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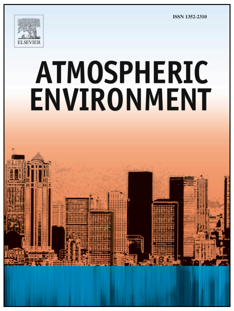

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Cost-effective reductions of PM2.5 concentrations and exposure in Italy

A. Ciucci[a], I. D'Elia[a,*], F. Wagner[b,c], R. Sander[b], L. Ciancarella[a], G. Zanini[a], W. Schöpp[b]

[a]*ENEA, National Agency for New technologies, Energy and Sustainable Economic Development, via Martiri di Monte Sole 4, 40129 Bologna, Italy*

[b]*International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria*

[c]*Andlinger Center for Energy and the Environment, Princeton University, Princeton, NJ, 08544, USA*

[*]Corresponding author. Tel.: +39 06 3627 2754; fax: +39 051 6098675

E-mail address: ilaria.delia@enea.it (I. D'Elia)

Abstract

In recent years several European air pollution policies have been based on a cost-effectiveness approach. In the European Union, the European Commission starts using the multi-pollutant, multi-effect GAINS (Greenhouse Gas Air Pollution Interactions and Synergies) model to identify cost-effective National Emission Ceilings and specific emission control measures for each Member State to reach these targets. In this paper, we apply the GAINS methodology to the case of Italy with 20 subnational regions. We present regional results for different approaches to environmental target setting for PM2.5 pollution in the year 2030. We have obtained these results using optimization techniques consistent with those of GAINS-Europe, but at a higher resolution. Our results show that an overall health-impact oriented approach is more cost-effective than setting a nation-wide limit value on ambient air quality, such as the one set for the year 2030 by the European Directive on ambient air quality and cleaner air for Europe. The health-impact oriented approach implies additional emission control costs of 153 million €/yr on top of the baseline costs, compared to 322 million €/yr for attaining the nation-wide air quality limit. We provide insights into the distribution of costs and benefits for regions within Italy and identify the main beneficiaries of a health-impact approach over a limit-value approach.

Key words: cost-effectiveness analysis, policy scenario, integrated assessment models, air pollution, environmental target setting approaches, population exposure.

HIGHLIGHTS

- The GAINS cost-optimization methodology has been applied to the Italian territory.
- Different environmental target setting approaches have been compared.
- A regulatory approach focusing on health impacts rather than on air quality is more cost-effective.
- Distribution of costs and benefits for the 20 Italian regions are presented.

1 Introduction

Air pollution is the single largest environmental health risk in Europe (EEA, 2015) and particulate matter (PM) has become a major concern for public health (WHO, 2015). The European Union (EU) limit and target values for particulate matter continued to be exceeded in large parts of Europe in 2013 (EEA, 2015). Recent studies based on scenario analysis have assessed the likelihood that the World Health Organization (WHO) air quality standards and limits will be met in the future, and what factors this may depend on, both at the European (for example, Kiesewetter et al., 2014 and 2015) and at the national level (Oxley et al., 2013; Vieno et al., 2016).

The cost-effectiveness approach has in recent years been applied in defining several European air pollution policies. This method has replaced earlier approaches to burden sharing, such as a uniform emission reduction target for all negotiating parties, which was adopted in the earlier stages of European air pollution control (Hordijk and Amann, 2007; Tunistra, 2007). In subsequent policy processes, cost-effectiveness and effect-based principles became the rationale to derive quantitative and differentiated national reduction targets based on the carrying capacity of vulnerable ecosystems (Amann et al., 2011a; Wagner et al., 2013a; Wagner et al., 2013b). The cost-effectiveness and effect-based principles have also been recently applied to the revision of the Gothenburg Protocol (Amann et al., 2011b), the review of the Thematic Strategy on Air Pollution (Amann et al., 2013) whose results lead to the adoption of the "Clean Air Policy Package" (COM, 2013; Amann et al., 2014a) and to the revision of the National Emission Ceilings (NEC) Directive (Amann et al., 2015).

Our analysis is focused on Italy, and we use the GAINS-Italy model (*Greenhouse Gas and Air Pollution Interactions and Synergies Model over Italy*, D'Elia et al., 2009) to apply the above methodologies to translate national environmental and health targets to regional emission control targets. GAINS-Italy has been developed in collaboration with the International Institute for Applied System Analysis (IIASA) as it is the national version of the GAINS-Europe model (Amann et al., 2011a) and allows the evaluation of impacts and costs. Starting from information on emission abatement technologies and economic scenarios of energy and productive sectors, GAINS-Italy produces alternative and/or future emission scenarios, alternative air quality scenarios and abatement costs at a 5-year interval starting from 1990 to 2050. Compared to GAINS-Europe, the development of GAINS-Italy gives many advantages to the national integrated model, i.e. GAINS-Italy represents 20 political regions individually and has a spatial resolution of 20x20 km^2 on a grid of 67x75 cells.

GAINS-Italy is the MINNI (*National Integrated Model to support the international negotiation on atmospheric pollution*) component dedicated to elaborating emission scenarios to support international evaluation and negotiation on atmospheric pollution. The MINNI model is an Integrated Modeling System that links atmospheric science with the economics of emission abatement measures and policy analysis. It was developed by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) to support the Italian Ministry of the Environment, the Land and the Sea on the methodological aspects of the policy design. MINNI consists of several interdependent and interconnected components, each of which describes individual system aspects and whose main components are a multi-pollutant *Atmospheric Modeling System* (AMS) and the national GAINS-Italy. They interact in a feedback system through the *Atmospheric Transfer Matrices* (ATMs) and the *RAINS-Atmospheric Inventory link* (RAIL).

In the present paper we analyze alternative cost-effectiveness approaches to reducing PM2.5 concentrations and exposure for Italy. We illustrate the distribution of costs and benefits across the regions when different approaches to air pollution control policy are used to meet the same health objectives. Specifically we analyze three policy scenarios obtained with different approaches for setting environmental objectives, the '*absolute limit value*' and the '*gap closure*' procedures, the latter applied either to PM2.5 concentrations and to the YOLL (*Years Of Life Lost*) indicator. We finally discuss the cost implications for these approaches at different ambition levels. Technical details can be found in the Supplementary Material.

2 Methodology

2.1 The optimization module in the GAINS-Italy model

Over the past three decades IIASA has developed the RAINS (*Regional Air Pollution Information and Simulation*, Schöpp et al., 1999) integrated model to support international negotiations on transboundary air pollution, and then its successor, the GAINS model, which extends the scope to greenhouse gases (Amann et al., 2011a). In particular, GAINS-Europe features an optimization module, which allows users to identify country-specific and sector-specific portfolios of technologies that achieve a given environmental/health target in the most cost-effective manner. We have adapted the optimization framework to the Italian context with its 20 (emitting) regions, and the same sectors/activities schema as in GAINS-Europe. Like its European counterpart, GAINS-Italy features a database, which holds sectors/activities/technologies/pollutant and geographical information; source-receptor relationships; technical and economic characteristics of control technologies; as well as the implementation rate of current and planned future legislation on greenhouse gas mitigation and pollution control and relevant affected sectors such as energy and agriculture. The database is accessible through a web-interface and offers upload and download features.

The objective in the optimization is to find, for a given future year, the mix of technologies that allows to achieve a given environmental target at minimum cost, where the costs are typically summed over all regions, sectors and technologies. As its European counterpart, the technologies considered in GAINS-Italy for the present purpose include only 'end-of-pipe' emission control technologies, i.e. measures that affect emission factors of one or more pollutants without changing the activity data (Wagner et al., 2013a); while non-technical measures have not been introduced in the database but can be evaluated through different and alternative scenarios. The optimization is formulated as a linear programming problem, i.e. all equations, definitions and constraints are linear in the decision variables. In the European version of GAINS, the ATMs are calculated with the EMEP chemistry transport model (Simpson et al., 2012) and have a resolution of roughly 28x28 km^2. They are used to calculate the regional background, while the urban and roadside increment have been taken into account respectively with the 7x7 km^2 CHIMERE Chemistry Transport Model and a chemical box model (Kiesewetter et al., 2014 and 2015).

In the Italian MINNI system a different path has been followed. The AMS simulates meteorological fields and computes gas and aerosol transport, diffusion and chemical reactions in atmosphere (Mircea et al., 2014). It is composed by the meteorological model RAMS (*Regional Atmospheric Modelling System*, Cotton et al., 2003); the emission processor EMMA (*EMission MAnager*, ARIA/ARIANET, 2008); the three-dimensional Eulerian model FARM (*Flexible Air Quality Regional Model*, Silibello et al., 2008; Gariazzo et al., 2007; Kukkonen et al., 2012) that includes transport and multiphase chemistry of pollutants in the atmosphere. The AMS has been applied to calculate the linear transfer coefficient of the ATMs (Briganti et al., 2011) that allows the GAINS-Italy model to calculate regional background concentrations of PM2.5 and NO_2 from emission scenarios of the whole Italian territory. As base case for the AMS calculations, the emissions for the year 2015 of the baseline "No Climate Policy scenario" (MATTM, 2011) were used for each of the four meteorological years, 1999, 2003, 2005, 2007. For each of these meteorological years we have calculated ATMs. In addition, we have also averaged the concentration fields of the four meteorological years to generate a new set of ATMs, which in the following we refer to as the meteorology-average ATM or average ATM for short. To calculate PM concentrations, regional emissions of primary particulate and of secondary particulate precursors, sulphur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3) and non-methane volatile organic compounds (NMVOC) have been considered. For each run, the regional reference emissions of each precursor were alternately and selectively abated by 25%. To test the approximation of the linear transfer coefficients, a comparison with a full run of the AMS for the year 2020 has been carried out (Briganti et al., 2011). This comparison showed that the ATMs consistently reproduce the complete AMS run.

Mircea et al. (2014) in presenting the operational evaluation of the AMS-MINNI for the year 2005 showed a general underestimation of simulated PM10 annual average concentration with respect to the measured data and observed variability comparable at urban and suburban stations, while for the year 2010, Ciancarella et al. (2016) showed a good agreement of simulated PM2.5 concentrations respect to the measured data at the rural stations; similar results thus hold for the ATMs.

Furthermore, for a detailed assessment of the impacts of a given GAINS-Italy emission scenario, the AMS system can be run at a resolution of 4x4 km^2 and 1x1 km^2.

2.2 Three target setting approaches

The current legislation (CLE) scenario represents the 'baseline' and reflects all policies that have been currently legislated, both those that affect activity levels (such as energy and agriculture policies), as well as pollution control policies for the period 1990-2050 (D'Elia et al., 2009). Our underlying energy scenario for the GAINS-Italy model is based on the new National Energy Strategy (Ministero dello Sviluppo Economico, 2013) and has been elaborated by the *Institute for Environmental Protection and Research* (ISPRA) with the Markal-Italy model (Gracceva and Contaldi, 2005). We have also compared the GAINS-Italy emission inventory estimated with a *top-down* approach (D'Elia and Peschi, 2013) to the latest national emission inventory submission (IIR, 2016). Discrepancies in reproducing the national total emission inventory have been considered acceptable if differences remain within a few percentage points (Amann et al., 2014b), i.e. in the interval between ±5%.

However, air pollution control technologies which represent these policies in the CLE scenario in GAINS may not always represent the most cost-effective mix to achieve the resulting emission levels. For this reason both GAINS-Europe and GAINS-Italy calculate a so-called cost-optimal baseline (COB) scenario, that represents the most cost-effective way to reach the baseline emission level (Wagner et al., 2013a). All costs reported in this paper are costs relative to the COB scenario; this is consistent with the GAINS policy analysis for international negotiations.

In GAINS an environmental impact indicator for target setting can be defined either at the grid cell or at a more aggregated level. Multiple types of targets can be defined simultaneously. Here our focus is on three alternative target setting approaches that have been used widely in air pollution policy.

First, in the '*absolute limit value*' approach a uniform environmental quality standard is set that must be attained in all regions, i.e. in each individual grid cell. For example, the annual average concentration of fine particles or of ozone must not exceed a certain limit value. As a consequence of such a policy, much of the improvement in air quality would occur in highly polluted areas, as these are specifically targeted by such a policy. Similarly, much of the effort to reduce emissions will occur in polluted areas: while some pollution is transported over distances, local emissions are a key determinant of local air quality. This has been demonstrated by the national source apportionment (http://ec.europa.eu/environment/air/quality/legislation/time_extensions.htm - Italy), which showed an average contribution of transboundary pollution both for PM10 and NO_2 less than 30% for the whole Italian territory with higher peaks at the boundaries. Thus, costs and benefits tend to be localized and correlated. The advantage of this target setting approach is that the air quality can directly be monitored and compared to the target value.

In the second approach, the '*local gap closure*' procedure, costs and benefits tend to be more evenly distributed across regions. This approach is based on the idea that all feasible options for future policy lie between what is currently planned (i.e. the CLE or COB scenario), and the Maximum Technically Feasible Emission Reductions (MTFR) scenario, and that a 'fair' policy should ensure that improvements in air quality should occur everywhere and in proportion to what is technically feasible. In the MTFR scenario, the best control technologies are employed to the maximum extent, resulting in the lowest technically feasible level of emissions. In determining MTFR scenarios, only technology options are considered while local and non-technical measures could offer additional emission and concentration reductions. The difference between the CLE and MTFR scenarios is the so-called 'gap'. A gap can be calculated, for example for *emissions*, and it will be different for different countries and different pollutants. A gap can also be calculated for *impact indicators* like concentration. It is useful to scale the gap and define a relative 'gap closure of X%' where X lies between 0% (no ambition) and 100% (maximum ambition): no matter what the absolute gap is, the gap closure requires that in all regions or grid cells a given indicator is reduced by X% of what is maximally feasible relative to the CLE/COB scenario. The choice of X depends on the ambition level policy makers would like to reach for the different impact indicators.

In the following, we apply the gap closure target setting procedure to the PM2.5 concentration level in each grid cell, so that in each grid cell the concentration is reduced by the same share of the local reduction potential. In this case, we will choose X so that we can compare scenarios that exhibit the same health benefits as the scenario obtained with the absolute limit value approach. For example, we first estimate the impact of an absolute limit value of 20 $\mu g/m^3$ that is applied in each grid cell in the year 2030, in compliance with the European Directive on ambient air quality and cleaner air for

Europe (EC, 2008); we call this policy scenario 'ABS'. Afterwards, we estimate the population weighted exposure level (PWEL) for the whole Italian territory. We then calculate the lowest gap closure X on the PM2.5 concentrations that achieves the same population weighted exposure level of the absolute scenario. This X turns out to be 31%, and we call the corresponding optimized policy scenario 'GC'.

The third approach targets the Y*ears Of Life Lost (YOLL)*, where we calculate the lowest gap closure on the total national YOLL that achieves the same population weighted exposure level of the absolute scenario. This value turns out to be 36% and we call the corresponding policy scenario 'HEALTH'. Each of the three target setting approaches results in a different set of cost-optimal emission control measures. By comparing scenarios that yield the same health benefits, we can compare the relative cost-effectiveness of the approaches.

3 Results

3.1 The Baseline and MTFR scenario at the year 2030

The baseline scenario assumes full implementation of current legislation, both European and national. The MTFR scenario shows to what level air pollutant emissions could be further reduced beyond what is required by current legislation, through full application of the available technical measures, without changes in the energy structures and without behavioural changes of consumers (Amann et al., 2014a). In the following table and figure (tab. 1 and fig.1), we show results for the baseline and MTFR scenarios in the year 2030 at the national level, while detailed data for all the 20 administrative Regions are reported in Appendix 1 (Supplementary materials).

Table 1 – The 2005 emission inventory (IIR, 2016) and the 2030 Baseline and MTFR scenarios for Italy (absolute emissions in kt and percentage reduction).

ITALY	2005 Emission Inventory	2030 Emission scenario		Change 2005-2030	
Pollutant	kt	Baseline (kt)	MTFR (kt)	Baseline (%)	MTFR (%)
SO_2	407	177	87	-56%	-79%
NO_X	1,249	568	499	-54%	-60%
PM2.5	165	124	63	-12%	-55%
NMVOC	1,281	767	522	-38%	-58%
NH_3	422	375	205	-11%	-51%

In the baseline scenario, SO_2, NO_X and NMVOC emissions are reduced significantly between 2005 and 2030 (by 56%, 54% and 38%, respectively), while for PM2.5 (12%) and NH_3 (11%) the

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reductions are smaller. The MTFR scenario shows, however, that also these two pollutants could be reduced significantly (by 55% for PM2.5 and 51% for NH_3).

Figure 1 shows the resulting annual mean PM2.5 concentration for the year 2030 in the baseline and MTFR scenarios on a 20 km grid for the average meteorological year. Comparing these results with the PM2.5 annual air quality value of 20 μg/m^3 required by the Air Quality Directive (EC, 2008), we observe exceedances of the limit value in the baseline scenario in the Po Valley and in the Milan and Naples areas, while in the MTFR scenario the limit value is attained everywhere (the maximum concentration across grid cells is 16 μg/m^3). A map with the name of the 20 Italian Administration Regions is reported in Appendix 3 (Supplementary Material).

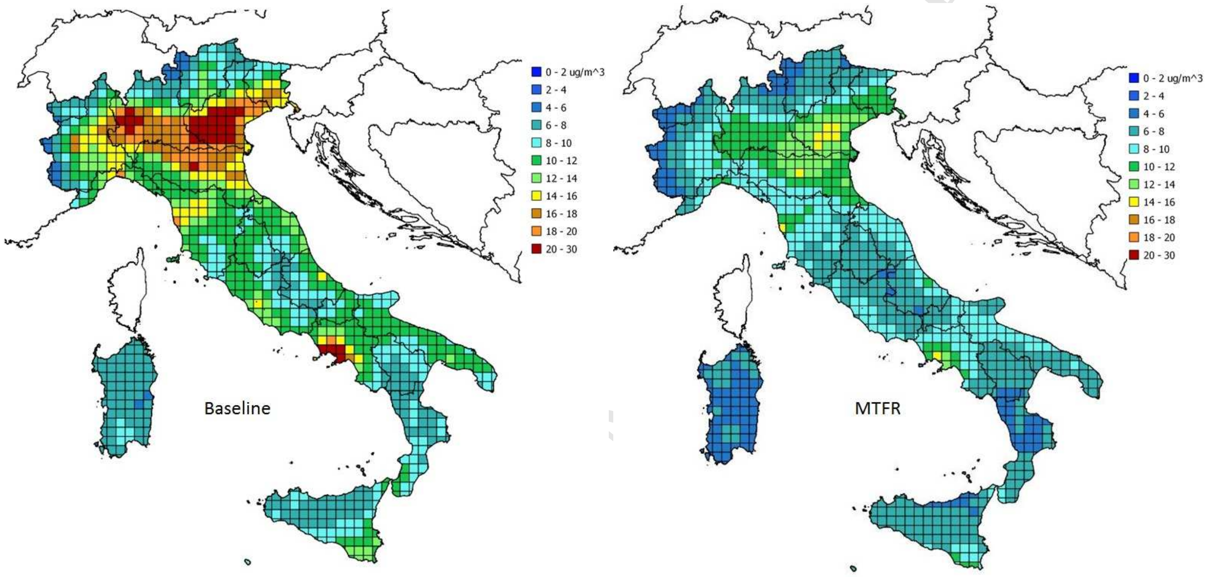

Figure 1 – Annual mean PM2.5 concentrations for the year 2030 with a spatial resolution of 20 km in the Baseline (left) and MTFR (right) scenario calculated by the GAINS-Italy model with the meteorological average year.

However, the WHO limit of 10 μg/m^3 cannot be attained everywhere, even in the MTFR scenario. Thus, only with additional changes in the energy system this limit could be attained.

3.2 Comparing target setting for policy scenarios

To illustrate the differences in the target setting approaches the ABS, GC and HEALTH scenarios have been compared. Figure 2 shows the additional costs by region (on top of the baseline scenario) in absolute values (million €/yr) and per capita for these three scenarios. The HEALTH scenario implies an additional air pollution cost of 153 million €/yr on top of the baseline costs (i.e. ~3 € per capita and year) (fig. 2). In contrast, GC implies 264 million €/yr (4 € per capita and year), while ABS implies 322 million €/yr (5 € per capita and year). At the national level, the gap closure approach targeting total national YOLL implies the lowest costs, but this is not true for all regions (fig. 2). Higher costs of HEALTH than GC are observed for example in the Lombardia Region (Northern Italy) where high PM2.5 concentrations are also correlated with a high population density.

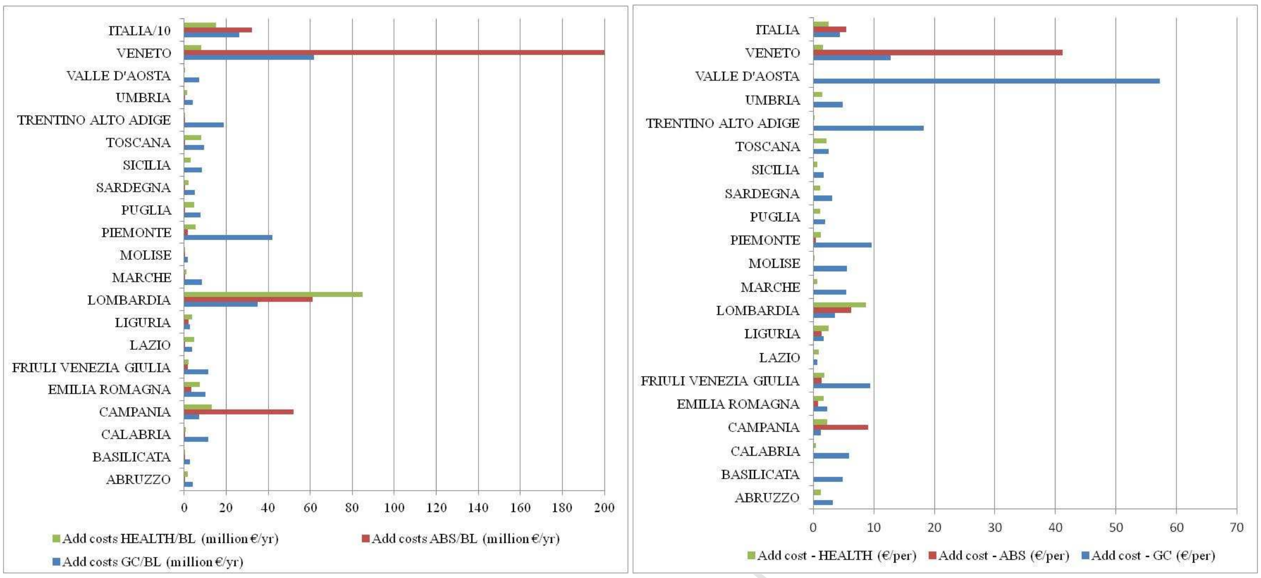

Figure 2 – Additional costs on top of the baseline (BL) costs in absolute values (million €/yr - left) and per capita (€/person – right) by Region to reduce PM2.5 concentration in the three policy scenarios: gap closure on PM2.5 concentrations (GC - blue bar), Absolute Value of 20 µg/m^3 (ABS - red bar) and gap closure on the health indicator (HEALTH - green bar) – for the year 2030.

Differences are evident not only in terms of costs but also in terms of emission reductions and PM2.5 concentrations. It is worth nothing that in the ABS scenario only few regions, where concentration limit are exceeded, are affected by policy changes. Table 2 shows that the implied reduction in PM2.5, NO_X and NMVOC emissions with respect to the baseline scenario are very similar across all the three policy scenarios, with reductions of NO_X and NMVOC being negligible.

Table 2 – Emission reductions at the national level for the year 2030 (in %) with respect to the 2030 baseline in the GC, ABS, HEALTH and MTFR scenarios.

ITALY/ 2030 Scenario	2030 Emission reduction respect to the Baseline scenario (%)			
POLLUTANT	GC	ABS	HEALTH	MTFR
SO_2	-28%	-15%	-26%	-51%
NO_X	-2%	-1%	-1%	-12%
PM2.5	-13%	-11%	-10%	-49%
VOC	-1%	-1%	-1%	-32%
NH_3	-14%	-4%	-10%	-45%

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In contrast, SO_2 and NH_3 are much further reduced in the GC and HEALTH scenarios than in the ABS scenario. However, regional emission reduction patterns actually differ significantly from this national pattern. Moreover, although all the three policy scenarios show comparable PM2.5 emission reductions at the national level, at the regional and sectoral level the emission reductions differ significantly across scenarios, implying that different specific policies would be required to implement them (fig. 3). For example, in the ABS scenario the primary PM2.5 emission reduction occurs principally in three regions (Campania, Lombardia and Veneto) and here largely in the domestic sector (improved combustion of biomass). On the other hand, in GC and HEALTH the reductions are more evenly distributed and all other regions experience a higher emission reduction (compare red, yellow and blue dots on the right axis). The largest contributors to reductions in the ABS scenarios are the industry and domestic sectors; while in GC and HEALTH the contribution of the domestic sector is lower. Thus, reaching the European air quality standard would require to target fireplaces and traditional stoves specifically in Campania, Lombardia and Veneto.

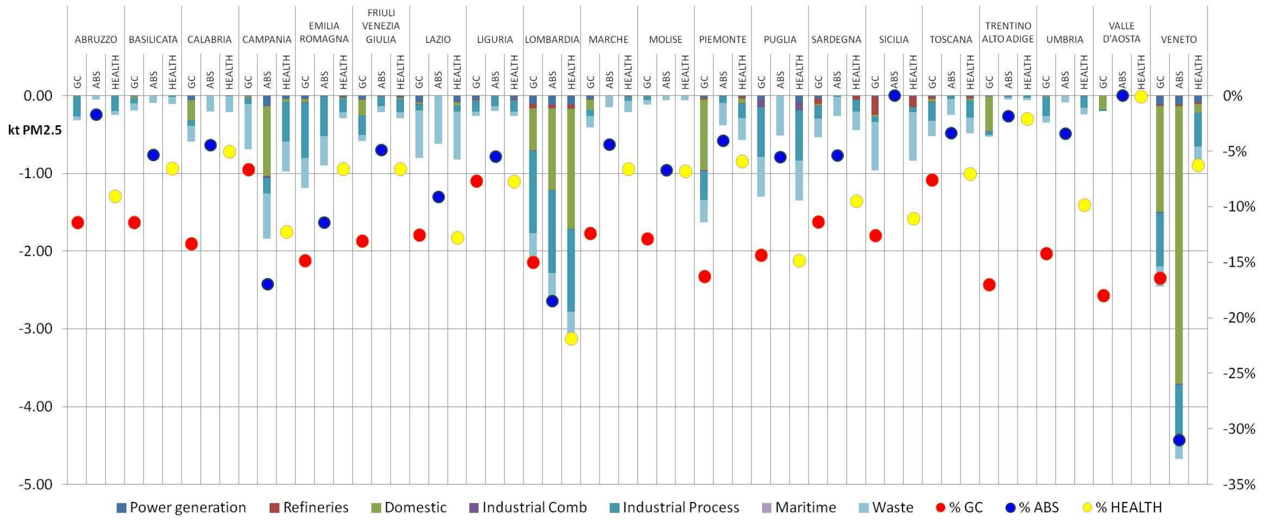

Figure 3 – Primary PM2.5 emission reduction relative to the 2030 baseline by region (dots on the right axis) and sector (bars on the left axis) for the HEALTH, GC and ABS scenarios.

The only regions that have to reduce NH_3 emissions in the ABS scenario are Campania in Southern Italy, Lombardia and Veneto in the North (cf. fig. 4) that are also the most polluted areas. In the GC and HEALTH scenarios NH_3 emission are also significantly reduced in Lombardia, Toscania and Emilia Romagna in Central Italy. In all the policy scenarios, the largest contributor to reductions is the livestock sector and especially cattle farming. Strikingly, while emissions reductions observed in the GC and HEALTH scenarios are higher, the associated costs are lower than in the ABS scenario (fig. 2) because emission reductions occur in regions and sectors where the reductions can be achieved more cost-effectively.

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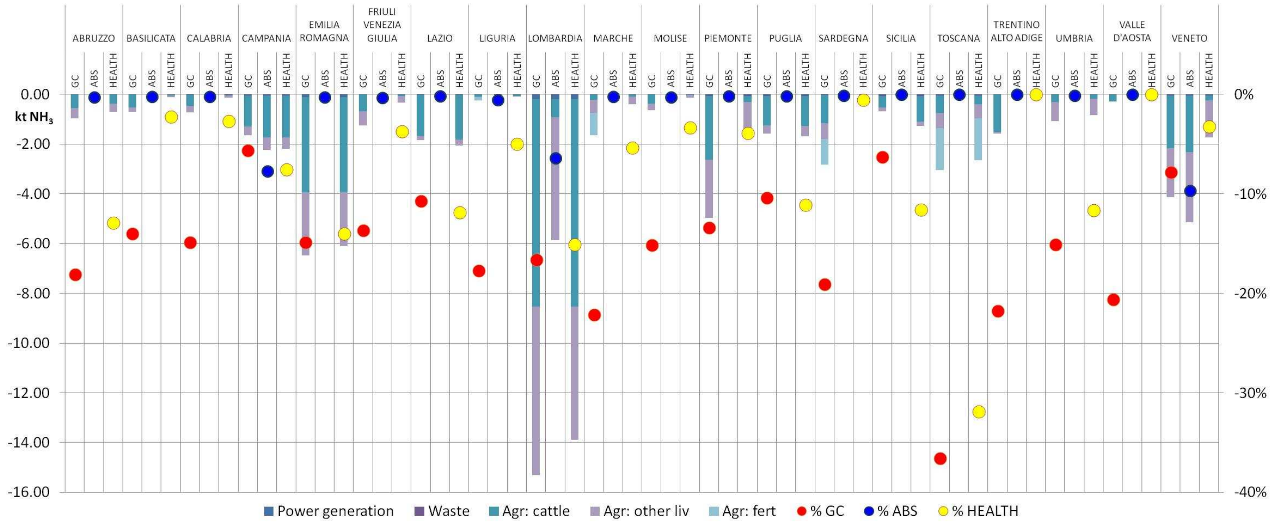

Figure 4 – NH_3 emission reduction relative to the 2030 baseline by region (dots on the right axis) and sector (bars on the left axis) for the HEALTH, GC and ABS scenarios.

Table 3 – Emission reductions (%) for the year 2030 by pollutant and geographical area and additional costs on top of the Baseline (BL) for the three policy scenarios and MTFR.

	2030 SO_2 emission reductions respect to Baseline (%)				2030 NO_X emission reductions respect to Baseline (%)				2030 PM2.5 emission reductions respect to Baseline (%)			
SCENARIOS	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR
ITALY	-28%	-15%	-26%	-51%	-2%	-1%	-1%	-12%	-13%	-11%	-10%	-49%
NORTH	-22%	-27%	-29%	-44%	-3%	-2%	-2%	-13%	-15%	-15%	-11%	-51%
CENTRE	-34%	0%	-34%	-52%	-1%	-1%	-1%	-11%	-11%	-6%	-9%	-48%
SOUTH and ISLANDS	-29%	-11%	-23%	-55%	-1%	-1%	-1%	-11%	-11%	-7%	-10%	-47%
	2030 NMVOC emission reductions respect to Baseline (%)				2030 NH_3 emission reductions respect to Baseline (%)				Add costs on top BL (€/person)			
SCENARIOS	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR
ITALY	-1%	-1%	-1%	-32%	-14%	-4%	-10%	-45%	4	5	3	88
NORTH	-1%	-1%	-1%	-36%	-14%	-5%	-10%	-51%	7	10	4	103
CENTRE	-1%	0%	-1%	-29%	-19%	0%	-15%	-39%	2	0	1	71
SOUTH and ISLANDS	-1%	0%	-1%	-28%	-11%	-3%	-7%	-33%	2	3	1	79

At a more aggregated geographical level (North, Centre, South and the two islands, and the average national data), Table 3 summarizes the distribution of emissions reductions and costs relative to the baseline for the policy and MTFR scenarios. We observe in general a more homogenous distribution of reductions and costs in the GC and HEALTH than in the ABS scenario. Turning to ambient air quality we observe that by definition the target value of 20 μg/m^3 is attained in all grid

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cells in the ABS scenario, even in the high PM2.5 concentration areas such as Milan, the Po valley and Naples.

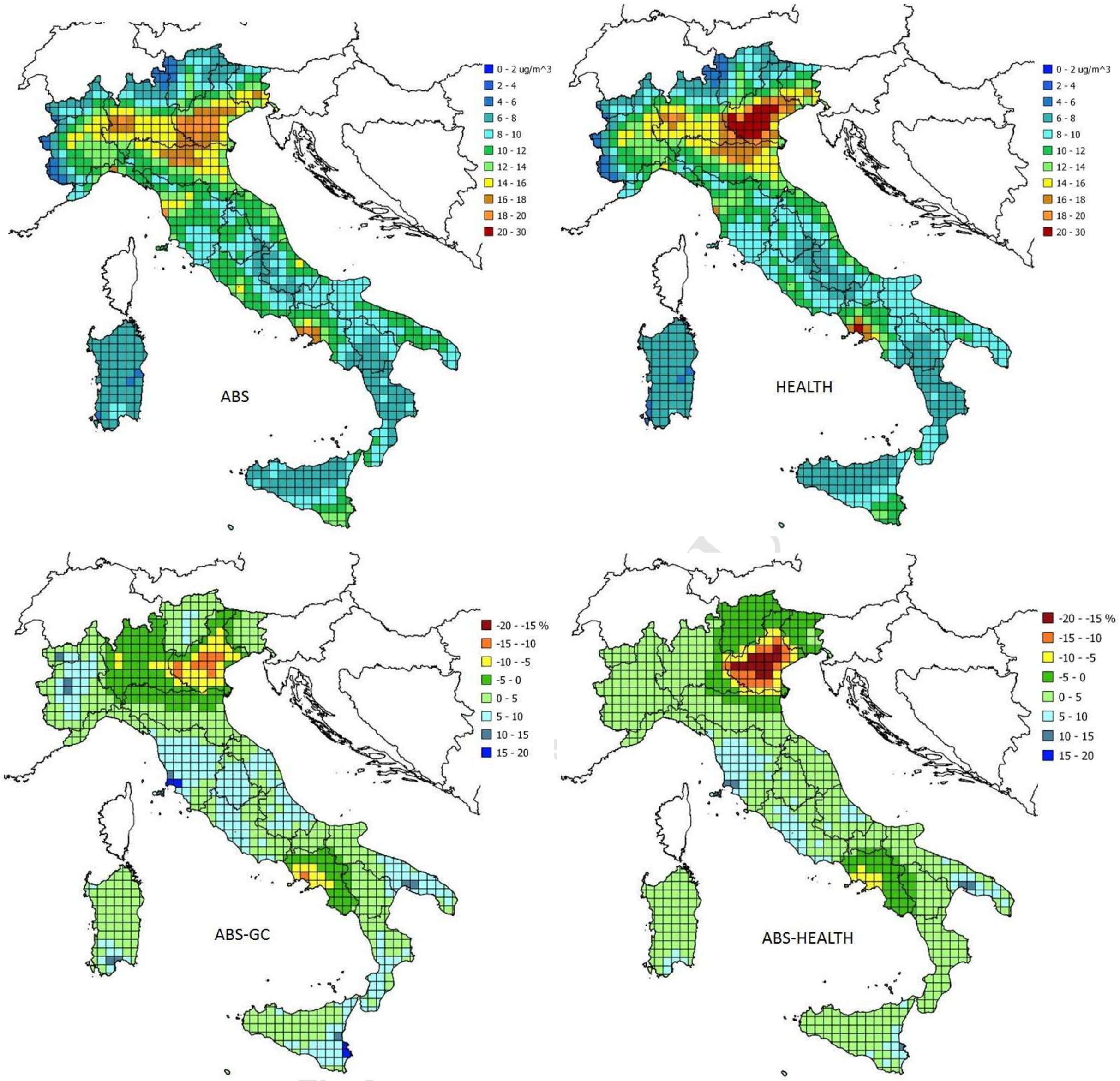

Figure 5 – Annual mean average PM2.5 concentration (μg/m^3) for the year 2030 in the ABS (top left) and HEALTH scenarios (top right) and concentration differences (in %) between ABS and GC scenarios (bottom left) and between ABS and HEALTH scenarios (bottom right).

In contrast, the maximum annual PM2.5 concentration in some areas still reaches almost 23 μg/m^3 and 24 μg/m^3 in GC and HEALTH, respectively, and is thereby up to 15% and 20% higher than in the ABS scenario (fig. 5). However, in both GC and HEALTH, in most areas the concentration level would be lower than ABS. Thus, we estimate that the number of people exposed to more than 20 μg/m^3 in GC and HEALTH would be reduced by 66% relative to baseline, and the share of

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people that can enjoy a level below 10 μg/m^3 would rise from 21% in the baseline to 33% (GC) and to 31% (HEALTH) instead of only 25% in ABS, cf. fig. 6.

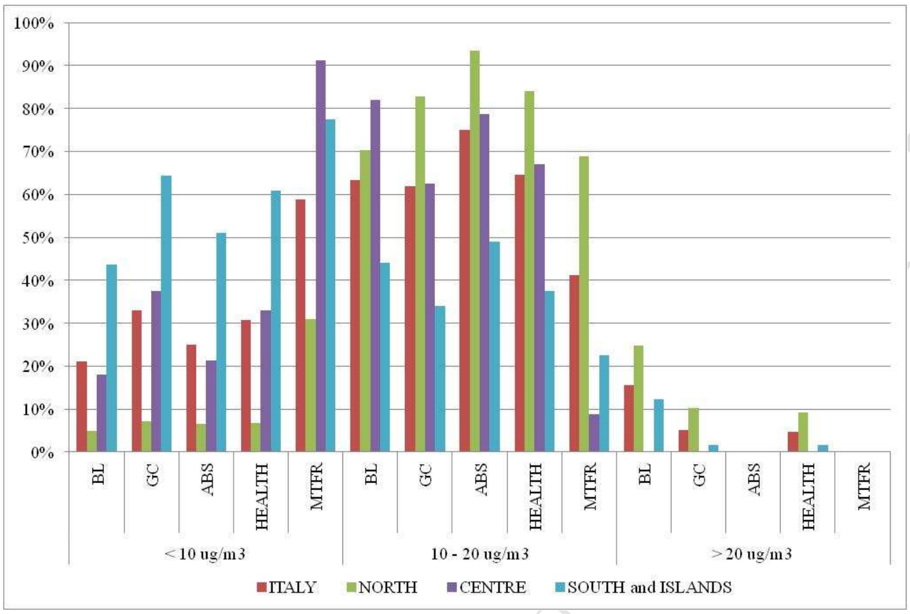

Figure 6 – Population exposure (%) for the year 2030 by geographical area in three PM2.5 concentration intervals (less than 10 μg/m^3, between 10 μg/m^3 and 20 μg/m^3, more than 20 μg/m^3) for the three policy scenarios and MTFR.

At the regional scale, in the 2030 baseline scenario the population in the northern area is largely exposed to higher PM2.5 concentrations and only 5% of the population is exposed to less than 10 μg/m^3 while 25% of the population is exposed to over 20 μg/m^3. For the south and islands this share is only 12%, while in the central area no part of the population is exposed to more than 20 μg/m^3. In the three policy scenarios, the share of people in the north exposed to less than 10 μg/m^3 does not vary, indicating that all three policy options generally improve higher concentration areas. In contrast, in the south and centre regions the different target setting options have different implications for the share of people living in areas exposed to less than 10 μg/m^3. Regional results, reported in Appendix 2 (Supplementary materials), show a large variation among northern regions and policy scenarios.

3.3 Other ambition levels

Our results are subject to uncertainties, relating to the specifics of the GAINS model formulation, model parameters and input data, as well as the general uncertainty about the future, and specifically future economic and energy-related activities (Amann et al., 2011a). For GAINS-

Europe, Schöpp et al. (2005) have developed a methodology to quantify uncertainties, and their conclusions equally apply to the Italian version of GAINS. Here, however, we take a pragmatic approach in the form of sensitivity analyses and explore how our results change as a result of changing (independently) two key ingredients in the analysis.

Namely, first we explore whether our qualitative conclusions about the different target setting approaches would change if we change the ambition level of the policy, i.e. the target level for the population weighted exposure level. In fig. 7 we show the emission reduction cost curve over a range of target levels of PWEL for the three target setting approaches.

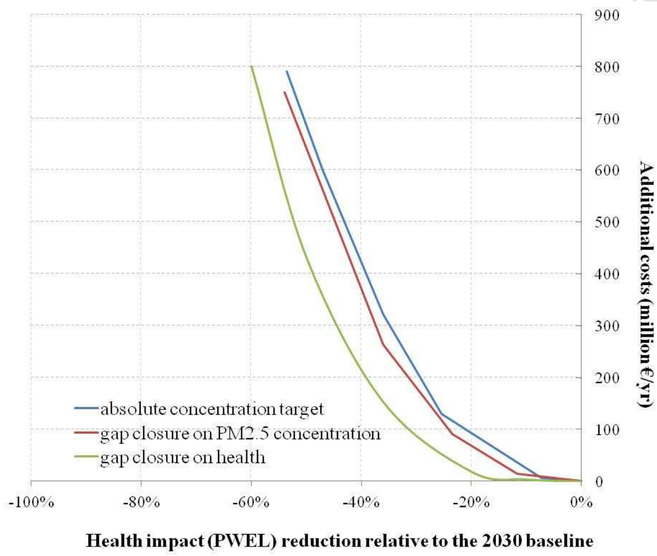

Figure 7 – Comparison of costs for reaching a given health impact reduction with three alternative target setting approaches.

The blue curve was generated by setting more and more ambitious absolute concentration targets (the lowest level that could be achieved in every grid is 16 μg/m^3), while the red (green) curve was generated by increasing the gap closure value from zero to 100% for the PM2.5 concentration level in each grid cell (the total national YOLL). We observe that to reach the same health impact levels the gap closure approach (in particular when applied to the national YOLL indicator) lowers the costs respect to an absolute target approach. Thus, in reducing the accumulated exposure to PM2.5 concentrations, setting an ambient air quality standard is economically less efficient than alternative approaches for reaching a given health objective where emission reductions could occur in more cost-effective regions and sectors. As a second sensitivity analysis we compare the alternative target setting approaches under different meteorology (fig. 8). The results confirm that the ABS target can only be achieved at higher costs than equivalent targets in the GC and HEALTH approaches,

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independently of the choice of historical meteorology for determining the dispersion and chemistry of the pollution.

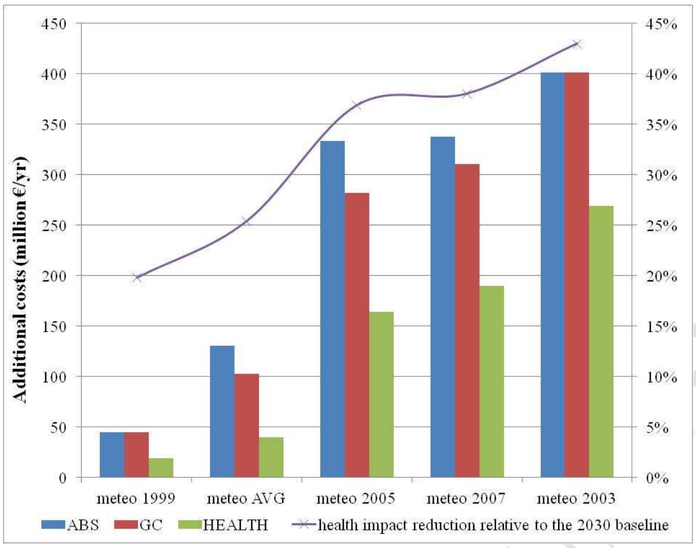

Figure 8 – Comparison of costs for reaching the same absolute limit value of 22 μg/m^3 for the three different target setting approaches under different meteorological years.

In addition, we have compared the emission control costs required for a 60% reduction in health impact for the GC and HEALTH. We have found (fig. 9) that GC costs are consistently 50-60% higher than in HEALTH costs, across all meteorologies considered here. Thus, applying the gap closure approach directly to the health impact indicator, rather than the concentration level, is the most cost-effective approach, independently of the meteorology.

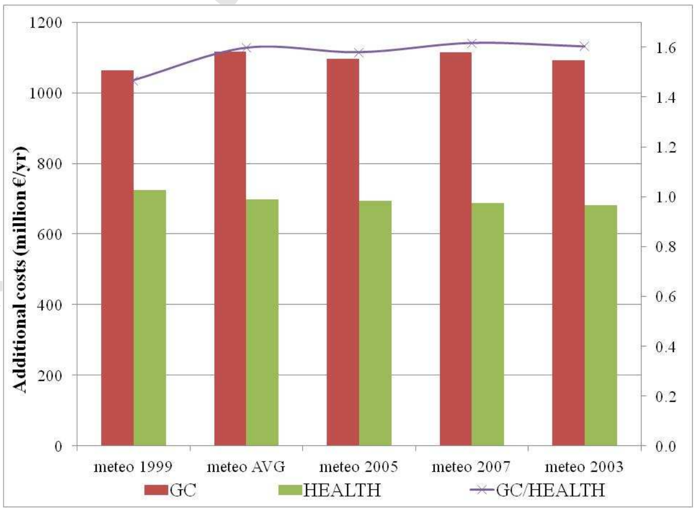

Figure 9 – Comparison of costs for reaching the same health impact reduction of 60% for the GC and HEALTH scenarios under different meteorological years.

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4 Conclusions

In this paper we have constructed and analysed cost-effective scenarios that achieve either certain air quality standards or health objectives. For the analysis we have implemented and used the Italian version of the GAINS model including an optimization algorithm that is fully consistent with the GAINS-Europe tool, which has been used by policy makers in the design and negotiations of future air pollution control policies. Here we have focused on long-term accumulated exposure to PM2.5 concentrations. We have compared three alternative target setting approaches for identifying cost-effective policy options: absolute air quality targets, expressed as limits on annual average PM2.5 concentrations; gap closure on PM2.5 concentration level in each grid cell, i.e. for each grid cell same progress in the reduction in concentration levels, measured against the potential reduction in each cell; and a gap closure on the total years of life lost of the whole Italian territory. We have specifically compared the cost-effectiveness of the approaches and found that the absolute air quality target is the economically least efficient approach to reducing the overall exposure to PM2.5 concentrations, and this is true across all feasible ambition levels and different meteorologies. For the specific case of reaching a universal air quality target of 20 $\mu g/m^3$ (or equivalent health benefit) we found that setting the absolute air quality target implies additional air pollution control costs of 322 million €/yr, while with a gap closure approach on PM2.5 concentration (on the YOLL indicator) the same health benefit could be achieved with 264 million €/yr (153 million €/yr). Different target setting approaches also suggest different emission reduction measures to be taken, and this has implications for implementation rules. We also found that an air quality target of 20 $\mu g/m^3$ by 2030 would lead to a very uneven distribution of reduction efforts and costs across the twenty Italian regions. Our analysis shows that substantial economic and health benefits could be gained by exploring alternative policy options for achieving a given set of health objectives. In the future GAINS-Italy could be used more widely to further explore specific portfolios of emission control measures beyond current national and EU legislation.

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Table 1 – The 2005 emission inventory (IIR, 2016) and the 2030 Baseline and MTFR scenarios for Italy (absolute emissions in kt and percentage reduction).

ITALY	2005 Emission Inventory	2030 Emission scenario		Change 2005-2030	
Pollutant	kt	Baseline (kt)	MTFR (kt)	Baseline (%)	MTFR (%)
SO_2	407	177	87	-56%	-79%
NO_X	1,249	568	499	-54%	-60%
PM2.5	165	124	63	-12%	-55%
NMVOC	1,281	767	522	-38%	-58%
NH_3	422	375	205	-11%	-51%

Table 2 – Emission reductions at the national level for the year 2030 (in %) with respect to the 2030 baseline in the GC, ABS, HEALTH and MTFR scenarios.

ITALY/ 2030 Scenario	2030 Emission reduction respect to the Baseline scenario (%)			
POLLUTANT	GC	ABS	HEALTH	MTFR
SO_2	-28%	-15%	-26%	-51%
NO_X	-2%	-1%	-1%	-12%
PM2.5	-13%	-11%	-10%	-49%
VOC	-1%	-1%	-1%	-32%
NH_3	-14%	-4%	-10%	-45%

Table 3 – Emission reductions (%) for the year 2030 by pollutant and geographical area and additional costs on top of the Baseline (BL) for the three policy scenarios and MTFR.

	2030 SO_2 emission reductions respect to Baseline (%)				2030 NO_X emission reductions respect to Baseline (%)				2030 PM2.5 emission reductions respect to Baseline (%)			
SCENARIOS	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR
ITALY	-28%	-15%	-26%	-51%	-2%	-1%	-1%	-12%	-13%	-11%	-10%	-49%
NORTH	-22%	-27%	-29%	-44%	-3%	-2%	-2%	-13%	-15%	-15%	-11%	-51%
CENTRE	-34%	0%	-34%	-52%	-1%	-1%	-1%	-11%	-11%	-6%	-9%	-48%
SOUTH and ISLANDS	-29%	-11%	-23%	-55%	-1%	-1%	-1%	-11%	-11%	-7%	-10%	-47%
	2030 NMVOC emission reductions respect to Baseline (%)				2030 NH_3 emission reductions respect to Baseline (%)				Add costs on top BL (€/person)			
SCENARIOS	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR	GC	ABS	HEALTH	MTFR
ITALY	-1%	-1%	-1%	-32%	-14%	-4%	-10%	-45%	4	5	3	88
NORTH	-1%	-1%	-1%	-36%	-14%	-5%	-10%	-51%	7	10	4	103
CENTRE	-1%	0%	-1%	-29%	-19%	0%	-15%	-39%	2	0	1	71
SOUTH and ISLANDS	-1%	0%	-1%	-28%	-11%	-3%	-7%	-33%	2	3	1	79

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HIGHLIGHTS

- The GAINS cost-optimization methodology has been applied to the Italian territory.
- Different environmental target setting approaches have been compared.
- A regulatory approach focusing on health impacts rather than on air quality is more cost-effective.
- Distribution of costs and benefits for the 20 Italian regions are presented.

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