. If there are country-specific differences and they are not explicitly picked up in the model, a problem of omitted variables will exist and the estimated coefficients of the explicitly included variables will be biased. Thus, the main advantage of using a panel data model instead of a cross-section model is that it is possible to capture the unobservable systematic differences among countries, namely, those which are part of their own idiosyncrasy (for example, weather, geography, culture, food, structure of the population, etc.). Finally, $\beta$, $\delta$, $\varphi$ are parameter vectors to be estimated.

Regarding the stochastic part of the model, two components have been defined: $v_{it} \approx iid\ N(0, \sigma_v^2)$,which is a standard symmetric noise term capturing random shocks and measurement errors; and $u_{it} \approx iid\ N^+(0, \sigma_u^2)$ which is a one-sided random term aiming to identify observations that are below their potential life expectancy. In other words, it is possible that there are observations in which the countries achieve a lower LE than that they could obtain given their socio-economic, environment and healthcare characteristics. The stochastic production frontier model permits differentiating between the observations that are on the frontier (achieving their maximum potential LE, with $u_{it} = 0$) from those that have an LE below what they could have obtained (with $u_{it} > 0$).

This paper is interested in studying how different investments in environmental and social policies have helped countries (located below their frontier) to become closer to their potential frontier. To achieve this objective, $u_{it}$ is allowed to follow a heteroskedastic distribution. In particular, following Caudill et al. (1995) it is assumed that the variance of the pre-truncated normal variable depends on a set of covariates that could explain differences between observed and potential life expectancy. That is to say:

$$\sigma_u^2 = g(z_{it}, \theta) \quad (2)$$

where $z_{it}$ is a set of covariates that can influence the distance of countries to the frontier, with $\theta$ being the set of parameters to be estimated. Increases in the variance represent increases in the distance to the frontier and vice versa. According to Kumbhakar and Lovell (2000), ignoring heteroskedasticity in the error term $u_{it}$ will lead to biased estimatioGiven the aim of this study, the variables used to explain the variance of this error term will be time and both social and environmental policies.

Once the model has been estimated, it is possible to compute the ratio of observed LE to the maximum (potential) LE. Hereafter this ratio (index) is labelled as TE. This index can take values between 0 and 1, where a value equal to 1 indicates that the country is located on the frontier. The higher the value of the TE index, the closer the country is to their potential LE.[7]

**Table 1**
Descriptive statistics.

| Variable | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|
| LE (years) | 79.67 | 2.90 | 70.70 | 83.50 |
| ln(GDP_c) | 0.0298 | 0.0186 | 0.0052 | 0.0931 |
| ln(Doctor_pop) | 0.0010 | 0.0005 | 0.0003 | 0.0032 |
| Poverty (%) | 16.53 | 4.11 | 7.90 | 26.40 |
| Den_pop | 150.97 | 220.18 | 2.91 | 1505.38 |
| NOx (Tonnes/km2) | 357.06 | 414.48 | 5.39 | 1698.55 |
| PM10 (Tonnes/km2) | 85.31 | 88.94 | 0.51 | 369.53 |
| PM2.5 (Tonnes/km2) | 55.38 | 58.81 | 0.32 | 220.91 |
| Share_renew (%) | 22.13 | 17.27 | 1.34 | 72.75 |
| $CO_2$ (million of tonnes) | 90.24 | 11.45 | 45.70 | 124.90 |
| Social Protection (%) | 22.79 | 5.59 | 10.30 | 33.10 |
| Time (years) | 7.39 | 3.57 | 1 | 13 |

N° observations: 329.

## 3. Results

The results produced by the estimation of the system of Eqs. (1)–(2) are showed in Table 2.[8] As expected, income per capita (GDPc) affects life expectancy positively and significantly. In particular, an increase of 1% in GDP per capita increases the potential LE 0.014% on average ($p = 0.00$). Taking into account that life expectancy is 79.67 years in the sample mean, this implies an increase in potential life expectancy of 13.38 months.[9]

Similarly, an increase in the endowment of health resources increases life expectancy. Specifically, an increase of 1% in the ratio of general practitioners per population implies an increase in potential life expectancy of approximately 0.004% ($p = 0.06$). It implies an increase in potential life expectancy of 3.8 months on average.

Regarding the socioeconomic variables that have also been included, inequality (measured as the percentage of poverty in the population)

[7] As $TE_{it} = \exp(-u_{it})$ by construction, the determinants of $TE_{it}$ are the same as the determinants of $u_{it}$.

[8] The Wald test is reported at the bottom of the Table 2. The result of this test indicates that the stochastic frontier model estimated is a better approach (with our data) compared to a non-frontier specification.

[9] The number of months of life expectancy gained was calculated as: $\frac{\partial LE}{\partial \ln GDPc} = \frac{\partial \ln LE}{\partial \ln GDPc} \times \overline{LE} \times 12$ (where $\overline{LE} = 79.67$). Similar calculations were performed for the other variables.

**Table 2**
Parameter estimates (Eqs. (1) and (2)).

| Variable | Coef. | | Std. err. | z | P > z |
|---|---|---|---|---|---|
| Parameter estimates (Eq. (1)) | | | | | |
| $\ln(GDP\_c)_{-1}$ | 0.0137 | *** | 0.0040 | 3.4400 | 0.0010 |
| $\ln(Doctor\_pop)_{-1}$ | 0.0044 | ** | 0.0024 | 1.8700 | 0.0620 |
| $Poverty_{-1}$ | −0.0056 | ** | 0.0026 | −2.1200 | 0.0340 |
| $\ln(Den\_pop)_{-1}$ | 0.0015 | | 0.0092 | 0.1700 | 0.8670 |
| $\ln(NOx)_{-1}$ | −0.0067 | ** | 0.0033 | −2.0400 | 0.0420 |
| $\ln(PM10\_2.5)_{-1}$ | −0.0028 | ** | 0.0014 | −2.0300 | 0.0420 |
| $\ln(PM2.5)_{-1}$ | −0.0047 | ** | 0.0023 | −2.0600 | 0.0390 |
| $Share\_renew_{-1}$ | 0.0006 | *** | 0.0001 | 4.8000 | 0.0000 |
| $CO2_{-1}$ | 0.0048 | | 0.0037 | 1.2900 | 0.1980 |
| Social protection-$_1$ | −0.0001 | | 0.0002 | −0.4700 | 0.6410 |
| Year_2007 | 0.0010 | | 0.0012 | 0.8200 | 0.4090 |
| Year_2008 | 0.0021 | * | 0.0012 | 1.7900 | 0.0740 |
| Year_2009 | 0.0039 | *** | 0.0012 | 3.1900 | 0.0010 |
| Year_2010 | 0.0047 | *** | 0.0014 | 3.2400 | 0.0010 |
| Year_2011 | 0.0085 | *** | 0.0015 | 5.6800 | 0.0000 |
| Year_2012 | 0.0085 | *** | 0.0016 | 5.2300 | 0.0000 |
| Year_2013 | 0.0113 | *** | 0.0018 | 6.3600 | 0.0000 |
| Year_2014 | 0.0144 | *** | 0.0019 | 7.6200 | 0.0000 |
| Year_2015 | 0.0114 | *** | 0.0021 | 5.5300 | 0.0000 |
| Year_2016 | 0.0136 | *** | 0.0021 | 6.3600 | 0.0000 |
| Year_2017 | 0.0133 | *** | 0.0022 | 6.0000 | 0.0000 |
| Year_2018 | 0.0147 | *** | 0.0023 | 6.3800 | 0.0000 |
| Constant | 4.5829 | *** | 0.0657 | 69.800 | 0.0000 |
| Parameter estimates (Eq. (2)) | | | | | |
| Time | −0.5852 | *** | 0.0957 | −6.1200 | 0.0000 |
| Social protection-$_1$ | −0.4409 | *** | 0.0664 | −6.6400 | 0.0000 |
| $Share\_renew_{-1}$ | −0.0006 | | 0.0193 | −0.0300 | 0.9750 |
| Constant | −0.2377 | | 1.1538 | −0.2100 | 0.8370 |

Observations: 329.
Notes: The model includes 29 country dummies not reported in the Table. Since the model is in logarithms, the estimated model is equivalent to considering the air pollutans in μm/m$^3$.
Wald chi2(49) = 28,536.43; Prob > chi$^2$ = 0.0000.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

has a negative effect on health. Specifically, an increase in inequality by 1% reduces potential life expectancy of the European population by approximately 0.006% ($p = 0.03$) which implies a decrease in potential life expectancy of 5.73 months on average. Population density is not however statistically significant. This result may be indicating the *trade-off* between urban development and health that exists in large cities: on the one hand, large cities have better access to health care, which could imply greater potential health. But on the other hand, the pollution of large cities, as well as the faster pace of life (which can prove more stressful), can offset the advantage of having access to better and faster healthcare.

More relevant to the objectives of this study are the effect of environmental variables on LE. The estimated parameters related to NOx and particulate matters are statistically significant and with the expected sign. Thus, a 1% increase in NOx levels represents a decrease in potential LE of 0.007% ($p = 0.04$), which in turn would imply, an average decrease of 6.7 months at the sample mean. With respect to particulate matters, an increase of 1% in particles of between 10 and 2.5 μm implies a decrease in the potential LE of 0.003% (p = 0.04) indicating a decrease of 2.68 months in potential LE on average. More harmful is the effect of the smallest particles, which reveals that a 1% percentage increase of particles up to 2.5 μm represents a decrease in potential LE of 0.0047% (p = 0.04) representing a decrease in potential life expectancy of 4.5 months on average. Regarding $CO_2$ emissions, this variable is not statistically significant. That is, no significant direct effect exists between health and CO2 emission in European countries. Although there is some evidence of a direct effect, especially in the developing countries of Africa or Asia, this relationship may be due to the fact that carbon dioxide levels may indicate high levels of other harmful air pollutants such as volatile organic compounds (Jacobson et al., 2019). However, for the sample and period considered in this study, once the model has controlled for other air pollution variables, the effect of $CO_2$ does not affect the potential life expectancy of European countries.

As already advanced in the text, this study also analyses the effect of investment in renewable energies on the health frontier. The results indicate that this type of investment is statistically significant bearing the expected positive sign which signifies an improvement in the potential LE of a country's population. Specifically, a 1% increase in the share of renewable energies over other types of energies implies an improvement in the potential LE of 0.0006% ($p = 0.00$). Taking into account that during the 2006–2018 period, investment in renewables increased by 21%, this means that, in the period analysed, investment in renewables contributed towards an increase in potential LE of 12 months.

On the contrary, social protection (Social_protection) does not shift the frontier (that is, it does not affect potential LE). Finally, generally speaking, the time dummies are positive and significant, indicating that, ceteris paribus, during the period analysed, the potential LE of the population has been improving. Specifically, potential LE in 2018 improved by approximately 0.015% (jointly significant at p = 0.00) compared to 2006 which implies an increase in potential LE of 14.3 months over this period.

The foregoing paragraphs describe the results obtained from the estimation of the health frontier (Eq. (1)) which in turn represents the maximum (potential) life expectancy of a country given its peculiarities. However, it is possible that some countries may not be achieving their maximum. In this sense, Eq. (2) explains the factors that can help these countries reach their potential LE. As already commented beforehand, the variables time, and investments in social protection policies and renewable energy were introduced in order to analyse how those observations situated below their potential frontier could reduce the distance to said frontier. The estimated parameters corresponding to Eq. (2) are also presented in Table 2, where a coefficient with a negative sign is interpreted as reducing the distance to the frontier and vice versa (see Caudill et al. (1995) for details).

The results are very relevant. Although, as seen in Eq. (1), investment in renewables shifted the potential frontier significantly (that is, it allows countries to improve their potential life expectancy), said investment does not affect those countries situated below their potential frontier (given that the coefficient is not statistically significant in Eq. (2). In contrast, investment in social policies (which did not displace the health frontier), has a negative coefficient ($p = 0.00$) in Eq. (2). The latter implies that social policies can assist countries situated below their potential LE to achieve it. Moreover, time has a positive effect on LE (p = 0.00), reducing the distance to the potential life expectancy.

Finally, once the health frontier function has been estimated, it is possible to obtain the ET indices that indicate, as explained above, the distance of countries from their potential LE, given their characteristics. Recall that ET takes values between 0 and 1. The higher the value of the index, the closer the country is to their potential LE. For the data mean, the value of the ET is around 99.7%. This means that on average, countries in Europe could increase their life expectancy by 3.6 months in order to reach their potential LE. Table 3 shows the ranking of the most efficient countries, that is, those that are closest to their potential LE and the months of potential improvement. Countries such as France, Sweden, Germany and Denmark are the closest to their potential life expectancy. Among the furthest from their potential LE are Estonia, Lithuania, Latvia and Turkey. In this regard, it is important to note that these results do not indicate that countries ranked in the top are those with the best air quality indices. For example, according to EEA (European Environment Agency) (2020), France and Sweden, some of the countries closest to their potential LE, are also among those with the highest NOx level which, according to the results obtained, is the most damaging pollutant for health. However, these countries can be seen to partly offset this detrimental effect by their high investment in factors with a positive and significant effect on health, such as investment in health services; renewables or the reduction of

**Table 3**
Observed and potential life expectancy (LE) and TE ranking.

| Country | Obs | Observed LE | Potential LE | Potential LE gain (months) | TE ranking |
|---|---|---|---|---|---|
| Austria | 13 | 81.07 | 81.10 | 0.33 | 6 |
| Belgium | 13 | 80.68 | 80.72 | 0.46 | 7 |
| Bulgaria | 12 | 74.27 | 74.43 | 1.93 | 23 |
| Croatia | 8 | 77.76 | 77.80 | 0.49 | 9 |
| Cyprus | 3 | 82.60 | 82.63 | 0.32 | 5 |
| Czechia | 8 | 77.84 | 78.02 | 2.16 | 24 |
| Denmark | 13 | 79.92 | 79.94 | 0.29 | 4 |
| Estonia | 13 | 76.40 | 77.33 | 11.12 | 29 |
| Finland | 10 | 80.66 | 80.71 | 0.56 | 12 |
| France | 13 | 82.10 | 82.12 | 0.25 | 1 |
| Germany | 13 | 80.61 | 80.63 | 0.28 | 3 |
| Greece | 12 | 80.93 | 80.98 | 0.61 | 13 |
| Iceland | 12 | 82.14 | 82.27 | 1.54 | 21 |
| Ireland | 12 | 81.07 | 81.18 | 1.30 | 19 |
| Italy | 13 | 82.48 | 82.52 | 0.50 | 8 |
| Latvia | 12 | 73.78 | 74.32 | 6.56 | 27 |
| Lithuania | 13 | 73.65 | 74.39 | 8.84 | 28 |
| Luxembourg | 11 | 81.69 | 81.77 | 0.92 | 14 |
| Malta | 8 | 81.91 | 82.00 | 1.02 | 16 |
| Netherlands | 13 | 81.19 | 81.24 | 0.54 | 10 |
| Norway | 13 | 81.65 | 81.73 | 0.93 | 15 |
| Poland | 9 | 77.33 | 77.42 | 0.99 | 17 |
| Portugal | 13 | 80.52 | 80.61 | 1.05 | 18 |
| Romania | 11 | 74.58 | 74.83 | 2.97 | 25 |
| Slovenia | 12 | 80.30 | 80.43 | 1.60 | 22 |
| Spain | 12 | 82.66 | 82.77 | 1.36 | 20 |
| Sweden | 13 | 81.86 | 81.88 | 0.27 | 2 |
| Turkey | 8 | 78.09 | 78.42 | 4.00 | 26 |
| United Kingdom | 13 | 80.72 | 80.76 | 0.54 | 11 |

Note: TE is calculated as TE = Observed LE/Potential LE.

inequality. The positive effect on health of investment in social protection policies should also be added to the prior effect given that it significantly reduces the distance to the potential LE as corroborated by the results obtained.

## 4. Discussion

The health effects of air pollution have been subject to intense study (Brunekreef and Holgate, 2002). Many European citizens are living in areas where exceedances of air quality standards occur, mainly with respect to nitrogen dioxide and particulate matters. In this context, a better understanding of how air pollution affects health and the comparison of the damaging effect of the main pollutants found in the EU requires investigation.

The results obtained indicate a significant and negative impact of air pollutants on health. Specifically, NOx emissions are the pollutants that have the greatest impact on the health of European citizens. This harmful effect is also found in other studies (Mauzerall et al., 2005; Boningari and Smirniotis, 2016; Chen et al., 2021). The effect of particulate matters on health was also analysed. These particles can be of a different origin, either natural or anthropogenic, including dust, ash, heavy metals, diesel, gasoline and chemical products that are produced as a result of activities such as combustion, incineration, transport, construction, industry, etc. In practice, they are classified into two large groups: those that do not enter the respiratory system (not inhalant) as they present a diameter greater than 10 μm and those that do enter the respiratory system when they present a diameter less than 10 μm (with those being smaller than 2.5 proving especially dangerous) (Chen and Chen, 2021; Tarín-Carrasco et al., 2021; Hung et al., 2020; Landrigan et al., 2018; Liu et al., 2019; Li et al., 2019). The results presented here indicate a significant and negative effect on health of these particulate matters and are in line with previous works that have analysed this topic from a macro perspective as in Jorgenson et al. (2021). Concretely, the results indicate that particulate matters with a diameter of less than 2.5 μm, are the particulate matters that have the greatest impact on the health of European citizens, well above the effect of larger particles (between 10 and 2.5 μm). As expected, the coefficient estimated using a combined data of developed and developing countries in Jorgenson et al. (2021) is greater (0.04% higher) than the coefficient obtained in this study using only European countries.

Based on the results of this study, it can be deduced that investment in renewable energy has a significant and favourable impact on health production, thereby increasing potential life expectancy. This result has relevant policy implications for environmental and health measures. In this context, the EU has carried out policy initiatives to encourage the expansion of renewable energy thereby contributing towards reducing the dependence on foreign energy sources and the long-run environmental consequences of emissions from more pollutant energies. Recently, for example, the European Commission proposed a new recovery instrument, denominated Next Generation EU, in order to help kick-start the economy and ensure that Europe bounces forward following the current health crisis. One of the conditions for this economic reactivation is to guarantee sustainable growth by prioritizing green investments. The main objective is to drive a shift towards a clean, circular, competitive and climate neutral economy. In this context, investment in clean technologies is key for clean energy transition. Such investment could encourage renewable and energy storage technologies, clean hydrogen, batteries, carbon capture and storage and sustainable energy infrastructure. The production and deployment of sustainable vehicles and vessels as well as alternative fuels should also be promoted, together with the financing of the installation of charging points, city and company clean fleet renewals and sustainable transport infrastructures. All the foregoing will enable the shift to more clean air in Europe (European Commission, 2020, page 7)[10], and as illustrated by the results of this study, to a healthier European population.

## 5. Conclusion

In recent decades, European countries have taken measures to reduce emissions and improve air quality, investing in renewable technologies. All of this has favoured an improvement in air quality. However, the problem of air pollution still persists. This is mainly due to the *trade-off* that exists between the objective of improving the quality of life (associated with industrial and social development), and the objective of preserving the environment.

The added value of this article is twofold. Firstly, the study relies on frontier methodology to construct a health production function that yields the potential life expectancy that individuals may achieve in a country, given environmental, social and country characteristics. That is, using this methodology it is possible to estimate the maximum potential health level that a country can achieve thus enabling an analysis of those factors that help or prevent it from reaching said potential. This methodology has already been applied in the study of health production frontiers. Some examples include Gravelle et al. (2003), Greene (2004) and La Fuente-Robledo et al. (2017). This paper extends the literature by comparing different air quality indicators and public policies aimed at reducing pollutants. To the best of our knowledge, this is the first paper that evaluates the impact on health attributable to less pollutant renewables, in addition to analysing the impact of the emissions of the main EU air pollutants that affect health (NOx, PM10, PM2.5).

From the results of this study, it is possible to draw some conclusions. Firstly, the expected results regarding the negative effect of air pollution on health are confirmed. Secondly, the model allows these effects to be compared. Thus, at the sample mean, NOx gases seem to be the ones that most affect the potential LE of the population. Regarding particulate matters, the results indicate that the smallest particles (up to 2.5 μm) are significantly more harmful than the larger ones (between

[10] Com/2020/456_final. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0456&rid=1 (page 7).

2.5 and 10 μm). Third, a greater use of renewable energies compared to other more polluting ones, contributes significantly to increasing the potential life expectancy of European citizens. Therefore, if the aim is to minimize the effects that the production of goods and services has on air quality and, consequently, on the health of citizens and the planet in general this requires investment in the necessary technology.

Likewise, the study reveals that social policies aimed at helping the vulnerable sector of the population can improve the situation of citizens living in countries that are not reaching their potential life expectancy.

These findings are relevant when analysing the effect of different policies, both social and environmental, the ultimate aim of which is to improve the health and well-being of citizens.

## CRediT authorship contribution statement

Ana Rodriguez-Alvarez: Conceptualization, Methodology, Software; Data curation, Writing- Original draft preparation. Investigation. Writing- Reviewing and Editing,

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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