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Assessment of health impacts and costs attributable to air pollution in urban areas using two different approaches. A case study in the Western Balkans

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ABSTRACT

In this study, two different air quality impact assessment methodologies were adopted and combined with a sensitivity analysis to estimate the unit costs. Air pollution health impact (mortality) assessment was carried out using one methodology based on log-linear concentration response functions (CRF) and another relying on the integrated exposure response curve (IER) from the Global Burden of Disease. Morbidity impacts were estimated with the CRF approach only. To assess the inequalities between low and high income countries, an area of low-medium income countries with a critical air pollution situation, was selected. The health impact and related external costs attributable to air pollution in 2019 were assessed in 30 urban areas of the Western Balkans region, one of Europe's air pollution hot spots. The evaluation was based on $PM_{2.5}$, O_3 and NO_2 concentrations in background sites from official monitoring networks. In 2019, the cost of mortality attributable to $PM_{2.5}$ in 26 urban areas was 7.8 and 9.0 billion Euro according to IER and CRF methodologies, respectively. The cost of O_3 associated with all-cause mortality estimated with the CRF methodology in 17 urban areas was 1.0 billion Euro while the one attributable to NO_2 pollution in 28 urban areas was 1.5 billion Euro. The study results suggest that the economic burden of air pollution in the Western Balkans is higher in terms of GDP than the one observed in EU27 in the same time window. The study concludes that CRF and IER methodologies are coherent, because the discrepancy in the results are explained by the differences in the assessed health outcomes. The two approaches are complementary because the combination of them makes it possible to obtain a wider range of outcomes. In addition, despite the different causes of death considered, the comparison between them is useful for cross-validation.

1. Introduction

Air pollution is the largest environmental risk factor for human health globally, with an excess of 1.8 million deaths in 2019, and its impact is expected to increase in cities where more than half of the global population lives (Southerland et al., 2022; Health Effects Institute, 2020)). The World Health Organization (WHO) estimates that nine out of ten people breathe outdoor air with pollution levels above their air quality guidelines leading to substantial health deterioration and consequent economic costs (World Health Organization, 2021). Moreover, the exposure to air pollution is increasing inequality among regions and communities across the globe. Quantitative relationship

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between exposure and impacts on human health are well known for particulate matter (PM_{10} and $PM_{2.5}$), O_3 and nitrogen dioxide (NO_2).

Lelieveld et al. (2015) estimated that outdoor air pollution causes 3.3 million premature deaths worldwide per year, which corresponds to 5.9 % of global mortality while in a more recent study by GBD 2019 Risk Factor Collaborators, $PM_{2.5}$ pollution in 2019 was associated with 4.1 million premature deaths globally equivalent to 7.3 % of the total number of global deaths (Abbafati et al., 2020). In 2019, 307,000 premature deaths were attributed to ambient air $PM_{2.5}$ exposure in Europe while the figures were 16,800 and 40,400 for O_3 and NO_2, respectively (European Environment Agency (EEA), 2021).

To assess the inequalities between low and high income countries by comparing the relative impacts of air pollution on their economies, the present study is focused on the Western Balkans (WB), an area of low-medium income countries with high air pollution levels. The WB includes Albania, Bosnia and Herzegovina, Kosovo*,[1] Montenegro, North Macedonia, and Serbia. In 2019, the WB population was 17.5 million with country populations between 0.6 million inhabitants in Montenegro and 6.9 million inhabitants in Serbia. WB countries are at different stages in the process of accessing the European Union. Albania, Montenegro, North Macedonia and Serbia are *candidate countries* while Bosnia and Herzegovina and Kosovo are *potential candidates,* as it is considered they need further steps to fulfil the requirements for EU membership. Air pollution is a major environmental and health problem in the WB with transboundary pollution processes affecting also EU countries. This region is considered one the European air pollution hot spots due to $PM_{2.5}$, sulfur dioxide (SO_2), O_3 and NO_2 levels frequently above the legislation limits (Belis et al., 2022). In 2019, the premature deaths attributable to $PM_{2.5}$ in the WB were nearly 28,000 (European Environment Agency (EEA), 2021).

The objective of the study is to compute the external costs (hereon costs) associated with air pollution impact on health in selected urban areas of the Western Balkans using different health impact assessment techniques and unit cost estimation approaches to evaluate the implications of using different methodologies on the air pollution cost estimates and to assess the inequalities associated with air pollution between the study area and the EU 27.

2. Materials and methods

2.1. Air quality data

The health impact of air pollution was assessed in 30 urban areas located in the Western Balkans with population ranging from 6 to 485 thousand inhabitants (Table 1). The population captured in this study is 3.6 million inhabitants representing 21 % of the entire WB population and 37 % of the region's urban population. Due to the sizeable extension of Belgrade, in this study are included only the three municipalities of this city considered to be well represented by the available air quality data: Novi Beograd, Stari Grad and Vračar. Similarly, the city of Skopje includes only the area of Karpos for the evaluation of $PM_{2.5}$.

$PM_{2.5}$, PM_{10}, O_3 and NO_2 background concentrations in 2019 were obtained from the EIONET - EEA's database (https://www.eionet.europa.eu/) complemented with AQ data from local networks with the same quality standards. Exposure was estimated with population-weighted country concentrations from urban and rural background stations > 75 % data coverage.

The annual average concentrations of $PM_{2.5}$, O_3 and NO_2 in the WB cities are shown in Fig. 1. Every pollutant is covered by a different subset of monitoring stations. On average, the levels of $PM_{2.5}$ and O_3 are higher in the north of the studied area (BIH and SRB) while the highest NO_2 levels are observed in the centre and south of the region (ALB, XKX).

Table 1
List of cities included in the present study including population and geographical coordinates. The city of Belgrade includes only the population of three municipalities: Novi Beograd, Stari Grad and Vračar while the city of Skopje includes only Karpos' population.

City	Country	ISO code 3	City Population	lat	lon
Banja Luka	Bosnia and Herzegovina	BIH	199,191	44.77	17.19
Beočin	Serbia	SRB	7,839	45.21	19.72
Beograd 3 Municip.	Serbia	SRB	316,498	44.82	20.46
Drenas-Municipality	Kosovo	XKX	6,143	42.37	20.53
Durres	Albania	ALB	175,110	41.31	19.44
Elbasan	Albania	ALB	100,903	41.11	20.08
Gjilan	Kosovo	XKX	90,178	42.28	21.27
Gorazde	Bosnia and Herzegovina	BIH	22,080	43.66	18.98
Hani i Elezit	Kosovo	XKX	9,403	42.15	21.29
Ilijaš	Bosnia and Herzegovina	BIH	20,504	43.96	18.27
Jajce	Bosnia and Herzegovina	BIH	30,758	44.34	17.27
Korce	Albania	ALB	58,259	40.62	20.78
Kosjerić	Serbia	SRB	12,090	44.00	19.90
Kragujevac	Serbia	SRB	150,850	44.01	20.92
Mitrovica	Kosovo	XKX	84,235	42.53	20.53
Nikšić	Montenegro	MNE	57,000	42.78	18.94
Niš	Serbia	SRB	185,987	43.32	21.91
Novi Sad	Serbia	SRB	289,128	45.13	19.99
Peja	Kosovo	XKX	96,450	42.65	20.28
Pristhine	Kosovo	XKX	210,000	42.66	21.15
Prizren	Kosovo	XKX	177,781	42.21	20.74
Sarajevo	Bosnia and Herzegovina	BIH	275,524	43.86	18.42
Shkoder	Albania	ALB	88,245	42.07	19.52
Skopje- Karpos	North Macedonia	MKD	59,810	42.00	21.43
Smederevo	Serbia	SRB	62,993	44.65	20.93
Tirana	Albania	ALB	485,000	41.35	19.85
Valjevo	Serbia	SRB	90,312	44.27	19.89
Vlore	Albania	ALB	89,546	40.40	19.48
Zaječar	Serbia	SRB	59,461	43.90	22.27
Zenica	Bosnia and Herzegovina	BIH	115,134	44.20	17.91

2.2. Health impact assessment

Two different methodologies were used in this study to estimate the impact of long-term exposure to air pollution on health (HIA). The concentration–response function (CRF) approach assumes a log-linear relationship between concentration and relative risks (Chen and Hoek, 2020; Héroux et al., 2015; Huangfu and Atkinson, 2020) while the integrated exposure response (IER) curves of the Global Burden of Disease (GBD) based on splines describe the abovementioned relationship for $PM_{2.5}$ with high detail along a wide range of concentrations (Murray et al., 2020).

A full set of health outcomes including mortality, years of life lost (YLL) and morbidity outcomes attributable to $PM_{2.5}$, O_3 and NO_2 and related costs were estimated in 30 cities selected on the basis of air quality (AQ) data availability. All-cause mortality expressed both as number of deaths and YLL was calculated using the CRF approach on the basis of the equations for long-term exposure proposed in the meta-analysis by Chen and Hoek (2020) for $PM_{2.5}$ and by Huangfu and Atkinson (2020) for O_3 (peak values) and NO_2. While the GBD calculations were made for six causes of death: low respiratory infections (LRI), tracheal, bronchus and lung cancer (hereon lung cancer), stroke, diabetes mellitus type 2 (DMT2), ischemic heart disease (IHD) and chronic obstructive pulmonary disease (COPD) using the IER approach (Murray et al., 2020). Postneonatal infant mortality was estimated

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[1] *This designation is without prejudice to position on status and is in line with the UNSCR 1244/99 and the ICJ Opinion on the Kosovo declaration of independence.

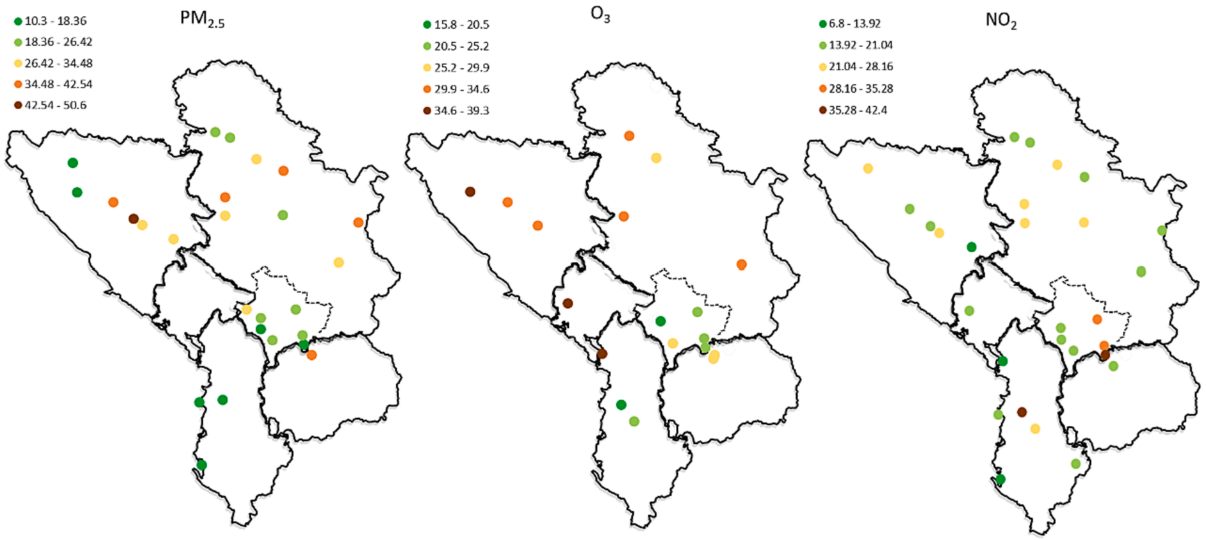

Fig. 1. Annual average concentrations (μg/m^3) of $PM_{2.5}$, O_3 and NO_2 in the WB cities considered in this study.

according to (Héroux et al., 2015). The HIA was computed with an updated version of the TM5-FASST tool (Van Dingenen et al., 2018) and validated with the WHO tool AirQ+ (https://www.who.int/europe/tools-and-toolkits/airq—software-tool-for-health-risk-assessment-of-air-pollution). The parameters of the CRF equations used in this study are provided in Table 2. A detailed description of the IER methodology is provided in Van Dingenen et al., (2018) and Belis et al. (2022) and the equations of the fitted IER curves used in the present study are shown in Table 3.

Morbidity outcomes associated with particulate matter ($PM_{2.5}$ or PM_{10}) were estimated using the CRFs proposed by Héroux et al. (2015) for: bronchitis in children (BR CHI), chronic bronchitis in adults (BR AD CHR), hospital admissions due to cardiovascular diseases (HA CVD) and respiratory diseases (HA RD), restricted activity days (RAD) and working lost days (WLD). In addition, morbidity attributable to $PM_{2.5}$ was estimated for the following outcomes on the basis of specific studies: asthma in children (AST CHI, (Khreis et al., 2017), lung cancer ((Hamra Ghassan et al., 2014), myocardial infarction (MI) and cerebrovascular

Table 2
Parameters of the concentration response functions (CRF) used in this study.

Pollutant	Metric	Type	Health outcome	CRF central	CRF low	CRF high	cut-off	Interval (μg/m^3)	age (years)	Source
$PM_{2.5}$	annual mean	mortality	Mortality, all-cause (natural)	1.08	1.06	1.09	5	10	all	Chen and Hoek, 2020
O_3	SOMO35	mortality	Mortality, respiratory diseases	1.02	0.99	1.05	0	10	all	Huangfu and Atkinson, 2020
O_3	SOMO35	mortality	Mortality, all (natural) causes	1.01	1	1.02	0	10	all	Huangfu and Atkinson, 2020
NO_2	annual mean	mortality	Mortality, all-cause (natural)	1.02	1.01	1.04	10	10	all	Huangfu and Atkinson, 2020
PM_{10}	annual mean	mortality	Postneonatal infant mortality, all-cause (natural)	1.04	1.02	1.07	15	10	<1	(Héroux et al., 2015)
PM_{10}	annual mean	morbidity	Prevalence of bronchitis in children	1.08	0.98	1.19	15	10	6–18	(Héroux et al., 2015)
PM_{10}	annual mean	morbidity	Incidence of chronic bronchitis in adults	1.117	1.04	1.189	15	10	18+	(Héroux et al., 2015)
$PM_{2.5}$	daily mean	morbidity	Hospital admissions, CVDs (including stroke)	1.0091	1.002	1.017	15	10	all	(Héroux et al., 2015)
$PM_{2.5}$	daily mean	morbidity	Hospital admissions, respiratory diseases	1.019	0.998	1.04	15	10	all	(Héroux et al., 2015)
$PM_{2.5}$	annual mean	morbidity	Reduced Activity Days	1.047	1.042	1.053	5	10	all	(Héroux et al., 2015)
$PM_{2.5}$	annual mean	morbidity	Work days lost, working-age population	1.046	1.039	1.053	5	10	20—65	(Héroux et al., 2015)
$PM_{2.5}$	annual mean	morbidity	Asthma in children	1.03	1.01	1.05	5	1	0–15	(Khreis et al., 2017)
$PM_{2.5}$	annual mean	morbidity	lung cancer	1.09	1.04	1.14	5	10	20+	(Hamra Ghassan et al., 2014)
$PM_{2.5}$	annual mean	morbidity	Stroke (cerebrovascular accident)	1.13	1.11	1.15	5	10	all	(Alexeeff et al., 2021)
$PM_{2.5}$	annual mean	morbidity	Diabetes mellitus 2	1.1	1.04	1.17	5	10	all	(Yang et al., 2020)
$PM_{2.5}$	annual mean	morbidity	Miocardial infarction	1.08	0.99	1.18	5	10	all	(Alexeeff et al., 2021)
$PM_{2.5}$	annual mean	morbidity	chronic obstructive pulmonary disease	1.18	1.13	1.23	5	10	20+	Park et al., 2021

Table 3
Parameters of the fitted curves to estimate the integrated exposure response (IER) curves (Murray et al., 2020) used in this study.

$PM_{2.5}$ range	Health outcome	age	EQ Central
0–90	ischaemic heart disease	25 to 29	y = -0.0002x2 + 0.0348x + 1
0–90	ischaemic heart disease	30 to 34	y = -0.0002x2 + 0.0309x + 1.0097
0–90	ischaemic heart disease	35 to 39	y = -0.0002x2 + 0.0282x + 1.0089
0–90	ischaemic heart disease	40 to 44	y = -0.0001x2 + 0.0258x + 1.0094
0–90	ischaemic heart disease	45 to 49	y = -0.0001x2 + 0.0233x + 1.0086
0–90	ischaemic heart disease	50 to 54	y = -0.0001x2 + 0.0211x + 1.0092
0–90	ischaemic heart disease	55 to 59	y = -0.0001x2 + 0.0189x + 1.0075
0–90	ischaemic heart disease	60 to 64	y = -9E-05x2 + 0.0162x + 1.0061
0–90	ischaemic heart disease	65 to 69	y = -9E-05x2 + 0.0145x + 1.0056
0–90	ischaemic heart disease	70 to 74	y = -8E-05x2 + 0.0126x + 1.0055
0–90	ischaemic heart disease	75 to 79	y = -7E-05x2 + 0.0108x + 1.0046
0–90	ischaemic heart disease	80 to 84	y = -6E-05x2 + 0.0091x + 1.0038
0–90	ischaemic heart disease	85 to 89	y = -5E-05x2 + 0.0074x + 1.0036
0–90	ischaemic heart disease	90 to 94	y = -4E-05x2 + 0.0059x + 1.0031
0–90	ischaemic heart disease	95 plus	y = -3E-05x2 + 0.0043x + 1.0023
0–90	STROKE	25 to 29	y = -6.9E-07x3 -7.2E-05x2 +0.038x + 0.999
0–90	STROKE	30 to 34	y = -5.0E-07x3 -8.09E-05x2 +0.034x + 0.999
0–90	STROKE	35 to 39	y = -4.5E-07x3 -7.7E-05x2 +0.031x + 0.999
0–90	STROKE	40 to 44	y = -4.5E-07x3 -6.6E-05x2 +0.028x + 0.999
0–90	STROKE	45 to 49	y = -2.5E-07x3 -7.9E-05x2 +0.026x + 0.999
0–90	STROKE	50 to 54	y = -1.4E-07x3 -8.4E-05x2 +0.023x + 0.999
0–90	STROKE	55 to 59	y = -1.2E-07x3 -7.9E-05x2 +0.021x + 0.999
0–90	STROKE	60 to 64	y =-1.01E-07x3 -0.0x2 +0.019x + 0.999
0–90	STROKE	65 to 69	y =-3.4E-08x3 -7.4E-05x2 +0.017x + 0.999
0–90	STROKE	70 to 74	y = -6.2E-08x3 -0.0x2 +0.014x + 0.999
0–90	STROKE	75 to 79	y = -4.7E-08x3 -0.0x2 +0.012x + 0.999
0–90	STROKE	80 to 84	y = 1.5E-08x3 -5.5E-05x2 +0.011x + 0.999
0–90	STROKE	85 to 89	y = -6.8-09x3 -4.3E-05x2 +0.009x + 0.999
0–90	STROKE	90 to 94	y = 9.1E-09x3 -2.7E-05x2 +0.005x + 0.999
0–90	STROKE	95 plus	y = 9E-06x3 − 0.0001x2 + 0.005x + 1.0005
0–90	chronic obstructive pulmonary disease	all	y = -2E-05x^{2} + 0.011x + 1
0–90	lower respiratory infections	all	y = -1E-05x2 + 0.0079x + 1
0–90	tracheal, bronchial and lung cancer	all	y = -7E-05x2 + 0.0125x + 1
0–90	Diabetes mellitus 2	all	y = -0.0004x2 + 0.0245x + 1

disease (CVAD) (Alexeeff et al., 2021), DMT2 ((Yang et al., 2020) and COPD (Park et al., 2021).

2.3. *Unit costs*

The value of statistical life (VSL) and the value of life year (VOLY) attributable to air pollution were estimated for every WB country applying the benefit transfer method (BT) to the OECD database of non-market welfare-based unit costs (https://www.oecd.org/env/tools-evaluation/env-value-statistical-life.htm) and converted to 2019 Euro (OECD, 2012a; OECD, 2012b) according to:

$$VSL_{c,2019} = VSL_{ref,year} \times \left(\frac{Y_{c,year}}{Y_{ref,year}}\right)^{b} \times (1 + \%\Delta P + \%\Delta Y)^{b} \tag{1}$$

where $VSL_{c,2019}$ is the *VSL* of WB country *c* in 2019; $VSL_{ref,year}$ is the base value (VSL for the reference country or region in the reference year); *Y* is the GDP per capita (in PPP terms); *b* is the income elasticity, $\%\Delta P$ represents price inflation, as estimated by the consumer price index; and $\%\Delta Y$ is the income growth between the reference year and 2019 (Narain and Sall, 2016). These authors recommend a VSL income elasticity of 1.2 for low and middle income countries. The VOLY was estimated as follows:

$$VOLY = \frac{VSL}{\left(1 - \frac{(1+r)^{-n}}{r}\right)} \tag{2}$$

where *n* is the discount period (remaining expected life year), and *r* is the discount rate (Ananthapavan et al., 2021). In the following, all the costs are expressed in Euro 2019 PPP equivalent.

3. Results

3.1. *Unit costs*

In Fig. 2a are shown the unit cost estimates obtained using two different references for the BT method: Czechia and the average of OECD countries. Czechia was used for a sensitivity test because is the country, among those available in the abovementioned OECD database, with the closest GDP *per capita* to the WB countries. This approach led to VSLs ranging between 0.83 and 1.43 million Euro. However, for the calculations of the costs in the present study we chose the VSLs obtained using the OECD average GDP *per capita* as reference (1.0 to 2.4 million Euro) because better aligned with recent studies (Spadaro et al., 2020; Amann et al., 2017; European Commission, 2022); .

The infant mortality (Fig. 2a) and the morbidity unit costs (Fig. 2b) were obtained with the BT method based on a study to support the revision of the EU Ambient Air Quality Directives (European Commission, 2022).

The highest morbidity unit costs were attributed to chronic bronchitis in adults (BR AD CHR) and chronic obstructive pulmonary disease (COPD) ranging from 8 to 26 thousand Euro, followed by cerebrovascular disease (CVAD), myocardial infarction (MI), lung cancer (including tracheal and bronchial cancer) and diabetes mellitus 2 (DMT2). Asthma in children (ASTH CHI) presented intermediate values (1.4 to 4 thousand Euro). The lowest unit costs were those attributed to reduced activity days (RAD) and working lost days (WLD) which fall in the range 30 to 80 Euro.

3.2. *Mortality*

In Fig. 3 the mortality associated with $PM_{2.5}$ in 26 cities (a) obtained with the CRF (left) and IER (right) methodologies and their respective costs (b) are shown.

In 2019, the total premature deaths attributable to $PM_{2.5}$ in these urban areas ranged between 4.6 and 5.3 thousand with an overall

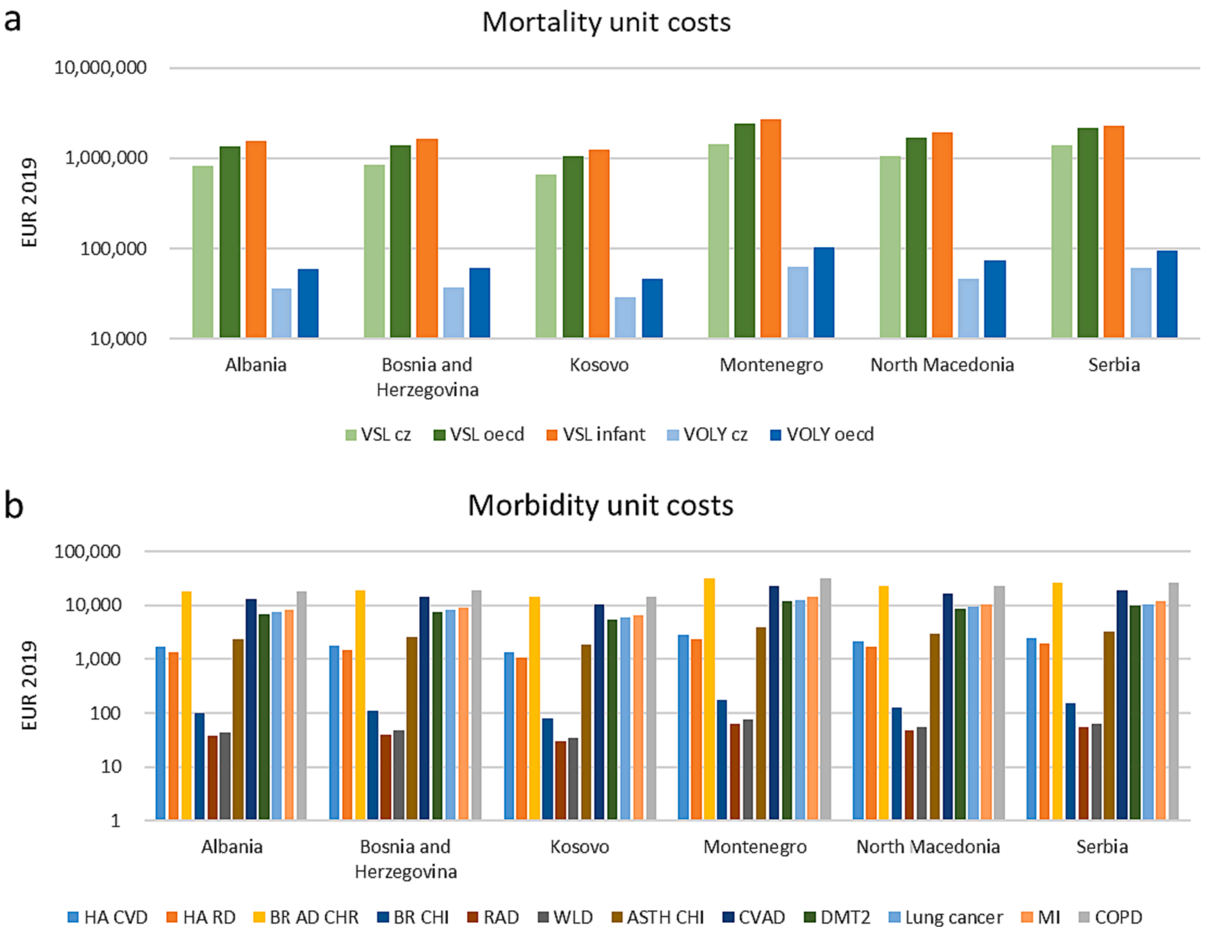

Fig. 2. Unit cost of mortality (a) and the morbidity outcomes (b) for every WB country used in the present study. VSL: value of statistical life, VOLY: value of life year, HA CVD: Hospital admissions cardio-vascular diseases, HA RD: hospital admissions respiratory diseases, BR AD CHR: chronic bronchitis in adults, BR CHI: bronchitis in children, RAD: reduced activity days, WLD: working lost days, ASTH CHI: asthma in children, CVAD: cerebrovascular disease, DMT2: diabetes mellitus 2, MI: myocardial infarction, COPD: chronic obstructive pulmonary disease.

mortality rate between 137 and 158 per 100,000 inhabitants (IER and CRF, respectively). The cumulative costs of $PM_{2.5}$-related mortality (VSL) in all cities were 7.8 and 9.0 billion Euro corresponding to 2.3 and 2.7 thousand Euro per capita according to IER and CRF methodologies, respectively. The average per city is a valuable statistical indicator, however it should be interpreted with caution due to the wide range of city sizes considered in the present study. The average mortality per city was 176 and 203 deaths, according to IER and CRF respectively, while the corresponding costs were 300 and 346 million Euro per city. The highest $PM_{2.5}$ impacts were observed in the main cities of the region located in the north of the study area, where both the concentrations of this pollutant and the population density were the highest (Belgrade, Sarajevo, Niš, Novi Sad). A significant correlation was observed between urban population and $PM_{2.5}$-associated costs ($R^2 = 0.87$; $p < 1.3 \times 10^{-8}$). The pictures obtained with the CRF and IER methodologies are highly comparable and the 13 % discrepancy is explained by the different outcomes considered in each of them. In the former approach the attribution is based on the all-cause mortality while in the latter it is based on the six most important causes of mortality associated with this pollutant (6 COD).

In Fig. 4 the mortality for each of the 6 COD associated with $PM_{2.5}$ in the 26 studied urban areas obtained with the IER methodology (left) and their respective costs (right) are shown. Stroke and IHD are the most important CODs with an average mortality of 70 and 67 deaths per city, respectively, representing 40 % and 38 % of the total number of deaths. The sum of the costs of these two CODs in all the studied urban areas totalises more than 6 billion Euro. By comparison, LRI is the COD with the lowest contribution to mortality costs equivalent to 116 million Euro (only 1.5 % of the total $PM_{2.5}$-related mortality costs).

A total of 75,100 and 86,800 YLL were attributed to $PM_{2.5}$ with the IER and CRF methodologies, respectively, leading to a total cost of 5.6 and 6.5 billion Euro. The 28 % lower costs attributed to $PM_{2.5}$ using YLL and VOLY compared to the ones obtained using the number of deaths and VSL is likely due to the former accounting for the life expectancy at death while the latter attributes the same value to all deaths. The total cost for all the studied cities of post-neonatal infant all-cause mortality, i.e. taking place between 1 and 12 months age, attributable to PM_{10} exposure with the CRF approach was estimated in 8.0 million Euro.

The all-cause mortality and respective costs associated with O_3 peak exposure (summer) according to CRF methodology in the 17 cities with available exposure data are shown in Fig. 5 (top). In 2019, the overall mortality associated with this pollutant in all the studied urban areas was 600 deaths with an associated cost of 955 million Euro equivalent to 19 deaths per 100,000 inhabitants and a cost of 298 Euro *per capita.* The average values per city were 35 deaths and 56 million Euro. The highest impacts were observed in cities located in the north of the study area (Sarajevo, Novi Sad) followed by some cities in the central and southern part of this region (Shkoder, Prizen, Niš).

The IER methodology provides estimations only for O_3-related deaths caused by COPD. A comparison with the O_3-related mortality costs associated with respiratory causes using CRF is provided in Fig. 5 (bottom left). The IER total cost (87 million Euro) is 24 % lower than the one obtained with CRF (115 million Euro) and the difference is explained by the latter representing the mortality associated with all

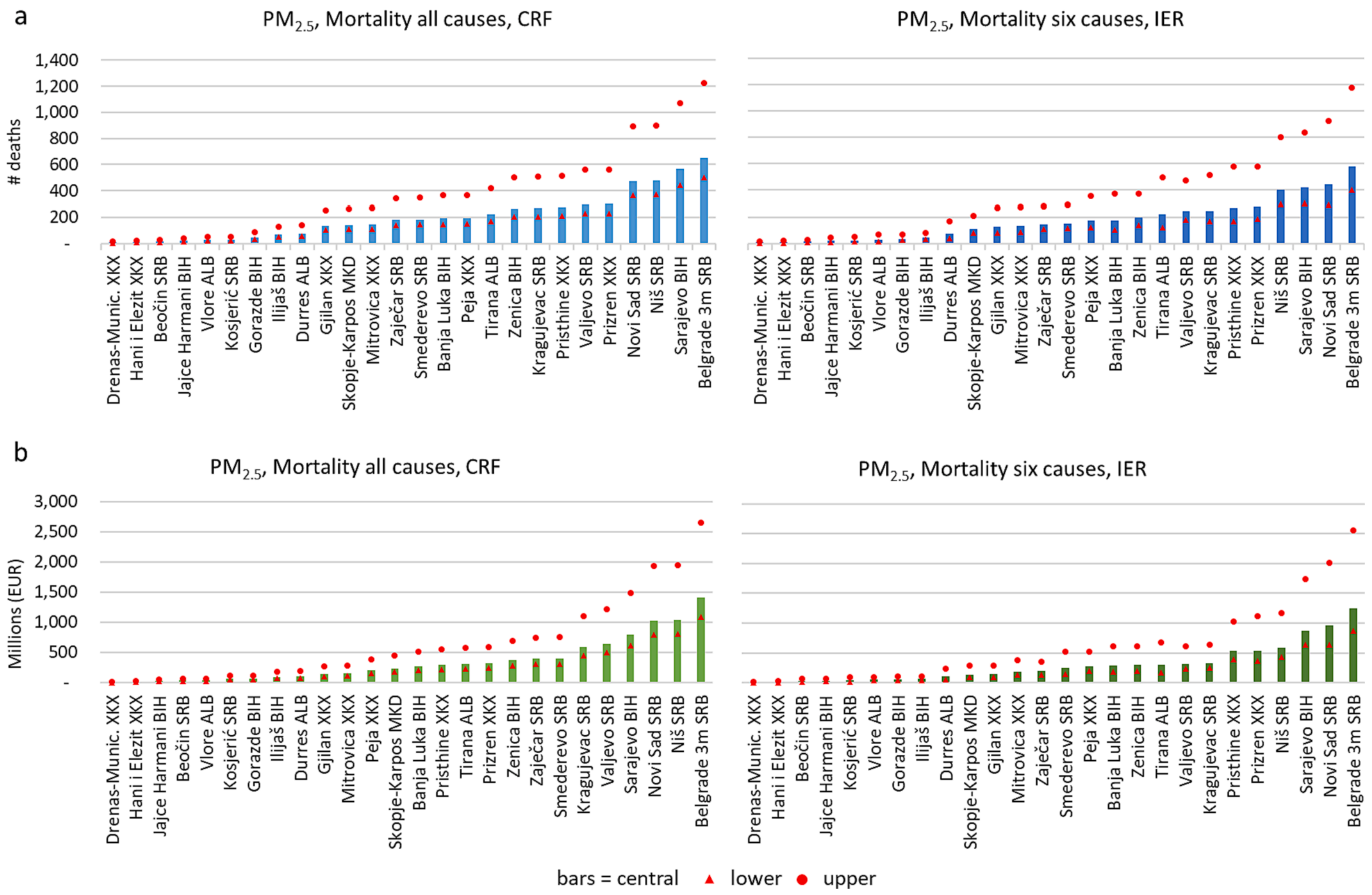

Fig. 3. Mortality associated with $PM_{2.5}$ in 26 cities obtained with the CRF (left) and IER (right) methodologies and their respective costs (bottom). The lower and upper boundaries of the 95% C.I. are also provided.

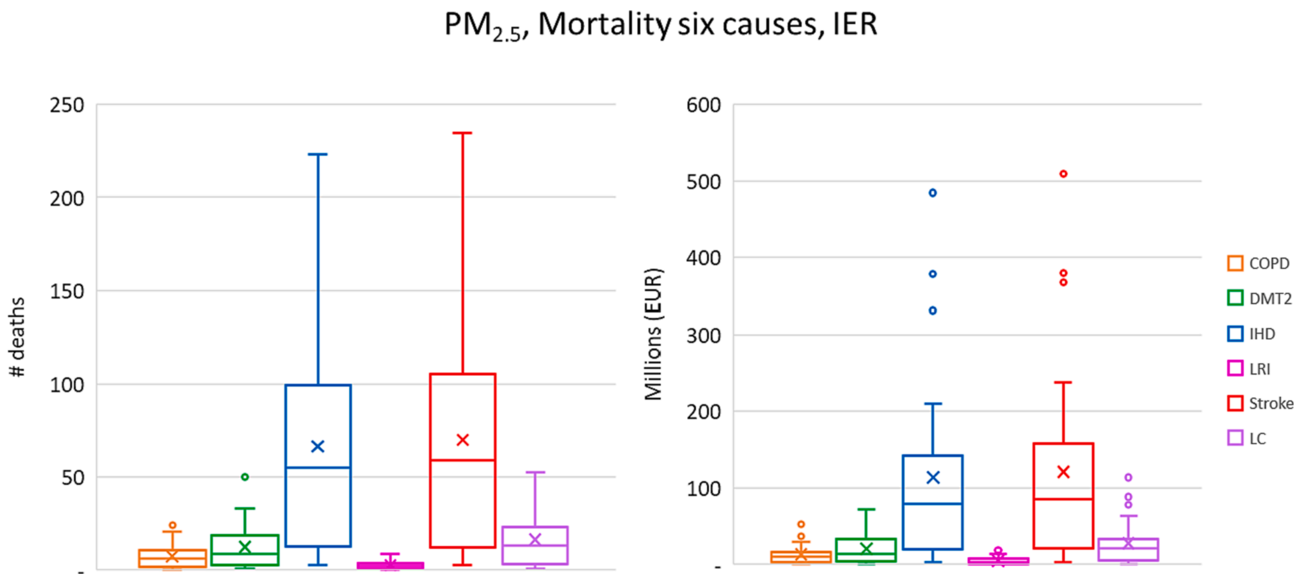

Fig. 4. Total mortality for the six causes of death associated with $PM_{2.5}$ in the 26 studied cities obtained with the IER methodology (left) and their respective costs (right). Values at a distance from the border of the box higher than 1.5 times the interquartile range are plotted as separated circles (mild outliers).

respiratory causes while the former only considers only COPD cause of death. Another difference between the two approaches for this pollutant is that the confidence interval of the CRF estimations is higher than the one of the IER.

The CRF all-cause mortality attributable to O_3 totalised 9.7 thousand YLL corresponding to 676 million Euro. Similar to $PM_{2.5}$, this figure is 29 % lower than the costs of mortality based on the number of deaths (Fig. 5 bottom right).

The all-cause mortality and respective costs associated with NO_2 in 2019 obtained with the CRF methodology are shown in Fig. 6 (top). The

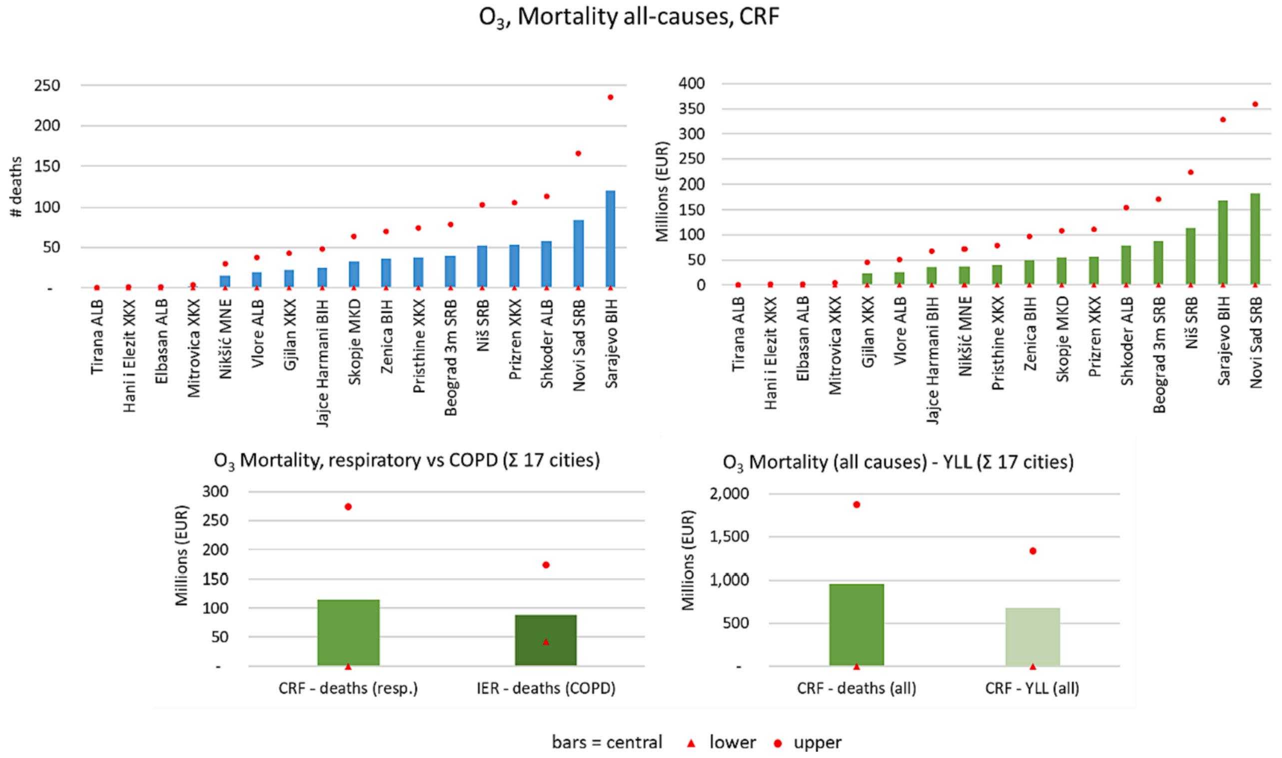

Fig. 5. All-cause mortality and respective costs associated with O_3 in 17 cities obtained with the CRF methodology (top). Comparison of O_3 -related mortality associated with respiratory causes and COPD costs (bottom left) and between VSL and YLL all-cause mortality costs (bottom right) are also shown. The lower and upper boundaries of the 95% C.I. are also provided.

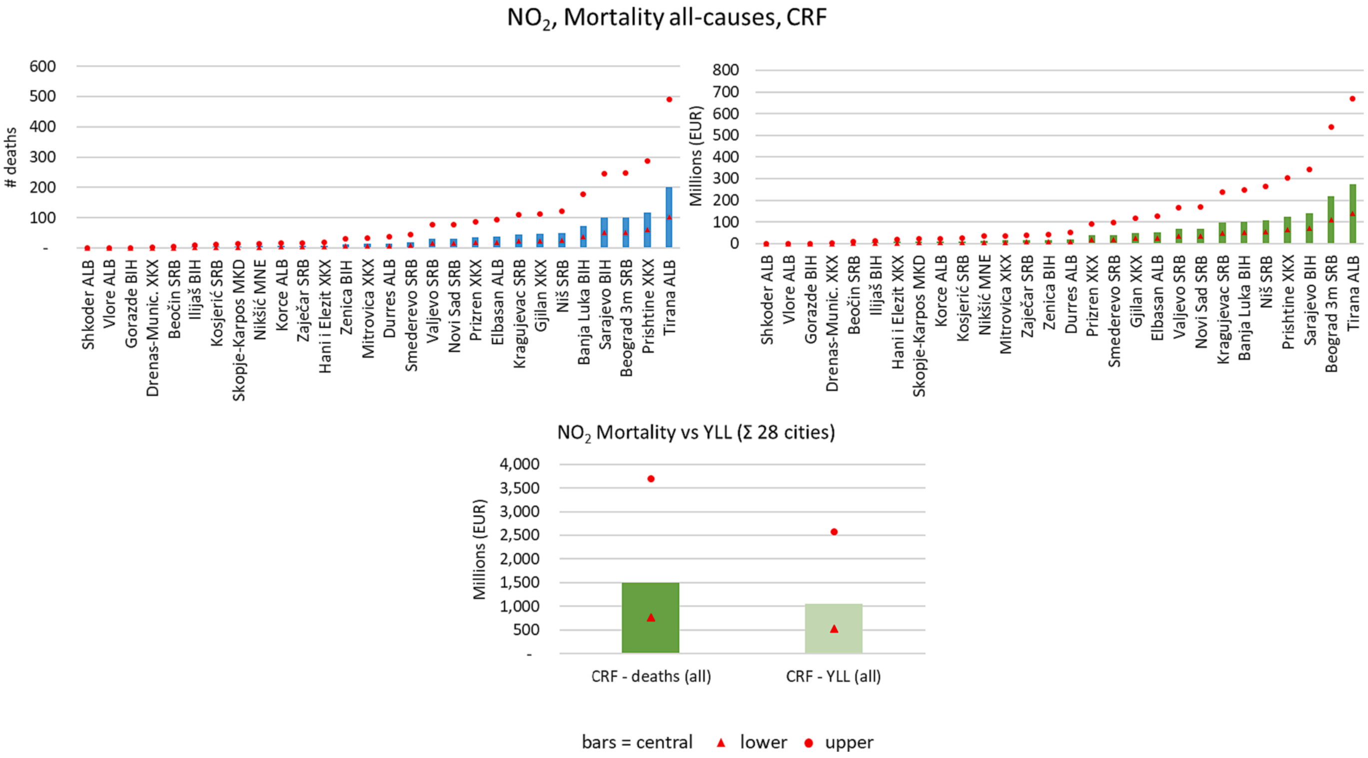

Fig. 6. All-cause mortality and respective costs associated with NO_2 in 28 cities obtained with the CRF methodology (top). Costs of NO_2 -related mortality associated with YLL all-cause (bottom). The lower and upper boundaries of the 95% C.I. are also provided.

mortality attributable to this pollutant in the 28 studied cities totalised 970 deaths with an associated total cost of 1.5 billion Euro equivalent to a mortality rate of 28 deaths per 100,000 inhabitants and a cost of 430 Euro *per capita*. The average values per city were 35 deaths and 54 million Euro. The highest impacts are observed in urban areas located in the south of the region (Tirana, Pristina) followed by most populated cities located in the central and northern areas (Belgrade, Sarajevo, Banja Luka).

A total of 15.5 thousand YLL were attributed to NO_2 exposure in 2019 equivalent to a cost of 1.0 billion Euro, a value 30 % lower than the costs of mortality obtained using the number of deaths as indicator (Fig. 6 bottom).

3.3. Morbidity

In Fig. 7 the distribution of morbidity outcomes in 2019 associated with particulate matter ($PM_{2.5}$ and PM_{10}) in 26 WB cities obtained with the CRF methodology (left) and respective costs (right) are shown. The wide range of results is due to the different pollution levels and sizes of the urban areas included in the study.The outcomes, related to diseases attributable to particulate matter ($PM_{2.5}$ or PM_{10}), with highest total incidence in the studied cities were MI (2,650 cases), COPD (2,550 cases), DMT2 (2,480 cases) and CVAD (2,250 cases). The total cost of these four outcomes was 137 million Euro equivalent to 41 Euro *per capita* with average costs per city of 5.2 million Euro.

Bronchitis in both children (BR CHI) and adults (BR AD) and asthma in children (ASTH CH) due to PM were below 200 cases each with a total cost for the three outcomes of 3.8 million Euro, equivalent to less than 150 thousand Euro per city. An overall cost of 3.3 million was estimated for the 384 cases of lung cancer attributed to PM pollution in the studied urban areas with an average of 130 thousand Euro per city.

The sum of hospital admissions for cardiovascular (HA CVD) and respiratory (HA RD) diseases due to PM pollution were less than one thousand with a total cost of 1.9 million Euro in all the urban areas (73.0 thousand Euro per city on average). The PM impact on morbidity outcomes unrelated to a specific disease, working lost days (WLD) and reduced activity days (RAD), in all the cities was 5.2 and 51 thousand days, respectively, with a pooled estimated cost of 2.5 million Euro in 2019 and an average cost per city of 97 thousand Euro. The overall costs of morbidity attributed to PM in the 26 WB cities in 2019 has been estimated in 150 million Euro equivalent to 45 Euro *per capita* and 5.7 million Euro per city.

4. Limitations of the approach and comparison with similar studies

The estimations reported in the present study are derived from measurements in background monitoring stations fulfilling legally binding quality standards (Table S1). This approach made it possible to use the most reliable information about air quality in the study area which are useful for validating estimations based on modelling exercises. However, adopting strict quality standards for measurements resulted in a reduced number of locations available for the analysis compared to the total number of monitoring stations. In addition, it is difficult to establish the spatial representativeness of point measures. In the majority of the cases we assumed that they represent the entire urban area (Martinez et al., 2018). However, in the certain cases (Belgrade and Skopje) the dimension of the city and the location of the monitoring station suggested to attribute the concentrations to an area smaller than the entire city (Figures S1 and S2).

Due to the unavailability of mortality with detail by age at the city level in the Western Balkans, the baseline mortality for the studied cities were estimated downscaling national data using the population as proxy (city mortality = city population/total national population) without considering specific city demographic profiles. According to a study on air quality in European cities (Western Balkans' cities are not included) downscaling from national to city level all-cause mortality may lead to 8 % −10 % overestimation of mortality attributable $PM_{2.5}$ and NO_2, respectively (Khomenko et al., 2021). Such potential bias should be considered in the interpretation of our results. To achieve a better understanding of this subject, further validation and uncertainty analysis with local studies is foreseen in a follow up study. The mortalities attributable to $PM_{2.5}$ resulting from the present study are comparable to those reported in a study by WHO for the reference years 2010 – 2015 in 11 Serbian cities using the data from the monitoring station and applying the GBD approach (WHO Regional Office for Europe, 2019). When comparing the results it should be considered that: a) they refer to different time windows; b) the WHO work assessed the $PM_{2.5}$ mortality based on different IER curves representing only 5 causes of death, and c) the cut off used in the WHO study was higher (10 $\mu g/m^3$) than the one adopted in the present study (5 $\mu g/m^3$). In the majority of the eight cities included in both studies the differences are below 12 % (Figure S3). The exceptions are Novi Sad and Smedrevo where the WHO estimations differ between 37 % and 48 % from those reported in the present study likely due to a different disaggregation of the national baseline mortality.

The estimation of air pollution costs is much dependent on the adopted reference values (VSL and VOLY). A sensitivity analysis revealed that using Czechia GDP *per capita* as reference for the BT instead of the one from OECD average would led to 38 % lower cost estimations, on average (Figure S4). The VSLs adopted in this study are on average 19 % and 10 % higher than those used in the WHO tools Carbon H and CLIMAQ-H to estimate the costs of air pollution in UNECE countries in 2020 and 2030, respectively, when expressed in the same currency (Spadaro et al., 2020; Pisoni et al., 2023, WHO Regional Office for Europe, 2023). By comparison, our VSLs are between 63 % and 68 %

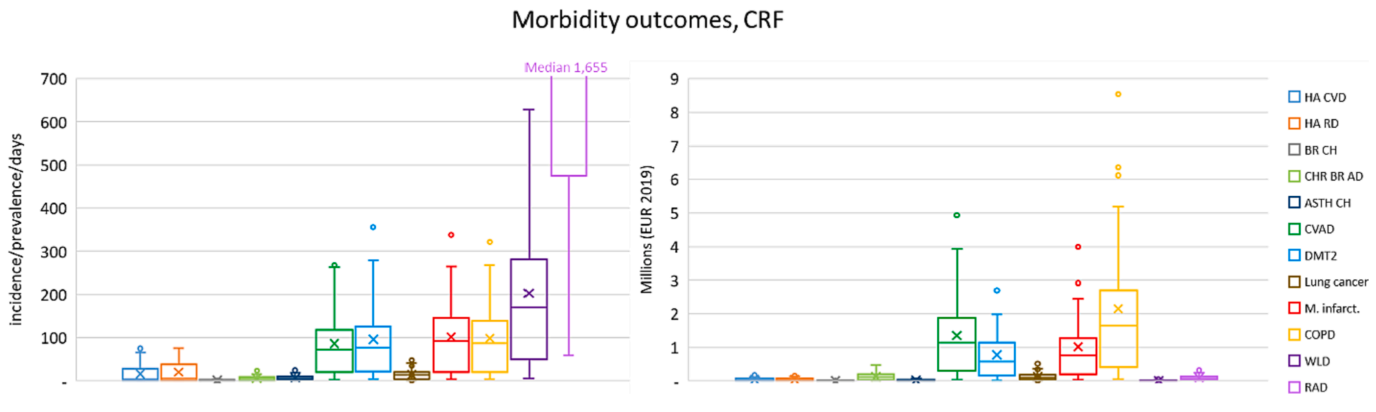

Fig. 7. Distribution of morbidity and respective costs associated with PM ($PM_{2.5}$ or PM_{10}) in 26 cities obtained with the CRF methodology. The box represents the interquartile range and the whiskers min and max values. The bar in the box is the median and the cross represents the average. Mild outliers are indicated as dots. HA CVD: Hospital admissions cardio-vascular diseases, HA RD: hospital admissions respiratory diseases, BR AD CHR: chronic bronchitis in adults, BR CHI: bronchitis in children, RAD: reduced activity days, WLD: working lost days, ASTH CHI: asthma in children, DMT2: diabetes mellitus 2, MI: myocardial infarction, COPD: chronic obstructive pulmonary disease.

higher than those adopted by the World Bank in previous estimations of 2016 air pollution costs in Bosnia and Herzegovina, North Macedonia and Kosovo (World Bank 2019a, 2019b, 2019c) expressed in the same currency. Moreover, the average of the VSLs selected for the present study is approximately half of the one (3.6 million Euro 2015) used for similar evaluations in EU27 (Amann et al., 2017; European Commission, 2022). In the present study we opted to use lower VSLs to account for the considerable differences between the WB economies and the EU27. The application of the VSL used for EU27 would nearly double the air pollution cost estimations of the present study leading to unrealistic shares of the WB GDP (see Section 5).

5. Discussion

The results of the present study, suggest that mortalities attributable to $PM_{2.5}$ with the IER and CRF approaches are comparable. The observed 13 % gap between them is explained by the different causes of mortality considered in each of these methodologies. The IER approach considers the six most important causes of death associated to $PM_{2.5}$ independently and therefore it is possible to obtain full estimations for each of them. By comparison, the CRF approach aims to estimate the impact of this pollutant on all-cause mortality which is more comprehensive and may include the effect of CODs which relationship with $PM_{2.5}$ is not well known yet. Nevertheless, with this approach it is not possible to split the output by single COD. Moreover, the IER approach achieves a detailed description of the exposure–response curve making it suitable to accomplish studies over a wider range of pollutant concentrations.

In the present study, the CRF approach estimates the O_3 -related impact for all-cause mortality while the IER approach provides estimations only for one cause of death. Nevertheless, it should be considered that the all-cause mortality CRF estimations involve a considerable uncertainty and even if very unlikely the non-effect cannot be completely excluded. When estimating the O_3 -related respiratory mortality with CRF the results come closer to those obtained with IER for COPD mortality with a 25 % difference which is likely reflecting respiratory lethal effects of air pollution other than COPD.

A difference of 28 % − 30 %, depending on the pollutant, has been observed between the air quality related mortality costs estimated using YLL compared to those based on number of deaths. The lower YLL values are likely reflecting the effect of accounting for the life expectancy at death compared with estimations based on crude mortality. Nevertheless, total mortality is a parameter relatively easy to monitor while the accuracy of life expectancy may impact on the uncertainty of YLL estimations.

Although a number of studies have investigated the interaction between $PM_{2.5}$- and NO_2-related mortality (Huangfu and Atkinson, 2020 and literature cited therein), there is no common approach for dealing with this issue. Some studies adjust mortality estimations due to interaction between pollutants (e.g. Fischer et al., 2015) while others do not find significant interactions (e.g. Yang et al., 2018). The approach adopted in the present study is to report premature deaths and related costs for each pollutant separately.

In 2019, the average $PM_{2.5}$-related mortality rate expressed per 100,000 inhabitants of the studied WB urban areas was between 137 and 158 which is nearly twice the EU 27 country average (69) in the same year (European Environment Agency (EEA), 2021) and is above the 99th percentile of air quality mortality rates estimated for 800 European cities in 2015 (Khomenko et al., 2021). Similarly, the O_3 and NO_2 premature death rates equal to 19 and 28 per 100,000 inhabitants computed in the present study are higher than EU27 average at country level in the same year, 4 and 9 deaths per 100,000 inhabitants, respectively European Environment Agency (EEA), 2021.

Due to the highest attributable mortality, $PM_{2.5}$ is the most important contributor to air pollution costs with values that outclass O_3 and NO_2 by a factor of 10 and 6 respectively (# deaths-VSL). Moreover, the $PM_{2.5}$-related mortality costs are 60 times those of morbidity attributable to this pollutant. Therefore, the comparison with the EU27 in the section below is mainly focused on $PM_{2.5}$ mortality costs.

The economic burden of $PM_{2.5}$ pollution in the 26 studied cities, which represents nearly one third of the WB's urban population, sums up to 8 % − 9 % of the region GDP, according to GBD and IER respectively. If we consider that in the same year the impact of air pollution in EU27 countries (including the entire country) was on average 10 % of the country GDP (on the basis of mortality reported in (European Environment Agency (EEA), 2021), we can conclude that the relative economic burden of air pollution in the Western Balkans is considerably higher than the one observed in the EU27 in the same time window (approximately by a factor of 3). This is in line with a recent study to support the Air Protection Action Plan in Serbia where the costs of mortality in 2015 estimated on the basis of the number of deaths (VSL) were more than one third of the country GDP (Republic of Serbia, 2022).

On the basis of a $PM_{2.5}$ source apportionment study (Belis et al., 2019) including ten of the WB cities studied in the present work, it was estimated that a 40 % of the health external costs due to $PM_{2.5}$-related mortality in 2019, equivalent to 243 million Euro per city, was attributable to the Energy sector. In the same subset of urban areas the residential combustion and the agricultural sector contribution was approximately 20 % of the costs (115–129 million Euro per city/year) each, while the remaining 20 % is to be allocated to transport, industry, waste management and other activity sectors (Fig. 8). The same line of reasoning leads to allocating 4.6 million Euro per city due to the $PM_{2.5}$-related costs of morbidity attributable to emissions in the energy, residential combustion and agricultural sectors.

6. Conclusions

The study covered the three main ambient air pollutants with well-known quantitative relationships between exposure and response. The exposure was assessed on the basis of air quality monitoring station measurements which is the most reliable information about air quality in the study area. In addition, the study compared and combined two different health impact assessment approaches (IER and CRF) with the aim of providing reference data for the validation of estimations based on modelling exercises.

Considering that the estimation of air pollution costs is highly dependent on the unit costs (VSL and VOLY), a careful review of the literature and a sensitivity analysis was carried to support this choice. The choice of using country specific unit costs made it possible to catch

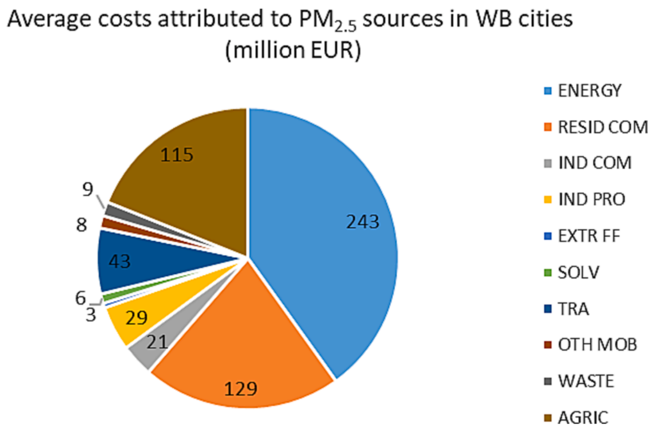

Fig. 8. Source apportionment of average costs (million EUR) per city attributed to $PM_{2.5}$-related mortality in ten Western Balkans cities (Durres, Tirana, Banja Luka, Sarajevo, Pristina, Skopje, Belgrade, Kragujevac, Nis and Novi Sad) in 2019. ENERGY: power plants, RESID COM: residential combustion, IND COM: combustion in industry, IND PRO: industrial processes, EXTR FF: extraction of fossil fuels, SOLV: use of solvents, TRA: road transport, OTH MOB: other transport, WASTE: waste management, AGRIC: agriculture.

the peculiarities of the region. The values derived with the BT method were at the centre of the range of those used in previous studies in the same area and near half of those used for EU27 countries in recent studies.

In 2019, $PM_{2.5}$–related mortality costs outclassed those of O_3 and NO_2 and the gap with morbidity costs was wider. The costs of mortality attributable to $PM_{2.5}$ in the 26 studied cities with IER and CRF methodologies were comparable (7.8 and 9.0 billion Euro respectively) with the small discrepancy between them explained by the different causes of mortality considered. The cost of O_3-related mortality reported in the present study in 17 cities using the CRF approach for all-cause mortality was 0.96 billion Euro while the one obtained with the IER approach associated with only one specific cause of death (COPD) was 87 million Euro. In 2019, the NO_2 pollution cost in 28 WB cities due to all-cause mortality estimated with the CRF method was 1.5 billion Euro. The air pollution costs based on YLL – VOLY were on average 29 % lower than those estimated using the number of deaths- VSL likely due to life expectancy at death being considered in the former approach. The gap between # deaths- and YLL-based methods should be taken into account when estimating the overall impacts and costs. In 2019, the costs of morbidity attributed to PM in the 26 WB cities totalised 150 million Euro equivalent to 45 Euro *per capita* and 5.7 million Euro per city.

One of the conclusions of the study is that CRF and IER methodologies are a) coherent, because the differences are explained by the different mortality outcomes considered by each of them, and b) complementary as the combination of both makes it possible to obtain a wider range of outcomes. In addition, despite the different causes of death considered by the two methodologies comparing them is useful for cross validation purposes.

The study also provides evidence about the inequalities associated with air pollution since the relative economic burden of air pollution in the WB is considerable higher than the one observed in the EU27 in the same time window. In addition, an analysis of the sources contributing to $PM_{2.5}$ in a subset of the WB cities suggests that reductions in the energy sector are those that may lead to the highest health and economic benefits followed by agriculture and residential combustion.

CRediT authorship contribution statement

Claudio A. Belis: Conceptualization, Methodology, Formal analysis, Validation, Writing – original draft. **Vlatka Matkovic:** Conceptualization, Formal analysis, Writing – original draft. **Marta Ballocci:** Methodology, Formal analysis, Writing – review & editing. **Marija Jevtic:** Data curation, Supervision. **Giovanni Millo:** Software. **Elida Mata:** Data curation. **Rita Van Dingenen:** Methodology, Validation, Writing – review & 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.

Data availability

Data will be made available on request.

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Disclaimer

The information and views set out are those of the authors and do not necessarily reflect the official opinion of the European Commission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108347.

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