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Original Research Article

Health Co-benefits of Climate Change Mitigation Action

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ABSTRACT

This study addresses the potential health benefits of climate change mitigation action. Carbon Reduction Benefits on Health tool and the MARket ALlocation model are used to evaluate the health co-benefits of the proposed energy sector policies and measures in North Macedonia's enhanced nationally determined contribution. The study hypothesises that implementing these policies and measures will reduce morbidity and mortality due to air pollution by 2030. The results indicate 629 prevented bronchitis cases, 2,788 fewer asthma symptom days among children, and 143 preventable deaths, leading to considerable welfare improvements and economic savings. The findings underscore the importance of considering health outcomes in climate policy decisions, emphasising the substantial public health benefits alongside climate gains as an incentive for emissions reduction. Sharing these findings with other countries will enhance efforts to limit the global temperature rise below 2 °C by the century's end.

KEYWORDS

Health co-benefits, Climate change mitigation, Nationally determined contributions, Air quality improvement, Decarbonisation of energy sector, Policies and measures.

INTRODUCTION

The health risks posed by climate change have been discussed by the World Health Organization (WHO) for more than a decade [1], emphasising the importance of global health engagement in climate discussions and policy formulation and highlighting the potential health benefits of climate change mitigation actions, such as reducing air pollution-related diseases, mitigating impacts of heat and cold extremes and promoting healthier lifestyles, while also stressing the role of the health sector in leading and supporting these efforts. In addition to tackling the undesirable economic, environmental, and social consequences of climate change, carbon abatement measures can also yield health co-benefits by reducing emissions of major air pollutants such as particulate matter (PM), sulphur dioxide (SO_2), and nitrogen oxides (NO_x). These pollutants directly or indirectly affect the local and regional air quality within a country and its neighbouring countries through transboundary transport of air pollution. Health benefits include reduced instances of illnesses and delayed premature mortality across the entire population, particularly among vulnerable sub-populations such as children, seniors, and individuals with preexisting health conditions, who are vulnerable to exposure to atmospheric pollutants. Mitigating adverse health effects also positively influences local and national economic productivity, healthcare expenditures, and personal finances, leading to intangible

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societal benefits from avoided disability due to pain and suffering. Therefore, climate policies aimed at reducing carbon emissions can simultaneously mitigate air pollution and its associated health impacts, resulting in increased healthy life expectancy for citizens.

The 2023 report of the Lancet Countdown on health and climate change [2] underscores the urgent need to reduce CO_2 emissions to reach net zero by 2050, emphasising the significant health co-benefits of urgent mitigation efforts. These include reducing deaths from air pollution, transitioning to healthier diets, and promoting accessible, active travel. Achieving these goals requires collaboration across sectors and prioritising universal access to clean, zero-emission energy while mitigating harmful industrial practices. Monitoring progress is crucial, focusing on maximising health co-benefits and minimising unintended harms.

Numerous studies address the intersection of climate mitigation efforts and improvements in air quality, specifically regarding their health co-benefits, across various scales, including global, regional, and national levels. One of the studies at the global level [3] utilises an integrated modelling framework to evaluate air pollution emission reductions and associated health impacts across various global mitigation pathways aligned with the Paris Agreement's 2 °C target. It quantifies health co-benefits by combining the Global Change Assessment Model (GCAM), the Fast Scenario Screening Tool (TM5-FASST), and an economic valuation approach. Findings indicate significant reductions in premature mortality, ranging from 17−23% by 2020−2050 compared to baseline scenarios, with varying ratios of health co-benefits to mitigation costs depending on technological options. Regional analysis highlights disparities, with regions like India and China experiencing notable benefits. The study emphasises the importance of integrated models for accurate co-benefit assessments. It also underscores the potential of health co-benefits to drive mitigation actions, particularly in countries like China and India. Additionally, regions such as Europe, Russia, and Asia (excluding Indonesia) exhibit health co-benefits that outweigh mitigation costs due to affordable low-carbon strategies and existing pollution levels. At the same time, countries with lower population densities, like Canada, Australia, South America, and the USA, also witness significant health co-benefits despite costs not surpassing mitigation expenses. Recognising these health co-benefits is crucial for global policy design. The same integrated modelling, combined with the GCAM and TM5-FASST models, was also applied to assess the health co-benefits of cancelling new coal-fired power plants globally as part of efforts toward deep decarbonisation [4]. The authors find significant reductions in air pollution-related premature mortality, particularly in developing Asia. The study underscores the importance of phasing out coal plants to meet Paris Agreement goals. It highlights the potential of air quality-related health co-benefits as an incentive for emissions reduction and suggests future research directions, including detailed economic analysis of coal retirement, monetisation of premature mortality, and exploration of impacts on other Sustainable Development Goals (SDGs). Another paper investigating the co-benefits of reduced air pollutant emissions alongside climate policy implementation employs the WorldScan computable general equilibrium model [5]. Accounting for emissions and abatement of both greenhouse gases (GHGs) (CO_2, N_2O, CH_4) and air pollutants (SO_2, NO_x, NH_3, $PM_{2.5}$), the applied model operates within a comprehensive economic framework covering five global regions (including two within the EU). This paper examines how climate policies indirectly affect air pollutant emissions and, thus, air quality, which is closely linked to human health. The study sheds light on the potential health benefits of climate action by estimating the co-benefits of decreased emissions through climate policies, particularly in regions lacking comprehensive air pollution regulations. However, uncertainties regarding the impact of multilateral air policies on trade dynamics highlight the need for further research to fully understand the health implications of climate policy co-benefits. Scovronick *et al.* [6] highlight the importance of considering the interplay between climate policies targeting CO_2 emissions and their impacts on air pollutant emissions by presenting a comprehensive cost-benefit model that integrates health co-benefits and climate co-harms, thus offering insights into the immediate global net benefits of climate action and underlining the potential economic value of prioritising health outcomes. The findings suggest that economically optimal levels of mitigation may align with ambitious climate targets, contingent on how society values improved health outcomes. The potential health co-benefits of Nationally Determined Contributions (NDCs) under the Paris Agreement are examined in **[7]**, focusing on nine representative countries (i.e., Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK, and the USA). By modelling scenarios for 2040, the research assesses the impact of existing NDCs and related policies on air pollution-related deaths, diet-related deaths, and deaths due to physical inactivity. The authors utilised several models to estimate various factors influencing health co-benefits, including the International Energy Agency's world energy model for fuel use projections, the Greenhouse gas − Air pollution Interactions and Synergies (GAINS) model for GHG emissions and air pollution estimates, an established food-system model for dietary changes, and data on active travel mode share for assessing physical activity-related benefits. Adopting more ambitious climate policies could significantly reduce annual deaths across the analysed countries compared to current pathways.

Considering the research at the regional level, the interaction between decarbonisation targets and air pollution control in the European energy system is examined in a comparative scenario analysis in **[8]**. The study integrates the European energy system model TIMES PanEU with the impact assessment model EcoSense to internalise health costs associated with air pollution. Results highlight the significant influence of ambitious GHG reduction targets on system transformations. The analysis underscores the interconnection of air pollution control and climate change mitigation policies, emphasising the need for a holistic approach considering their simultaneous impacts. Regardless of the scenario, emissions are reduced similarly across the board, suggesting that integrating air pollution costs motivates an earlier transition to a low- or zero-carbon society. Another study investigating the interplay between climate policy pathways and their indirect effects on air pollution and human health in Europe **[9]**, with projections by 2050, uses a comprehensive modelling approach that integrates global and regional climate and chemistry-transport models with a health impact assessment tool. By combining consistent air pollution and climate policy scenarios with population data, the study evaluates morbidity and mortality impacts of $PM_{2.5}$ and ozone (O_3) pollution, expressed in terms of monetised damage equivalent. The study employs emission scenarios developed under the Global Energy Assessment (GEA) and Representative Concentrations Pathways (RCPs) from the IPCC's 5th assessment report, along with models like MESSAGE for energy system analysis and CHIMERE for air quality assessment. Results indicate that existing European air quality policies effectively reduce health impacts from $PM_{2.5}$, with even more significant benefits under stringent global climate policies, including substantial reductions in premature deaths and life years lost.

Another study **[10]** employed an interdisciplinary multi-modelling approach to assess air pollution's health and economic impacts under climate change mitigation strategies in South Korea, integrating a computable general equilibrium model, an air quality model, and a health impact assessment model. Using emissions data generated by the Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) model and air quality concentrations calculated by the Community Multiscale Air Quality (CMAQ) model, the health impact assessment model estimated the health impacts of $PM_{2.5}$ and O_3 concentrations. The findings highlight the significant health gains achievable through climate change mitigation efforts, underscoring the importance of such actions in achieving climate targets and improving public health.

Similarly, Yang *et al.* **[11]** assessed the impact of carbon and pollution control policies on air quality and human health in China, using an integrated framework combining various models (an energy-economic model, an air quality model, and a concentration-response model). The authors developed seven combined scenarios for 2030 based on three energy scenarios and three end-of-pipe control scenarios, showing significant reductions in emissions, pollutant concentrations, and premature deaths compared to the baseline scenario. Notably, the most stringent scenario could decrease nationwide $PM_{2.5}$- and O_3-related mortality, with three-quarters of the avoided deaths attributed to end-of-pipe control measures. The findings underscored the importance of joint control of $PM_{2.5}$ and O_3 in future policymaking to address the dual challenges of climate change and air pollution, especially in provinces in heavily polluted and densely populated regions. Another paper **[12]** evaluates the health impacts of reducing air pollutants in China employing the intake fraction (IF) method **[13]** and concentration-response (CRF) function **[14]** enabled through the Integrated Benefits Calculator (IBC) from the LEAP (Long-range Energy Alternatives Planning system) model. Health co-benefits are assessed for four scenarios (developed to estimate energy demand and carbon emissions from 2020 to 2050), focusing on mortality reductions due to NO_x reduction. The LEAP model was also applied in **[15]** to assess energy consumption and emissions in China's transport sector under four scenarios from 2010 to 2050. Emissions include CO_2, CO, SO_2, NO_X, PM_{10}, and $PM_{2.5}$. Health benefits, including substantial economic losses mitigated by reduced mortality, were observed across scenarios, emphasising the importance of considering health impacts in environmental policy formulation. Another study that tackles China's transport sector **[16]** explores the potential benefits of replacing internal combustion engine vehicles with alternative energy vehicles (AEVs) (e.g., electric, hydrogen fuel cell, and natural gas vehicles), focusing on air quality, health, carbon emissions, and economics. The authors use the WRF-Chem model (Weather Research and Forecasting model coupled with Chemistry) to analyse scenarios and simulate changes in ambient $PM_{2.5}$, O_3, and NO_2 concentrations. Their findings highlight significant co-benefits associated with transitioning to AEVs, mainly when powered by non-fossil fuel sources, resulting in notable reductions in air pollution and related premature mortalities and years of life lost. The results underscore the importance of rapidly decarbonising the power system to maximise climate, air quality, and health benefits from AEV deployment in China. Liu *et al.* **[17]** developed a GHG policy assessment model (GHG-PAM) utilising annually published energy balance tables and examined its applicability in the case of the Chinese city of Suzhou. Four scenarios were examined to evaluate the co-benefits of Suzhou's mitigation policies, projecting CO_2 emissions and fine particulate matter (PM) emissions. The study unveiled significant air pollution-related health co-benefits from GHG reduction policies in Suzhou by evaluating the impacts on population health measured in disability-adjusted life years (DALYs). The findings suggest immediate and local health gains from reducing GHG emissions, alongside direct climate mitigation benefits, enhancing the cost-effectiveness of such actions. Another study for China **[18]** examines the near-term air quality and CO_2 co-benefits of current sector-based policies, focusing on the potential benefits of four sectoral mitigation strategies. The study uses the GAINS model to evaluate scenarios involving sector-specific fuel switching, technology upgrades, and conventional air pollution controls across industry, power, transportation, and residential sectors. Air quality simulations conducted with the WRF-Chem model consider both primary $PM_{2.5}$ and secondary $PM_{2.5}$ formed from precursors such as SO_2, NO_x, and NH_3. Health co-benefits are estimated in terms of avoided premature deaths associated with exposure to ambient $PM_{2.5}$, emphasising the importance of industrial energy efficiency improvements and technology upgrades of air pollution control for enhancing air quality, health, and climate outcomes in China. GAINS model was also used in **[19]** combined with IMED/HEL (Integrated Model of Energy, Environment and Economy for Sustainable Development/health) and IMED/CGE (Computable General Equilibrium) models to evaluate the co-benefits of climate change mitigation actions in China's road transport sector towards the 2 °C target. The study aims to assess $PM_{2.5}$ pollution-related health impacts nationally and provincially by 2050, distinguishing between contributions from climate actions and air pollution control measures. Findings indicate that the road transport sector could significantly reduce $PM_{2.5}$ concentrations and associated health impacts, and populous provinces with heavy industry stand to benefit more from these actions, highlighting the importance of sectoral approaches in climate policy planning for public health and economic gains. Woodward *et al.* **[20]** explore the implications of China's climate policies on population health, examining the Intended Nationally Determined Contribution (INDC) commitments and national planning documents while reviewing the literature on health trade-offs and synergies. They find positive impacts on air quality and health from measures like coal burning controls but warn of potential risks depending on policy implementation. The study emphasises the need to understand unexpected impacts and vulnerabilities, supporting both modelling and observational research, especially as emission reductions accelerate to meet climate targets. The study also clarifies the complex interplay between climate policies and population health in China through three case studies, including air pollution reduction, flood prevention, and urban health promotion.

The present study contributes to existing literature by analysing North Macedonia, a developing country at the forefront of climate change policy in the West Balkan region. As a non-Annex I party to the UNFCCC, North Macedonia ratified the Paris Climate Agreement in November 2017, initially focusing its NDC on reducing CO_2 emissions from fossil fuel combustion. With energy supply, buildings, and transport as dominant sectors, the country aimed for a 30−36% reduction in CO_2 emissions by 2030 compared to the Business As Usual (BAU) scenario [21]. As a candidate country for European Union (EU) membership and a participant in the Energy Community, North Macedonia aligned with the EU's 2050 climate neutrality goal. In April 2021, North Macedonia submitted an enhanced NDC, pledging a 51% reduction in GHG emissions compared to 1990 levels by 2030, with an 82% reduction in net emissions [22]. This enhanced NDC focuses on mitigation through 63 policies and measures (PAMs) covering energy, agriculture, land use, forestry, and waste sectors. Beyond mitigation efforts, North Macedonia’s enhanced NDC includes economic and environmental evaluations of PAMs using the Marginal Abatement Cost (MAC) Curve tool and addresses social aspects such as job creation, gender responsiveness, and youth engagement. North Macedonia’s enhanced NDC also evaluates the role of the private sector in mitigation actions and identifies synergies with Sustainable Development Goals, circular economy benefits, and regional development contributions, aligning with EU initiatives and fostering regional cooperation. In addition to analysing the economic, environmental, and social aspects of the PAMs in the enhanced NDC, this study estimates the health co-benefits associated with improvements in ambient air quality resulting from proposed measures in the energy sector. Utilising the Carbon Reduction Benefits on Health (CaRBonH) calculation tool developed by the World Health Organization [23], the study hypothesises that implementing these policies and measures will significantly reduce morbidity and mortality due to air pollution. Previous research has primarily focused on urban air pollution impacts, particularly in Skopje, utilising data from air quality monitoring stations to identify notable health impacts associated with long-term $PM_{2.5}$ exposure, including premature mortality and hospital admissions due to cardiovascular and respiratory diseases, which highlights the importance of implementing air quality standards to mitigate these health effects. However, this study broadens the scope by examining urban outdoor air pollution nationwide. The findings are expected to provide valuable insights to support the country's NDC process, reaffirming its commitment to transitioning to a low-carbon economy. Furthermore, the study will set a best practice example of 'going beyond carbon reduction' by addressing additional societal aspects. Sharing these findings with other countries will enhance global efforts to limit the global temperature rise to below 2 °C by the end of the 21st century.

METHODS

The method applied in the study is based on application of two models:

- Long-term generation expansion planning model – MARKAL, which defines the optimal future capacity mix over 30 years and, based on the results, estimates the GHG and air pollutant emissions;
- Carbon Reduction Benefits on Health (CaRBonH) – a calculation tool to quantify the health and related economic gains from reducing air pollutants emissions.

Carbon Reduction Benefits on Health calculation tool

In order to analyse the health and economic co-benefits arising from reductions in domestic carbon emissions as stipulated in North Macedonia's enhanced NDCs submitted in 2021, the Carbon Reduction Benefits on Health (CaRBonH) calculation tool version 1.0R, from 10 November 2018, was employed [23]. WHO Regional Office for Europe developed the tool to quantify the health and related economic gains from implementing climate mitigation policies and measures as reported in the initial NDCs submitted to UNFCCC. It covers 53 Member States of the WHO European Region. This Excel-based tool is divided into four sections: User input, Tool output, Tool calculations, and Databases.

User input. The required input data consists of emission reductions for both GHGs and air pollutants, estimated in kilotons per year. The air pollutants encompass $PM_{2.5}$, SO_2, NO_x, and NH_3 emissions. Emission data can be specified by country for both 2020 and 2030. GHG emission reductions are aligned with the NDC pledges relative to a user-defined reference year. Reductions in other pollutants are compared against a BAU emissions scenario for 2020 and 2030. Users can input data for a single country/region or a group of countries. Notably, the European Union (EU) countries are merged into a single region − EU-28, with a single input for this region's data.

Tool output. The tool generates two main outputs: first, it calculates the reduced population-weighted exposure to air pollutants represented as changes in PM2.5 concentration. Second, it estimates the health and economic co-benefits of reducing these emissions due to carbon mitigation interventions. These outputs are presented both in tabular form and graphically for clarity. The table detailing reduced population-weighted exposure provides insights into changes in $PM_{2.5}$ concentrations resulting from national and regional emissions reductions, considering transboundary pollution effects.

Health benefits derived from reduced emissions include prevented cases of illness (morbidity), fewer premature deaths, and life years gained from extending life expectancy (*LE*) among the exposed population of all ages. Morbidity outcomes considered in the tool include additional cases of bronchitis in children; asthma symptom days in children; new incidences of chronic bronchitis in adults; work lost days (*WLD*) in adult employed population; restricted activity days (*RAD*); and hospital admissions (*HA*) for diagnosed respiratory and circulatory illnesses.

Economic benefits regarding healthcare expenditure savings, productivity gains, and the overall societal benefit of preventing premature deaths or extending life expectancy are assessed [24]. The tool also considers the influence of transboundary pollution by allocating results according to reductions in national emissions and additional health benefits from emissions reductions in other countries.

Tool calculations. This section of the tool comprises four worksheets designed to calculate the change in ambient air concentrations of $PM_{2.5}$ resulting from reductions in both domestic and regional emissions of $PM_{2.5}$, SO_2, NO_x, and NH_3, thereby assessing population exposure changes. These calculations rely on source-receptor tables, also known as country-to-country blame matrices, for each pollutant, which have been developed by the European Monitoring and Evaluation Programme of the European Commission [25]. Detailed information on the calculations conducted in these worksheets is provided in the manual for the CaRBonH tool [23].

Databases. The tool includes pre-loaded databases containing default data on economics, epidemiology, and demographics for 2010, 2020, and 2030 at the country level. Economic parameters represent costs per incidence case, i.e., illness, death, or years of life lost (*YLL*). The costs per case of illness include healthcare expenditures (including medication, medical, and hospital costs) and productivity losses stemming from work-lost days. Deaths are monetised using the value of statistical life while *YLL* years are costed using the statistical value of a life year. The Value of Statistical Life (*VSL*) represents the rate at which individuals are willing to exchange income for a reduction in their mortality risk [26]. The concept of the "Value of a Statistical Life Year" (*VOLY*) is linked to *VSL*. Specifically, assuming that *VOLY* remains constant over an individual's remaining lifetime and denoting *T* as the number of expected remaining life years, *VOLY* and *VSL* are related by equation (1), where δ represents an appropriate discount rate [26].

$$VSL = \sum_1^T VOLY \cdot (1 - \delta)^{-1} \tag{1}$$

Epidemiological data are based on concentration-response functions (CRF) recommended in the WHO–HRAPIE project [27]. Exposure costs for specific health outcomes related to air pollution are calculated by multiplying the CRF by the cost per incidence case (unit health cost). Demographic statistics by country and age group are also provided. Users can modify or supplement the data in the pre-loaded databases. The data for North Macedonia in these databases are presented in **Tables 1−3**.

Table 1. North Macedonia, demographics statistics (pre-loaded data in CaRBonH)

	Population by age group (thousands)						Mortality		
Year	6−12	5−19	18+	27+	15−64	All	CMR [%]	Deaths	*LE*
2010	176	414	1,597	1,312	1,456	2,062	0.92	19,061	75
2020	159	351	1,671	1,427	1,443	2,088	0.97	20,328	77
2030	158	341	1,678	1,473	1,368	2,078	1.02	21,214	78

Table 2. North Macedonia (WHO Region Eur-B [a]), Recommended Concentration-Response Functions of WHO-HRAPIE project (pre-loaded data in CaRBonH)

	Children		Adults	Labour force	All ages (morbidity)		All ages	
							Mortality	
Year	Bronchitis	Asthma	Chronic bronchitis	*WLD* [a]	*RAD* [a]	Hospital admissions	Deaths	*YLL*
2010	3.49E-04	1.54E-03	3.75E-05	3.25E-03	7.95E-02	4.77E-05	5.05E-05	6.81E-04
2020	3.03E-04	1.34E-03	4.08E-05	3.19E-03	7.97E-02	4.87E-05	5.58E-05	6.90E-04
2030	2.76E-04	1.22E-03	4.29E-05	3.06E-03	8.00E-02	4.92E-05	6.26E-05	6.88E-04

[a] Eur-B, Europe with low child and adult mortality; *RAD*, Restricted Activity Days; *WLD*, Work Lost Days

Table 3. North Macedonia (WHO Region Eur-B, Economic Status UMI [b]), unit health costs as international dollars (Int$) at 2005 prices, undiscounted (pre-loaded data in CaRBonH)

	Children		Adults	Labour force	All ages (morbidity)		All ages	
							Death	
Year	Bronchitis	Asthma	Chronic bronchitis	*WLD*	*RAD*	Hospital admissions	*VSL*	*VOLY*
2010	241	16	23,754	50	36	975	1,011,824	38,262
2020	316	21	31,303	66	47	1,350	1,320,696	49,942
2030	448	30	44,674	93	66	2,031	1,864,756	70,516

[b] UMI, upper middle income ($4,036−$12,475 per year)

MARKet ALlocation model

The GHG emission reduction potential of the energy-related policies and measures proposed in the country's enhanced NDC submission was evaluated using the MARKet ALlocation (MARKAL) model [28].

MARKAL is a commercially available linear-programming-based modelling framework utilised for planning energy sector development at local, national, and regional levels. Its primary objective is to simulate the energy market through least-cost optimisation (**Figure 1**).

MARKAL model encompasses the entire energy system, from resources and conversion technologies to end-use sectors (see Figure 2). For any given modelling scenario, the MARKAL model's objective is to meet the forecasted energy needs while minimising the total cost of the energy system, adequately discounted over the planning horizon. To meet this objective, the MARKAL model considers a large amount of input data (assumptions) and potential constraints, e.g., a CO_2 tax, limits on GHG emissions and/or renewable energy standards [28]. To sum up, MARKAL finds the least costly way to meet the various constraints related to the availability and the costs of existing and new energy technologies and resources to satisfy the energy demand. In addition, it calculates the environmental effect of the solution by calculating the GHG emissions related to the fuels used.

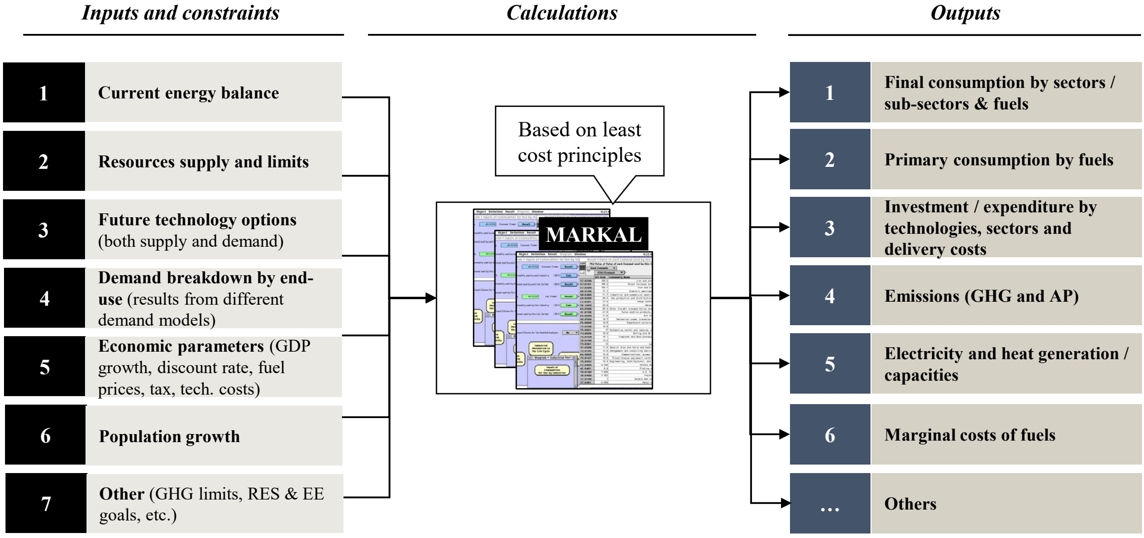

Figure 1. MARKAL model structure [29]

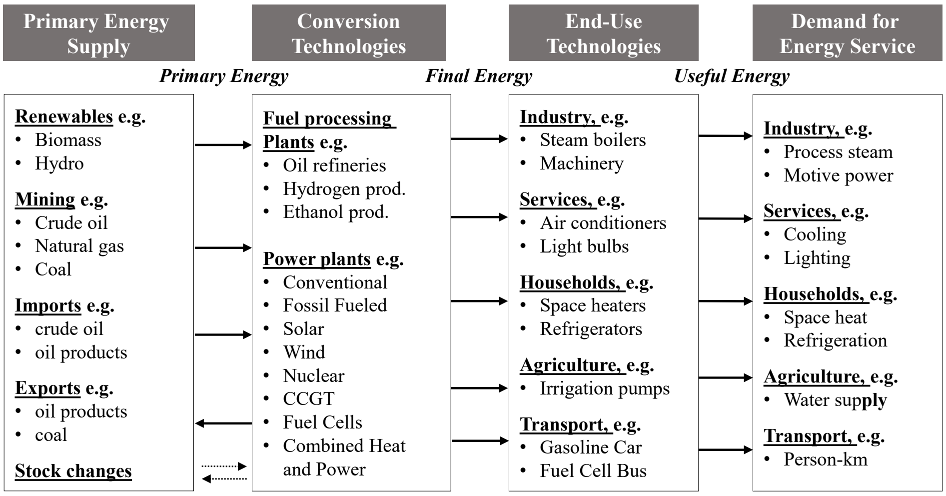

Figure 2. MARKAL key components [28]

The MARKAL model and its associated software tools were employed to construct an energy model tailored for North Macedonia, known as MARKAL-Macedonia. This model was developed to facilitate policymaking and analyse potential future energy system development options. The base year for the model is 2012, and it can be projected up to 2050 with an annual time step. The MARKAL-Macedonia model, refined over a decade, has undergone continuous enhancements throughout its applications. It has facilitated analyses of diverse policies and programs promoting energy efficiency and renewable energy sources **[30]**. The model has a crucial role in assessing the impacts of various low-emission development pathways **[31, 32]**, evaluating implications from shifts in the fuel mix for electricity generation **[33]**, and determining grid extension requirements and costs for enhancing renewable electricity penetration **[34]**, studying the effect of climate change on energy demand **[35]**. Additionally, it was used to explore possibilities for energy transition tailored to national conditions and align with the EU Green Deal **[36]**. Moreover, the MARKAL model, together with analyses conducted with other tools **[37, 38, 39]**, has played a pivotal role in crafting the national energy and climate policy through its utilisation in the development of the National Energy Strategy **[29]**, conducting climate change mitigation analyses for UNFCCC reporting documents such as National Communications **[40, 41]** and Biennial Update Reports **[42, 43]**, and formulating INDCs **[21]** and their extended updates **[22]**.

For this study, enhancements were made to the MARKAL-Macedonia model to enable the calculation of emissions of key air pollutants at the national level, including particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), and ammonia (NH_3), related to the implementation of the proposed measures outlined in the enhanced NDC. This involved integrating emission factors from the EMEP/EEA guidebook on air pollutant emission inventory **[44]** into the model to generate the required input data for the CaRBonH tool. Specifically, the tasks included:

- Estimating PM, SO_2, NOx, and NH_3 emissions for the period 2021–2030 under both the BAU and NDC scenarios, delineated by total emissions and sector-wise breakdown;
- Quantifying carbon reductions specific to each sector;
- Determining sector-specific reductions in pollutant emissions.

INPUT DATA INTO THE HEALTH IMPACTS CALCULATION TOOL

The enhanced NDC of North Macedonia outlines a commitment to significantly reduce GHG emissions by 2030 compared to 1990 levels, primarily focusing on decarbonising the energy sector by phasing out coal and other fossil fuels **[45]**.

This study aims to assess the health and economic co-benefits associated with climate change policies, particularly those on emission reductions within the energy sector. Relative to the 1990 baseline, North Macedonia anticipates a substantial reduction of annual GHG emissions by 51%, corresponding to 6,420 kt CO_2-eq. The energy sector is projected to account for most of this reduction, contributing approximately 98.5%, or 6,321 kt CO_2-eq (see **Figure 3**).

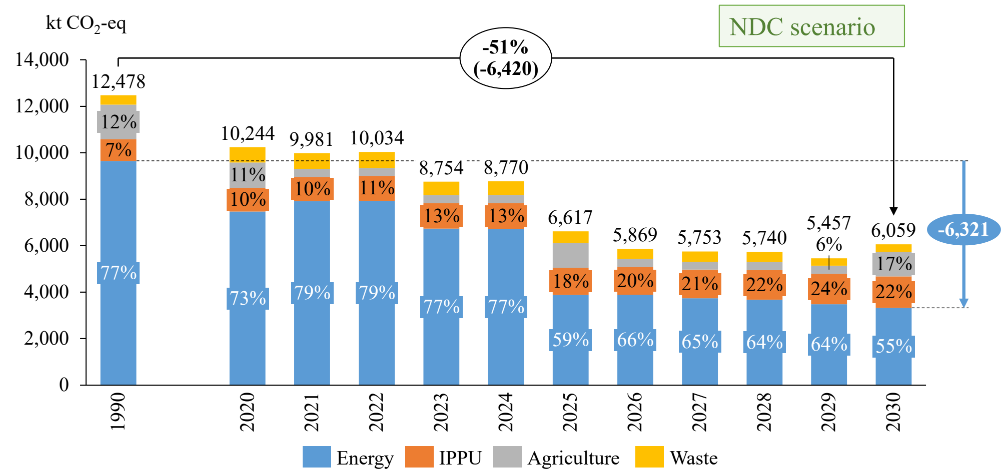

Figure 3. Projections of the total annual GHG emissions [kt CO_2-eq] under the NDC scenario; historical emissions data from **[43]**

Similarly, the emission of major air pollutants at the national level, exerting direct or indirect influences on local and regional air quality across North Macedonia, was estimated, focusing primarily on the energy sector. These pollutants encompass particulate matter (**Figure 4**), sulfur dioxide (**Figure 5**), nitrogen oxides (**Figure 6**), and ammonia (**Figure 7**). Emissions from the energy sector primarily stem from fuel combustion activities related to energy supply, transport, industry (manufacturing industries and constructions), and residential and commercial sectors. Notably, $PM_{2.5}$ emissions (**Figure 4**) are predominantly attributed to the residential sector, energy supply, and industry, with minimal contributions from the transport and commercial sectors. Under the NDC scenario, anticipated energy efficiency measures lead to a reduction of 2.15 kt in PM2.5 emissions by 2030 compared to the BAU scenario. The SO_2 emissions (**Figure 5**) mainly originate from the energy supply and industry sectors, with some contributions from the residential and commercial sectors.

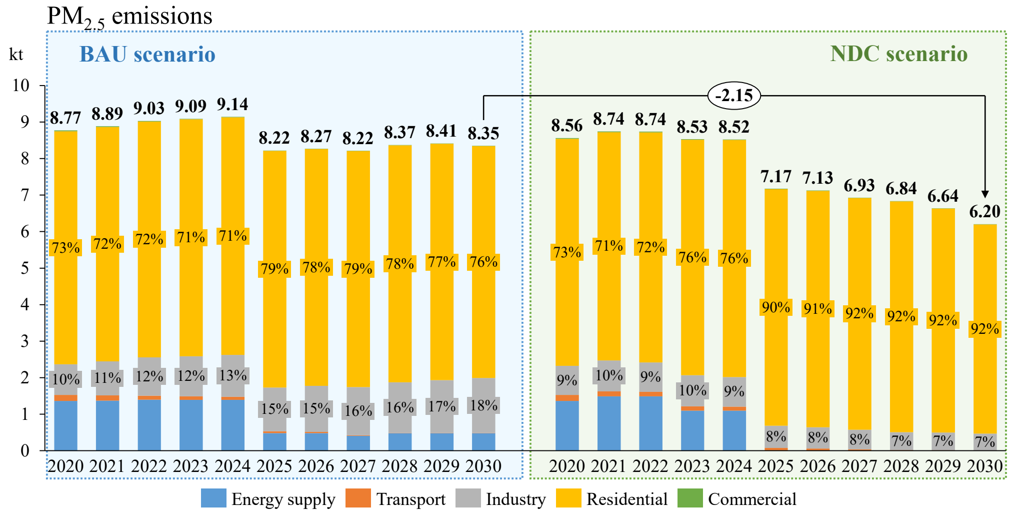

Figure 4. Projections of the annual $PM_{2.5}$ emissions [kt] under the NDC scenario

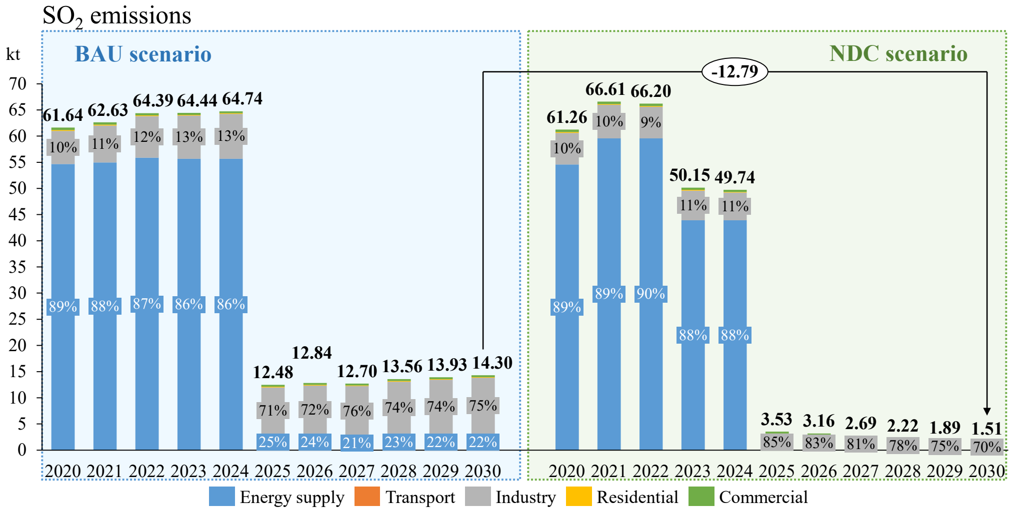

Figure 5. Projections of the annual SO_2 emissions [kt] under the NDC scenario

Notably, a significant decline in SO_2 emissions will be observed by 2025 due to the installation of desulfurisation equipment in the coal power plant Bitola in the BAU scenario or the decommissioning of coal power plants in the NDC scenario. Consequently, SO_2 emission reductions of 12.79 kt are projected by 2030 relative to the BAU scenario.

A similar trend is observed for NO_x emissions (**Figure 6**), with the closure of coal power plants and fuel switches in the energy supply and industry sectors leading to a reduction of over 5 kt in 2030 compared to the BAU scenario. However, NH_3 emissions (Figure 7) remain consistent across both scenarios. While NH_3 emissions from biomass burning (primarily in the household sector) decrease due to the electrification of the heating sector in the NDC scenario, emissions from the transport sector increase simultaneously.

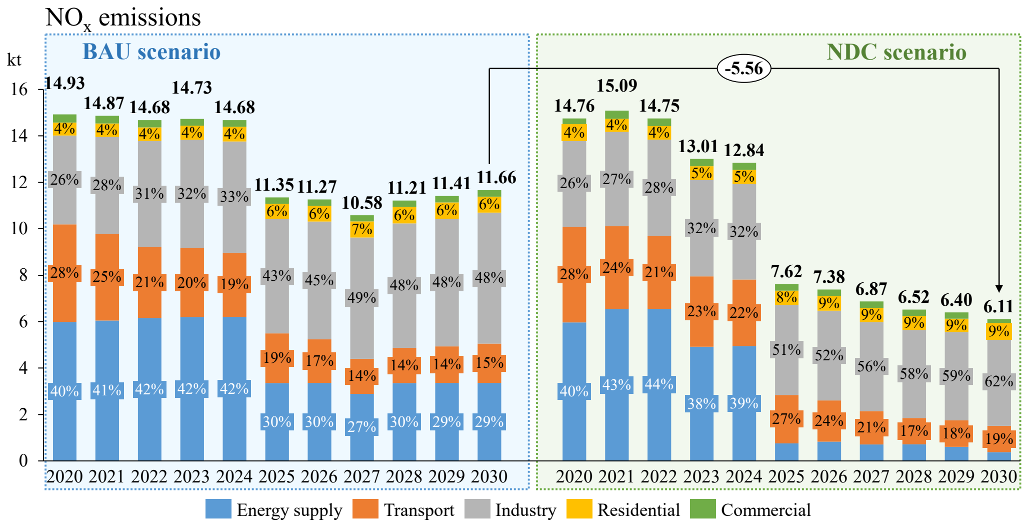

Figure 6. Projections of the annual NO_x emissions [kt] under the NDC scenario

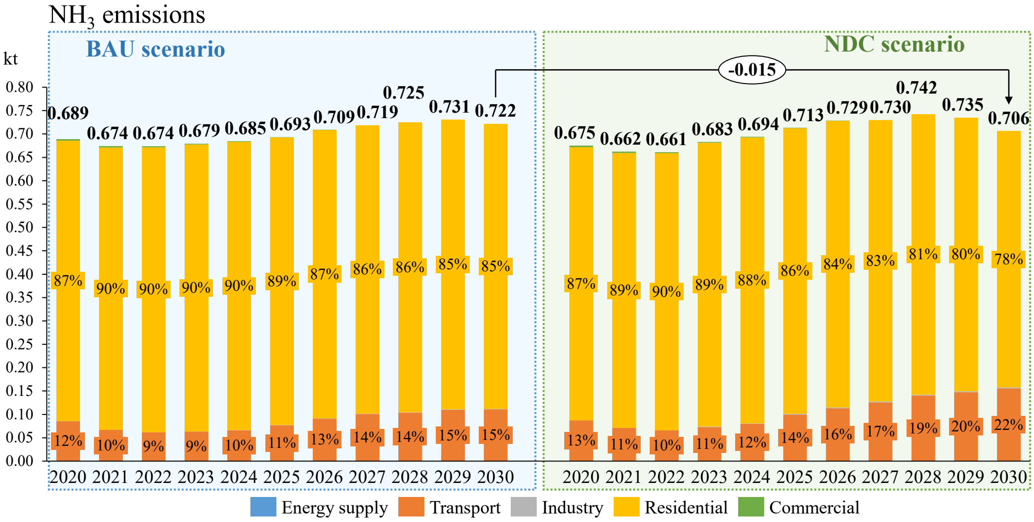

Figure 7. Projections of the annual NH_3 emissions [kt] under the NDC scenario

Based on the NDC scenario, the following input data for the CaRBonH tool were estimated.

- Changes in the GHG emissions in 2030 compared to the base year 1990, entered as absolute values (in kt of CO_2-eq) and as a percentage of the base year emissions.
- Changes in emissions of other pollutants in 2030, calculated relative to emissions under a BAU scenario (**Figure 8**, **Table 4**).

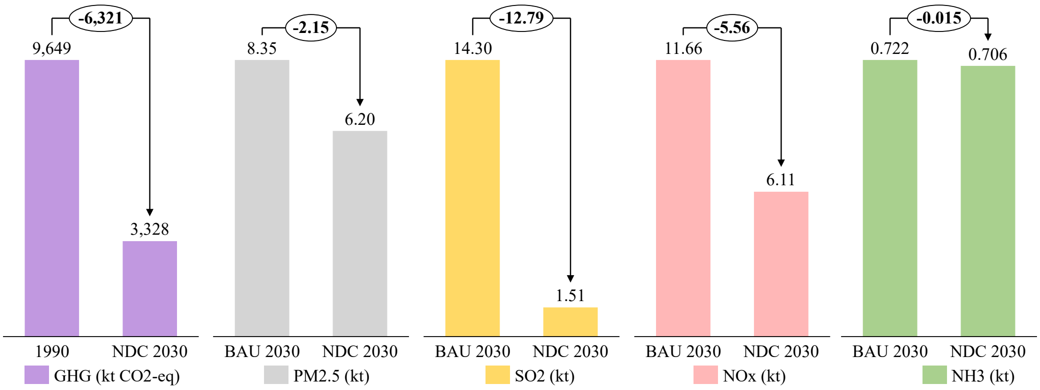

Figure 8. Estimated energy-related emissions reductions [kt] of GHG and air pollutant in the NDC scenario

Table 4. Input data to CaRBonH tool based on the NDC pledges of North Macedonia

Year	Emission reductions in kt per year					
	GHG		$PM_{2.5}$	SO_2	NO_x	NH_3
	% base year	Reduction				
2030	65.5%	6,321	2.15	12.79	5.56	0.02

RESULTS AND DISCUSSION

This chapter presents findings derived from the CaRBonH tool. It explores three main subtopics: changes in population-weighted $PM_{2.5}$ concentration, health co-benefits, and economic benefits associated with reduced $PM_{2.5}$ concentration. Each subtopic discusses specific outcomes and implications related to air quality improvement.

Change in population-weighted $PM_{2.5}$ concentration

The outputs from the CaRBonH tool demonstrate that implementing energy-related carbon mitigation measures outlined in North Macedonia's enhanced NDC would lead to a notable reduction in GHG emissions and air pollutants by 2030. Specifically, this would decrease population exposure to $PM_{2.5}$ concentrations by 1.097 $\mu g/m^3$. Furthermore, the reduced emissions from North Macedonia are expected to impact transboundary pollution at a regional scale, consequently influencing ambient $PM_{2.5}$ concentration levels in neighbouring countries like Albania, Serbia, and Montenegro (**Figure 9**).

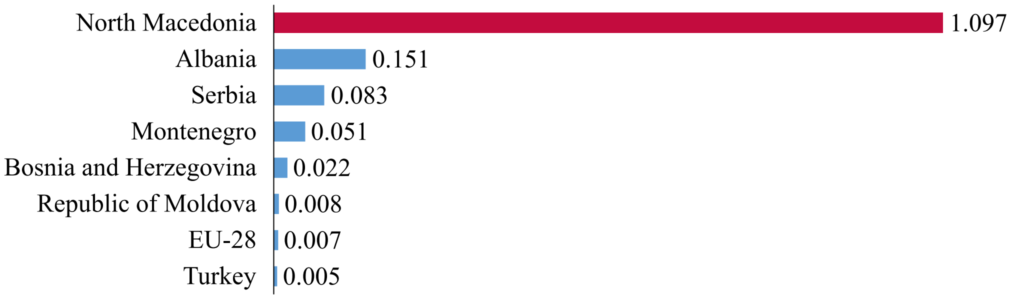

Figure 9. $PM_{2.5}$ concentration changes (reduced exposure), in $\mu g/m^3$

Health co-benefits of reduced $PM_{2.5}$ concentration

The health co-benefits arising from North Macedonia's NDC commitments in the energy sector, achieved through improved air quality from reduced air pollutant emissions, are summarised in **Table 5**. This table also outlines the health benefits extended to neighbouring countries included in the CaRBonH tool. Overall, the implementation of NDC pledges in North Macedonia is projected to prevent 504 premature deaths and result in 5,032 life-years gained. Moreover, the results indicate a decrease in overall morbidity, including 2,259 prevented cases of bronchitis and 11,436 fewer asthma attacks in children, along with 344 fewer cases of bronchitis in adults. Additionally, the initiative is expected to avoid approximately 92,170 work lost days (*WLD*) among the adult employed population, prevent 346 hospital admissions (*HA*), and avert nearly 584,520 restricted activity days (*RAD*) across all age groups.

Table 5. Health benefits of reductions in $PM_{2.5}$ ambient air concentrations, expressed in avoided number of cases

Country/Region	Children		Adults	Labour force	All ages		Mortality	
	Bronchitis	Asthma	Bronchitis	*WLD*	*RAD*	*HA*	Deaths	*YLL*
Albania	141	623	18	7,066	29,802	13	23	264
Armenia	1	4	0	67	354	0	0	3
Azerbaijan	2	9	0	137	701	0	1	7
Belarus	5	23	1	275	1,169	1	1	14
Bosnia and Herzegovina	18	81	4	1,219	5,446	4	6	57
Georgia	1	5	0	80	436	0	0	4
Iceland	0	0	0	0	0	0	0	0
Israel	12	55	2	795	3,621	1	2	19
Kazakhstan	1	6	0	75	405	0	0	4
Kyrgyzstan	0	0	0	4	20	0	0	0
Montenegro	5	22	1	503	2,154	2	2	19
Norway	0	1	0	23	48	0	0	0
Republic of Moldova	9	41	1	503	2,136	2	2	26
Russian Federation	24	104	3	979	5,352	4	6	62
Serbia	126	558	36	13,322	57,973	42	66	560
Switzerland	1	4	0	29	143	0	0	1
Tajikistan	0	2	0	20	112	0	0	1
North Macedonia	629	2,788	98	6,973	182,320	112	143	1,568
Turkey	188	831	18	2,940	36,812	19	17	287
Turkmenistan	0	1	0	14	71	0	0	1
Ukraine	44	194	6	883	11,277	7	13	122
Uzbekistan	5	22	1	281	1,453	1	1	15
EU-28	1,047	6,062	155	55,980	242,718	138	221	1,998
Total	2,259	11,436	344	92,166	584,521	346	504	5,032

In North Macedonia, improved air quality translates into a decrease in morbidity, with 629 fewer cases of bronchitis in children, 2,788 fewer asthma symptom days in children, 98 fewer cases of chronic bronchitis in adults, and 6,973 averted work-lost days among the adult employed population, alongside 182,320 restricted activity days avoided and 112 fewer hospital admissions (Table 5).

The reduction in air pollutant emissions is projected to prevent 143 deaths in North Macedonia in 2030, constituting 28% of total avoidable deaths (**Figure 10a**). The EU-28 region witnesses the largest share of prevented deaths due to its representation of the population exposure across 28 countries, some of which are more affected by North Macedonia's emissions reductions due to their proximity (e.g., Greece, Bulgaria, Romania, Croatia, and Slovenia). This reduction in deaths in North Macedonia represents approximately 4.8% of the 3,000 premature deaths attributed to exposure to average annual $PM_{2.5}$ concentrations of 30.7 $\mu g/m^3$ estimated by the European Environment Agency (EEA) [46].

The benefits of reduced air pollution in terms of years of life lost (*YLL*) will result in 1,568 years gained in 2030 at the national level, constituting 31% of the total life-years gained in the region (**Figure 10b**). This figure represents approximately 4.2% of the *YLL* attributable to $PM_{2.5}$ exposure in the country in 2018, estimated by the EEA to be around 37,200 *YLL* [46].

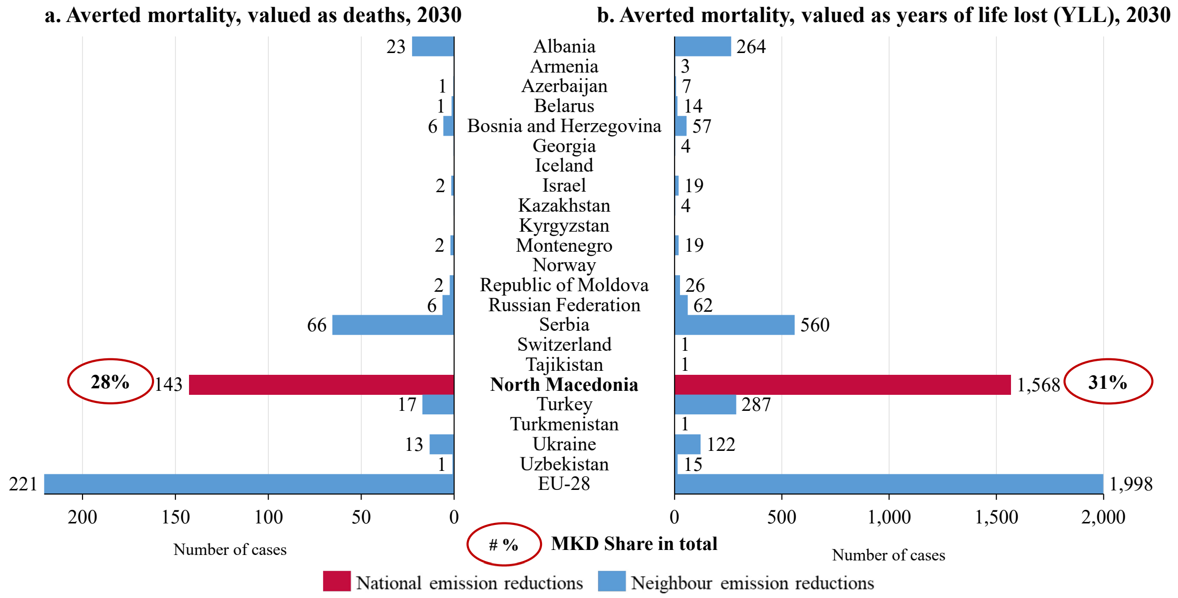

Figure 10. Avoided premature deaths and avoided years of lost life in 2030 due to the emissions reductions with NDC measures

Economic benefits of reduced PM2.5 concentration

The economic value of the health benefits, as summarised in **Table 6**, is estimated by considering the market costs of healthcare expenditures and the value of prevented productivity losses, combined with the social costs associated with avoided premature deaths or gained life years.

The results indicate that the overall economic benefit of prevented illnesses and mortality in 2030 amounts to 1,457 million USD2005 (USD in 2005 prices), assessed using the Value of Statistical Life (*VSL*) metric (as shown in **Figure 11** and **Table 6**). Alternatively, if the Value of a Life Year (*VOLY*) metric is used, the economic benefit totals 624 million USD2005 (**Figure 12** and **Table 6**).

Welfare improvements, attributed to avoiding premature deaths, constitute most of the total benefits, accounting for 1,357 million USD2005 or 94% of the total when valued using the *VSL* metric (as illustrated in **Figure 13a** and **Table 6**). Similarly, when valued using the *VOLY* metric, they represented 524 million USD2005 or 86% of the total (as shown in **Figure 13b** and **Table 6**).

North Macedonia's estimated economic benefit from avoided premature deaths ranges from 111 million USD2005 using the *VOLY* metric to 266 million USD2005 using the *VSL* metric (as detailed in **Table 6**). These figures correspond to 1.2% and 2.8% of the country's GDP in 2019 (in 2005 prices).

Table 6. Economic benefits from reduced $PM_{2.5}$ concentrations in 2030 [million USD2005] (*WLD*, work lost days; *RAD*, restricted activity days; *HA*, hospital admissions; *YLL*, years of life lost)

Economic benefits of reductions in $PM_{2.5}$ ambient air concentrations [a]									TOTAL	
Country/Region	Children		Adults	Labour force	All ages		Mortality		Mortality valued as	
	Bronchitis	Asthma	Bronchitis	*WLD*	*RAD*	*HA*	Deaths	*YLL*	Deaths	*YLL*
Albania	0.0	0.0	0.6	0.5	1.5	0.0	32	14	35	17
Armenia	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
Azerbaijan	0.0	0.0	0.0	0.0	0.0	0.0	1	0	1	1
Belarus	0.0	0.0	0.1	0.0	0.1	0.0	4	2	5	2
Bosnia and Herzegovina	0.0	0.0	0.1	0.1	0.3	0.0	9	3	10	4
Georgia	0.0	0.0	0.0	0.0	0.0	0.0	1	0	1	0
Iceland	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
Israel	0.0	0.0	0.1	0.1	0.4	0.0	5	3	6	3
Kazakhstan	0.0	0.0	0.0	0.0	0.0	0.0	1	0	1	0
Kyrgyzstan	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
Montenegro	0.0	0.0	0.1	0.0	0.1	0.0	4	1	4	2
Norway	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
Republic of Moldova	0.0	0.0	0.0	0.0	0.1	0.0	3	1	3	1
Russian Federation	0.0	0.0	0.3	0.2	0.9	0.0	28	11	30	12
Serbia	0.1	0.0	1.5	1.2	3.7	0.1	118	38	124	45
Switzerland	0.0	0.0	0.0	0.0	0.0	0.0	1	0	1	0
Tajikistan	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
North Macedonia	0.3	0.1	4.4	0.6	12.0	0.2	266	111	283	128
Turkey	0.2	0.0	1.4	0.5	4.4	0.1	58	37	65	44
Turkmenistan	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
Ukraine	0.0	0.0	0.2	0.0	0.4	0.0	14	5	15	6
Uzbekistan	0.0	0.0	0.0	0.0	0.0	0.0	1	0	1	0
EU-28	1.0	0.4	15.4	11.1	34.0	0.7	810	296	872	359
Total [million USD2005]	1.6	0.6	24.2	14.6	58.2	1.1	1,357	524	1,457	624

[a] Economic benefits from emissions reductions only in North Macedonia

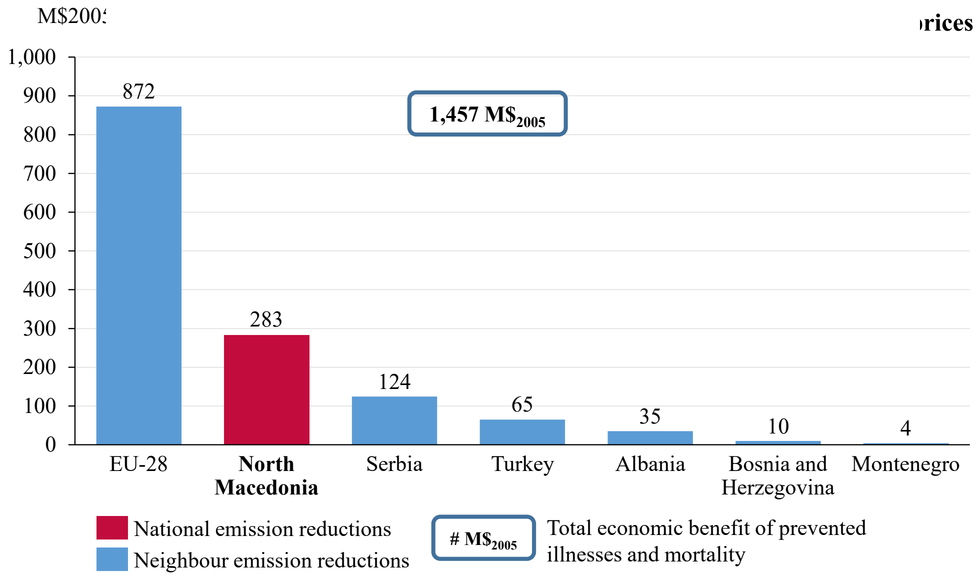

Figure 11. Total economic benefit (valued using *VSL*) of emission reductions in 2030, in million USD in 2005 prices

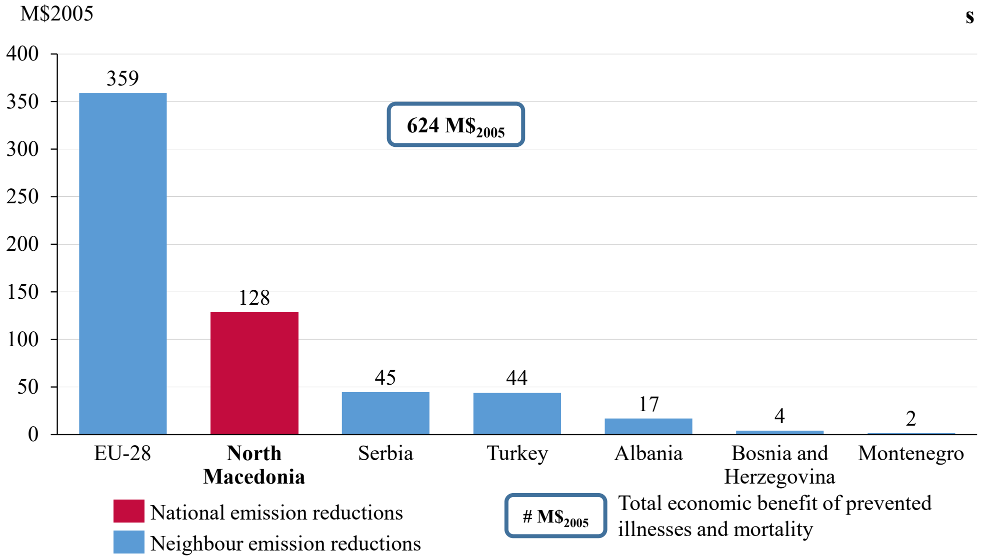

Figure 12. Total economic benefit (valued using *VOLY*) of emission reductions in 2030, in million USD in 2005 prices

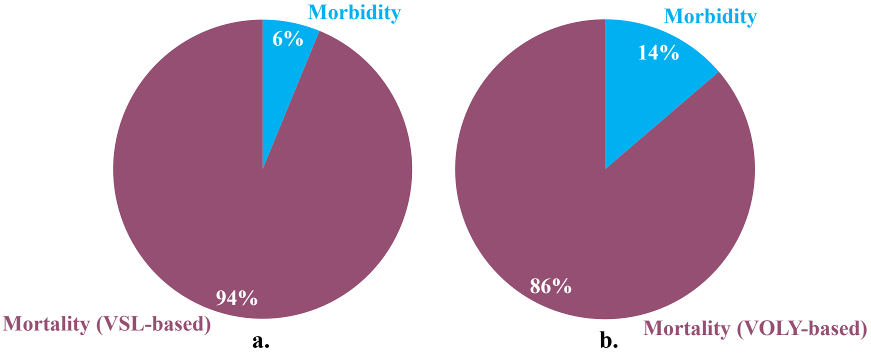

Figure 13. Mortality and morbidity avoided costs in total economic benefits

The per capita savings resulting from the improved air quality in North Macedonia are estimated at 136 USD2005 if mortality is valued as deaths or 62 USD2005 if mortality is valued as *YLL*, as depicted in **Figure 14**. Accounting for the transboundary pollution effect, the emission reductions in North Macedonia will contribute to savings of 12 USD2005 per person in Serbia and Albania and 6 USD2005 per person in Montenegro, based on *VSL* metrics.

The economic benefit of preventing illnesses in North Macedonia per capita is calculated at 8.47 USD2005(in 2005 prices), derived from the ratio of total morbidity costs to the population in 2030. It correlates to about 2.75% of the country's health expenditures per capita in 2018, estimated at nearly 308 USD2005 [47].

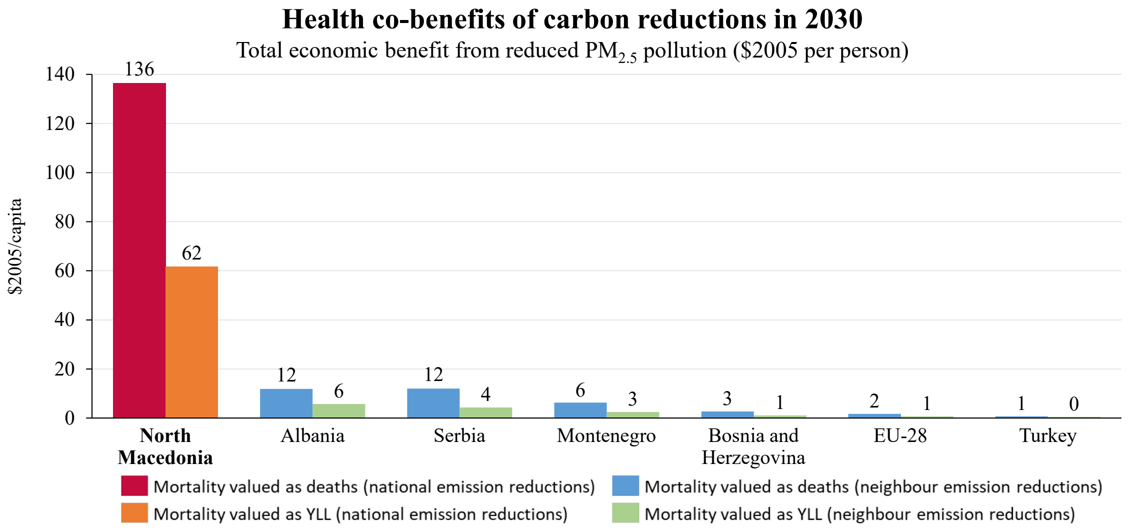

Figure 14. Total economic benefits of emission reductions in 2030 [USD2005 per capita]

The total economic benefit from avoiding morbidity cases in 2030 amounts to approximately 100 million USD2005, constituting 7% to 16% of the total economic benefits, depending on the valuation of mortality (111 million USD2005 and 266 million USD2005) (Table 6). Figure 15 illustrates the breakdown of morbidity benefits by outcomes. The left circle represents the total benefits for all countries in the CaRBonH tool, while the right circle illustrates benefits only for North Macedonia. In the broader context, most cost savings arise from reducing restricted activity days (58%), with around 24% attributed to avoided bronchitis in adults and approximately 15% from prevented work-lost days. Similarly, in North Macedonia, about 68% of morbidity benefits result from avoided restricted activity days, nearly 25% from prevented bronchitis in adults, and 4% from work-lost days. Reduced hospital admissions and avoided cases of bronchitis and asthma in children contribute to the remaining 3% of benefits in both scenarios.

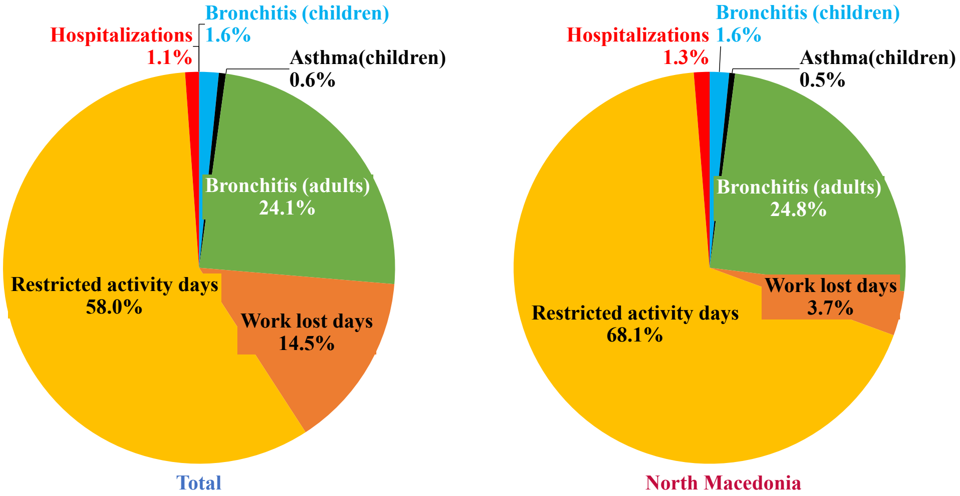

Figure 15. Breakdown of morbidity benefits by outcome in 2030

CONCLUSIONS

In conclusion, this study sheds light on the significant impacts of carbon reduction measures on air quality and public health in North Macedonia and neighbouring regions. The results demonstrate tangible benefits, including a notable decrease in population exposure to PM2.5

concentrations and a substantial reduction in premature deaths and life years gained. The projected reduction of 143 premature deaths and the avoidance of 629 cases of bronchitis in children stand out as particularly impactful outcomes. Additionally, the anticipated decrease of 6,973 work-lost days among the adult employed population and the prevention of 182,320 restricted activity days underscore the tangible improvements in quality of life that can be achieved through carbon mitigation interventions.

Furthermore, the economic analysis demonstrates significant welfare improvements, with estimated economic benefits ranging from 111−266 million USD2005, depending on the valuation metric used. These figures represent a substantial portion of the country's GDP, highlighting the potential economic value of investing in carbon reduction initiatives for health promotion.

In addition to the economic benefits and job creation potential, the quantified health benefits resulting from NDC carbon reductions offer North Macedonia a valuable opportunity to strengthen the social dimension of its climate action plan. Moreover, by integrating the economic co-benefits of reducing air pollutant emissions into the existing assessment framework, policymakers can enhance the overall effectiveness of NDC policies and measures. It represents a crucial path for methodological refinement and underscores the importance of ongoing research in this area.

The comprehensive analysis of health and economic co-benefits at the national level enables a deeper understanding of the synergies and trade-offs between the NDC and key Sustainable Development Goals, particularly SDG3: Good Health and Well-being.

Overall, this study is a compelling example of the multifaceted benefits of carbon reduction initiatives and underscores the importance of continued efforts to advance the transition to a decarbonised world. It provides a valuable framework for informing policy decisions and guiding future research efforts to address the interconnected challenges of climate change, air pollution, and public health on national, regional and global scales.

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NOMENCLATURE

HA	Hospital Admissions	[-]
LE	Life Expectancy	[year]
PM_{10}	Particulate Matter, particle diameter ≤10 µm	[µg/m^3]
$PM_{2.5}$	Particulate Matter, particle diameter ≤2.5 µm	[µg/m^3]
RAD	Restricted Activity Days	[day]
VOLY	Value of a Life Year	[USD2005]
VSL	Value of Statistical Life	[USD2005]
WLD	Work Lost Days	[day]
YLL	Years of Life Lost	[year]

Abbreviations

BAU	Business As Usual
CRF	Concentration-Response Function
EEA	European Environment Agency
GHG	GreenHouse Gas
MKD	North Macedonia
NDC	Nationally Determined Contribution

USD2005	US dollar in 2005 prices
WHO	World Health Organization

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