

Accepted Manuscript

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PII: S1352-2310(16)30397-1

DOI: [10.1016/j.atmosenv.2016.05.049](https://doi.org/10.1016/j.atmosenv.2016.05.049)

Reference: AEA 14637

To appear in: *Atmospheric Environment*

Received Date: 21 September 2015

Revised Date: 20 May 2016

Accepted Date: 24 May 2016

Please cite this article as: Ciucci, A., D'Elia, I., Wagner, F., Sander, R., Ciancarella, L., Zanini, G., Schöpp, W., Cost-effective reductions of PM_{2.5} concentrations and exposure in Italy, *Atmospheric Environment* (2016), doi: 10.1016/j.atmosenv.2016.05.049.

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Cost-effective reductions of PM_{2.5} concentrations and exposure in Italy

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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 PM_{2.5} 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 **1 Introduction**

2
3 Air pollution is the single largest environmental health risk in Europe (EEA, 2015) and particulate
4 matter (PM) has become a major concern for public health (WHO, 2015). The European Union
5 (EU) limit and target values for particulate matter continued to be exceeded in large parts of Europe
6 in 2013 (EEA, 2015). Recent studies based on scenario analysis have assessed the likelihood that
7 the World Health Organization (WHO) air quality standards and limits will be met in the future, and
8 what factors this may depend on, both at the European (for example, Kieseewetter et al., 2014 and
9 2015) and at the national level (Oxley et al., 2013; Vieno et al., 2016).

10 The cost-effectiveness approach has in recent years been applied in defining several European air
11 pollution policies. This method has replaced earlier approaches to burden sharing, such as a uniform
12 emission reduction target for all negotiating parties, which was adopted in the earlier stages of
13 European air pollution control (Hordijk and Amann, 2007; Tunistra, 2007). In subsequent policy
14 processes, cost-effectiveness and effect-based principles became the rationale to derive quantitative
15 and differentiated national reduction targets based on the carrying capacity of vulnerable
16 ecosystems (Amann et al., 2011a; Wagner et al., 2013a; Wagner et al., 2013b). The cost-
17 effectiveness and effect-based principles have also been recently applied to the revision of the
18 Gothenburg Protocol (Amann et al., 2011b), the review of the Thematic Strategy on Air Pollution
19 (Amann et al., 2013) whose results lead to the adoption of the “Clean Air Policy Package” (COM,
20 2013; Amann et al., 2014a) and to the revision of the National Emission Ceilings (NEC) Directive
21 (Amann et al., 2015).

22 Our analysis is focused on Italy, and we use the GAINS-Italy model (*Greenhouse Gas and Air*
23 *Pollution Interactions and Synergies Model over Italy*, D’Elia et al., 2009) to apply the above
24 methodologies to translate national environmental and health targets to regional emission control
25 targets. GAINS-Italy has been developed in collaboration with the International Institute for
26 Applied System Analysis (IIASA) as it is the national version of the GAINS-Europe model (Amann
27 et al., 2011a) and allows the evaluation of impacts and costs. Starting from information on emission
28 abatement technologies and economic scenarios of energy and productive sectors, GAINS-Italy
29 produces alternative and/or future emission scenarios, alternative air quality scenarios and
30 abatement costs at a 5-year interval starting from 1990 to 2050. Compared to GAINS-Europe, the
31 development of GAINS-Italy gives many advantages to the national integrated model, i.e. GAINS-
32 Italy represents 20 political regions individually and has a spatial resolution of 20x20 km² on a grid
33 of 67x75 cells.

1 GAINS-Italy is the MINNI (*National Integrated Model to support the international negotiation on*
2 *atmospheric pollution*) component dedicated to elaborating emission scenarios to support
3 international evaluation and negotiation on atmospheric pollution. The MINNI model is an
4 Integrated Modeling System that links atmospheric science with the economics of emission
5 abatement measures and policy analysis. It was developed by the Italian National Agency for New
6 Technologies, Energy and Sustainable Economic Development (ENEA) to support the Italian
7 Ministry of the Environment, the Land and the Sea on the methodological aspects of the policy
8 design. MINNI consists of several interdependent and interconnected components, each of which
9 describes individual system aspects and whose main components are a multi-pollutant *Atmospheric*
10 *Modeling System* (AMS) and the national GAINS-Italy. They interact in a feedback system through
11 the *Atmospheric Transfer Matrices* (ATMs) and the *RAINS-Atmospheric Inventory link* (RAIL).
12 In the present paper we analyze alternative cost-effectiveness approaches to reducing PM2.5
13 concentrations and exposure for Italy. We illustrate the distribution of costs and benefits across the
14 regions when different approaches to air pollution control policy are used to meet the same health
15 objectives. Specifically we analyze three policy scenarios obtained with different approaches for
16 setting environmental objectives, the ‘*absolute limit value*’ and the ‘*gap closure*’ procedures, the
17 latter applied either to PM2.5 concentrations and to the YOLL (*Years Of Life Lost*) indicator. We
18 finally discuss the cost implications for these approaches at different ambition levels. Technical
19 details can be found in the Supplementary Material.

21 **2 Methodology**

23 **2.1 The optimization module in the GAINS-Italy model**

24 Over the past three decades IASA has developed the RAINS (*Regional Air Pollution Information*
25 *and Simulation*, Schöpp et al., 1999) integrated model to support international negotiations on
26 transboundary air pollution, and then its successor, the GAINS model, which extends the scope to
27 greenhouse gases (Amann et al., 2011a). In particular, GAINS-Europe features an optimization
28 module, which allows users to identify country-specific and sector-specific portfolios of
29 technologies that achieve a given environmental/health target in the most cost-effective manner. We
30 have adapted the optimization framework to the Italian context with its 20 (emitting) regions, and
31 the same sectors/activities schema as in GAINS-Europe. Like its European counterpart, GAINS-
32 Italy features a database, which holds sectors/activities/technologies/pollutant and geographical
33 information; source-receptor relationships; technical and economic characteristics of control
34 technologies; as well as the implementation rate of current and planned future legislation on

1 greenhouse gas mitigation and pollution control and relevant affected sectors such as energy and
2 agriculture. The database is accessible through a web-interface and offers upload and download
3 features.

4 The objective in the optimization is to find, for a given future year, the mix of technologies that
5 allows to achieve a given environmental target at minimum cost, where the costs are typically
6 summed over all regions, sectors and technologies. As its European counterpart, the technologies
7 considered in GAINS-Italy for the present purpose include only ‘end-of-pipe’ emission control
8 technologies, i.e. measures that affect emission factors of one or more pollutants without changing
9 the activity data (Wagner et al., 2013a); while non-technical measures have not been introduced in
10 the database but can be evaluated through different and alternative scenarios. The optimization is
11 formulated as a linear programming problem, i.e. all equations, definitions and constraints are linear
12 in the decision variables. In the European version of GAINS, the ATMs are calculated with the
13 EMEP chemistry transport model (Simpson et al., 2012) and have a resolution of roughly 28x28
14 km². They are used to calculate the regional background, while the urban and roadside increment
15 have been taken into account respectively with the 7x7 km² CHIMERE Chemistry Transport Model
16 and a chemical box model (Kiesewetter et al., 2014 and 2015).

17 In the Italian MINNI system a different path has been followed. The AMS simulates meteorological
18 fields and computes gas and aerosol transport, diffusion and chemical reactions in atmosphere
19 (Mircea et al., 2014). It is composed by the meteorological model RAMS (*Regional Atmospheric*
20 *Modelling System*, Cotton et al., 2003); the emission processor EMMA (*EMission MAnager*,
21 ARIA/ARIANET, 2008); the three-dimensional Eulerian model FARM (*Flexible Air Quality*
22 *Regional Model*, Silibello et al., 2008; Gariazzo et al., 2007; Kukkonen et al., 2012) that includes
23 transport and multiphase chemistry of pollutants in the atmosphere. The AMS has been applied to
24 calculate the linear transfer coefficient of the ATMs (Briganti et al., 2011) that allows the GAINS-
25 Italy model to calculate regional background concentrations of PM_{2.5} and NO₂ from emission
26 scenarios of the whole Italian territory. As base case for the AMS calculations, the emissions for the
27 year 2015 of the baseline “No Climate Policy scenario” (MATTM, 2011) were used for each of the
28 four meteorological years, 1999, 2003, 2005, 2007. For each of these meteorological years we have
29 calculated ATMs. In addition, we have also averaged the concentration fields of the four
30 meteorological years to generate a new set of ATMs, which in the following we refer to as the
31 meteorology-average ATM or average ATM for short. To calculate PM concentrations, regional
32 emissions of primary particulate and of secondary particulate precursors, sulphur dioxide (SO₂),
33 nitrogen oxides (NO_x), ammonia (NH₃) and non-methane volatile organic compounds (NMVOC)
34 have been considered. For each run, the regional reference emissions of each precursor were

1 alternately and selectively abated by 25%. To test the approximation of the linear transfer
2 coefficients, a comparison with a full run of the AMS for the year 2020 has been carried out
3 (Briganti et al., 2011). This comparison showed that the ATMs consistently reproduce the complete
4 AMS run.

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

10 Furthermore, for a detailed assessment of the impacts of a given GAINS-Italy emission scenario,
11 the AMS system can be run at a resolution of 4x4 km² and 1x1 km².

12

13 **2.2 Three target setting approaches**

14 The current legislation (CLE) scenario represents the ‘baseline’ and reflects all policies that have
15 been currently legislated, both those that affect activity levels (such as energy and agriculture
16 policies), as well as pollution control policies for the period 1990-2050 (D’Elia et al., 2009). Our
17 underlying energy scenario for the GAINS-Italy model is based on the new National Energy
18 Strategy (Ministero dello Sviluppo Economico, 2013) and has been elaborated by the *Institute for*
19 *Environmental Protection and Research* (ISPRA) with the Markal-Italy model (Gracceva and
20 Contaldi, 2005). We have also compared the GAINS-Italy emission inventory estimated with a *top-*
21 *down* approach (D’Elia and Peschi, 2013) to the latest national emission inventory submission (IIR,
22 2016). Discrepancies in reproducing the national total emission inventory have been considered
23 acceptable if differences remain within a few percentage points (Amann et al., 2014b), i.e. in the
24 interval between $\pm 5\%$.

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

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

1 First, in the '*absolute limit value*' approach a uniform environmental quality standard is set that
2 must be attained in all regions, i.e. in each individual grid cell. For example, the annual average
3 concentration of fine particles or of ozone must not exceed a certain limit value. As a consequence
4 of such a policy, much of the improvement in air quality would occur in highly polluted areas, as
5 these are specifically targeted by such a policy. Similarly, much of the effort to reduce emissions
6 will occur in polluted areas: while some pollution is transported over distances, local emissions are
7 a key determinant of local air quality. This has been demonstrated by the national source
8 apportionment (http://ec.europa.eu/environment/air/quality/legislation/time_extensions.htm - Italy),
9 which showed an average contribution of transboundary pollution both for PM10 and NO₂ less than
10 30% for the whole Italian territory with higher peaks at the boundaries. Thus, costs and benefits
11 tend to be localized and correlated. The advantage of this target setting approach is that the air
12 quality can directly be monitored and compared to the target value.

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

29 In the following, we apply the gap closure target setting procedure to the PM_{2.5} concentration level
30 in each grid cell, so that in each grid cell the concentration is reduced by the same share of the local
31 reduction potential. In this case, we will choose X so that we can compare scenarios that exhibit the
32 same health benefits as the scenario obtained with the absolute limit value approach. For example,
33 we first estimate the impact of an absolute limit value of 20 µg/m³ that is applied in each grid cell in
34 the year 2030, in compliance with the European Directive on ambient air quality and cleaner air for

1 Europe (EC, 2008); we call this policy scenario ‘ABS’. Afterwards, we estimate the population
 2 weighted exposure level (PWEL) for the whole Italian territory. We then calculate the lowest gap
 3 closure X on the PM_{2.5} concentrations that achieves the same population weighted exposure level
 4 of the absolute scenario. This X turns out to be 31%, and we call the corresponding optimized
 5 policy scenario ‘GC’.

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

12

13 3 Results

14

15 3.1 The Baseline and MTR scenario at the year 2030

16 The baseline scenario assumes full implementation of current legislation, both European and
 17 national. The MTR scenario shows to what level air pollutant emissions could be further reduced
 18 beyond what is required by current legislation, through full application of the available technical
 19 measures, without changes in the energy structures and without behavioural changes of consumers
 20 (Amann et al., 2014a). In the following table and figure (tab. 1 and fig.1), we show results for the
 21 baseline and MTR scenarios in the year 2030 at the national level, while detailed data for all the
 22 20 administrative Regions are reported in Appendix 1 (Supplementary materials).

23

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

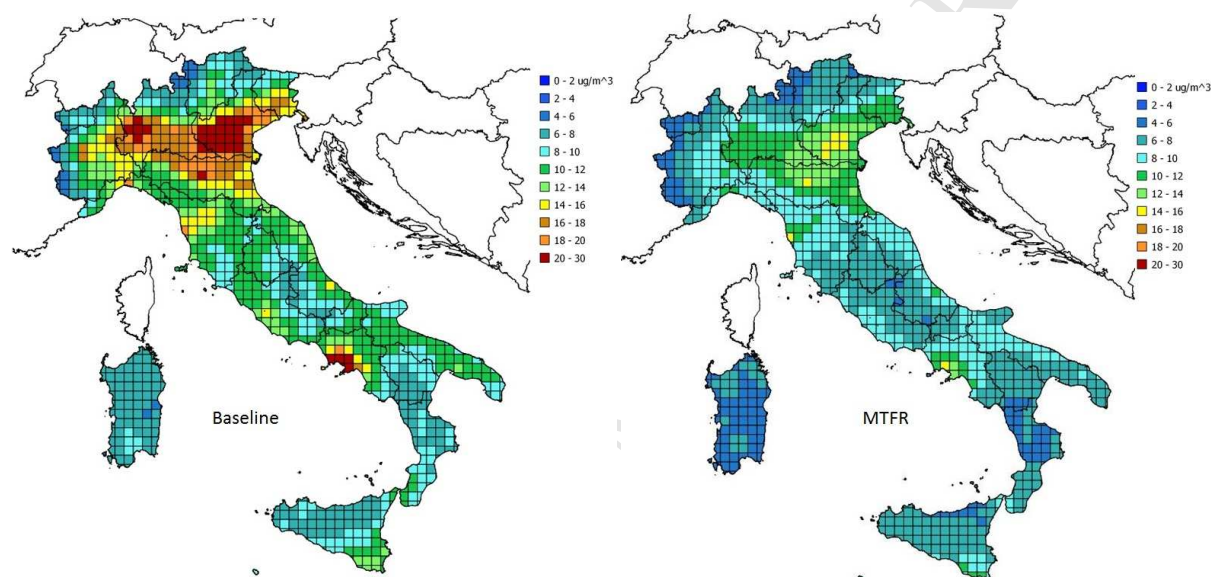
ITALY	2005 Emission Inventory	2030 Emission scenario		Change 2005-2030	
		Baseline (kt)	MTR (kt)	Baseline (%)	MTR (%)
Pollutant	kt				
SO ₂	407	177	87	-56%	-79%
NO _x	1,249	568	499	-54%	-60%
PM _{2.5}	165	124	63	-12%	-55%
NM _{VOC}	1,281	767	522	-38%	-58%
NH ₃	422	375	205	-11%	-51%

26

27 In the baseline scenario, SO₂, NO_x and NM_{VOC} emissions are reduced significantly between 2005
 28 and 2030 (by 56%, 54% and 38%, respectively), while for PM_{2.5} (12%) and NH₃ (11%) the

1 reductions are smaller. The MTFR scenario shows, however, that also these two pollutants could be
 2 reduced significantly (by 55% for PM_{2.5} and 51% for NH₃).

3 Figure 1 shows the resulting annual mean PM_{2.5} concentration for the year 2030 in the baseline and
 4 MTFR scenarios on a 20 km grid for the average meteorological year. Comparing these results with
 5 the PM_{2.5} annual air quality value of 20 µg/m³ required by the Air Quality Directive (EC, 2008),
 6 we observe exceedances of the limit value in the baseline scenario in the Po Valley and in the Milan
 7 and Naples areas, while in the MTFR scenario the limit value is attained everywhere (the maximum
 8 concentration across grid cells is 16 µg/m³). A map with the name of the 20 Italian Administration
 9 Regions is reported in Appendix 3 (Supplementary Material).



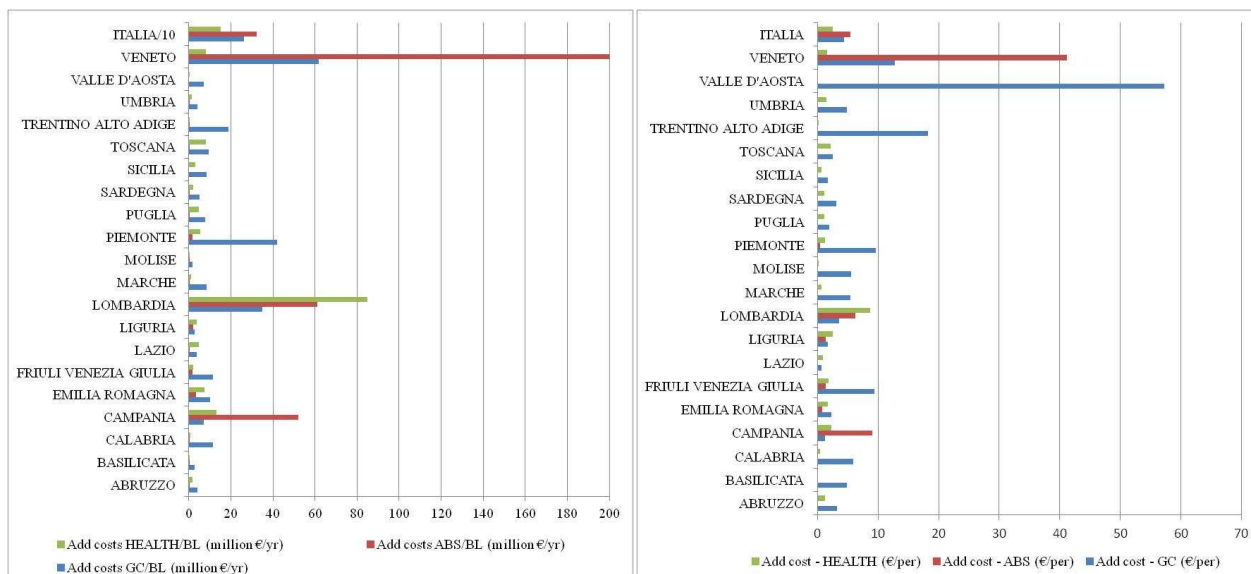
10
 11 Figure 1 – Annual mean PM_{2.5} concentrations for the year 2030 with a spatial resolution of 20 km
 12 in the Baseline (left) and MTFR (right) scenario calculated by the GAINS-Italy model with the
 13 meteorological average year.

14
 15 However, the WHO limit of 10 µg/m³ cannot be attained everywhere, even in the MTFR scenario.
 16 Thus, only with additional changes in the energy system this limit could be attained.

17 18 3.2 Comparing target setting for policy scenarios

19 To illustrate the differences in the target setting approaches the ABS, GC and HEALTH scenarios
 20 have been compared. Figure 2 shows the additional costs by region (on top of the baseline scenario)
 21 in absolute values (million €/yr) and per capita for these three scenarios. The HEALTH scenario
 22 implies an additional air pollution cost of 153 million €/yr on top of the baseline costs (i.e. ~3 € per
 23 capita and year) (fig. 2). In contrast, GC implies 264 million €/yr (4 € per capita and year), while
 24 ABS implies 322 million €/yr (5 € per capita and year). At the national level, the gap closure

1 approach targeting total national YOLL implies the lowest costs, but this is not true for all regions
 2 (fig. 2). Higher costs of HEALTH than GC are observed for example in the Lombardia Region
 3 (Northern Italy) where high PM_{2.5} concentrations are also correlated with a high population
 4 density.



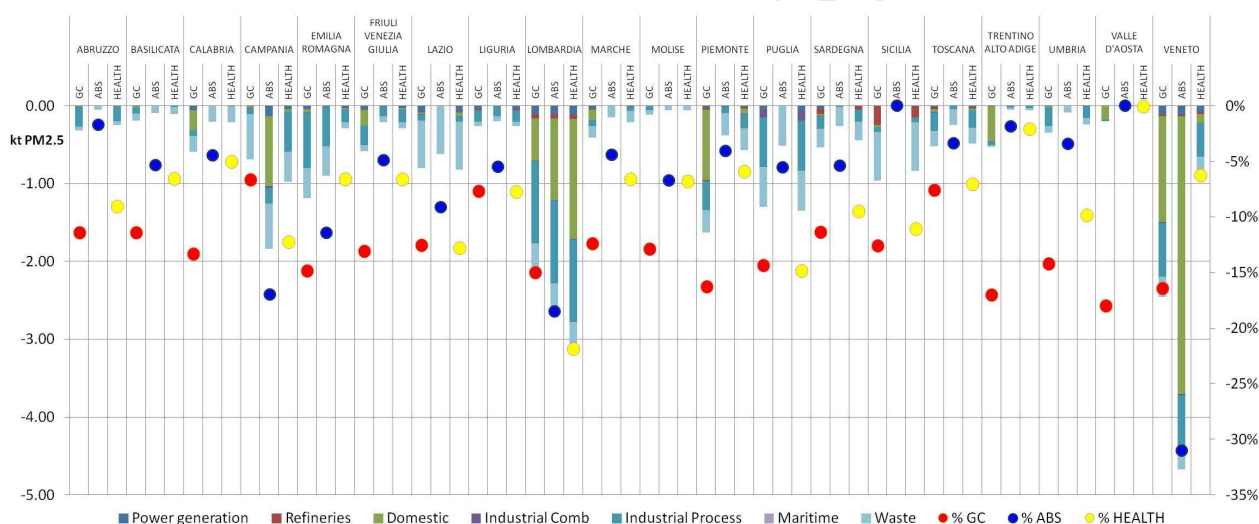
5
 6 Figure 2 – Additional costs on top of the baseline (BL) costs in absolute values (million €/yr - left)
 7 and per capita (€/person – right) by Region to reduce PM_{2.5} concentration in the three policy
 8 scenarios: gap closure on PM_{2.5} concentrations (GC - blue bar), Absolute Value of 20 µg/m³ (ABS
 9 - red bar) and gap closure on the health indicator (HEALTH - green bar) – for the year 2030.

10
 11 Differences are evident not only in terms of costs but also in terms of emission reductions and
 12 PM_{2.5} concentrations. It is worth nothing that in the ABS scenario only few regions, where
 13 concentration limit are exceeded, are affected by policy changes. Table 2 shows that the implied
 14 reduction in PM_{2.5}, NO_x and NMVOC emissions with respect to the baseline scenario are very
 15 similar across all the three policy scenarios, with reductions of NO_x and NMVOC being negligible.

16
 17 Table 2 – Emission reductions at the national level for the year 2030 (in %) with respect to the 2030
 18 baseline in the GC, ABS, HEALTH and MTRF scenarios.

ITALY/ 2030 Scenario	2030 Emission reduction respect to the Baseline scenario (%)			
POLLUTANT	GC	ABS	HEALTH	MTRF
SO ₂	-28%	-15%	-26%	-51%
NO _x	-2%	-1%	-1%	-12%
PM _{2.5}	-13%	-11%	-10%	-49%
VOC	-1%	-1%	-1%	-32%
NH ₃	-14%	-4%	-10%	-45%

1 In contrast, SO_2 and NH_3 are much further reduced in the GC and HEALTH scenarios than in the
 2 ABS scenario. However, regional emission reduction patterns actually differ significantly from this
 3 national pattern. Moreover, although all the three policy scenarios show comparable $\text{PM}_{2.5}$
 4 emission reductions at the national level, at the regional and sectoral level the emission reductions
 5 differ significantly across scenarios, implying that different specific policies would be required to
 6 implement them (fig. 3). For example, in the ABS scenario the primary $\text{PM}_{2.5}$ emission reduction
 7 occurs principally in three regions (Campania, Lombardia and Veneto) and here largely in the
 8 domestic sector (improved combustion of biomass). On the other hand, in GC and HEALTH the
 9 reductions are more evenly distributed and all other regions experience a higher emission reduction
 10 (compare red, yellow and blue dots on the right axis). The largest contributors to reductions in the
 11 ABS scenarios are the industry and domestic sectors; while in GC and HEALTH the contribution of
 12 the domestic sector is lower. Thus, reaching the European air quality standard would require to
 13 target fireplaces and traditional stoves specifically in Campania, Lombardia and Veneto.



14
 15 Figure 3 – Primary $\text{PM}_{2.5}$ emission reduction relative to the 2030 baseline by region (dots on the
 16 right axis) and sector (bars on the left axis) for the HEALTH, GC and ABS scenarios.

17
 18 The only regions that have to reduce NH_3 emissions in the ABS scenario are Campania in Southern
 19 Italy, Lombardia and Veneto in the North (cf. fig. 4) that are also the most polluted areas. In the GC
 20 and HEALTH scenarios NH_3 emission are also significantly reduced in Lombardia, Toscana and
 21 Emilia Romagna in Central Italy. In all the policy scenarios, the largest contributor to reductions is
 22 the livestock sector and especially cattle farming. Strikingly, while emissions reductions observed
 23 in the GC and HEALTH scenarios are higher, the associated costs are lower than in the ABS
 24 scenario (fig. 2) because emission reductions occur in regions and sectors where the reductions can
 25 be achieved more cost-effectively.

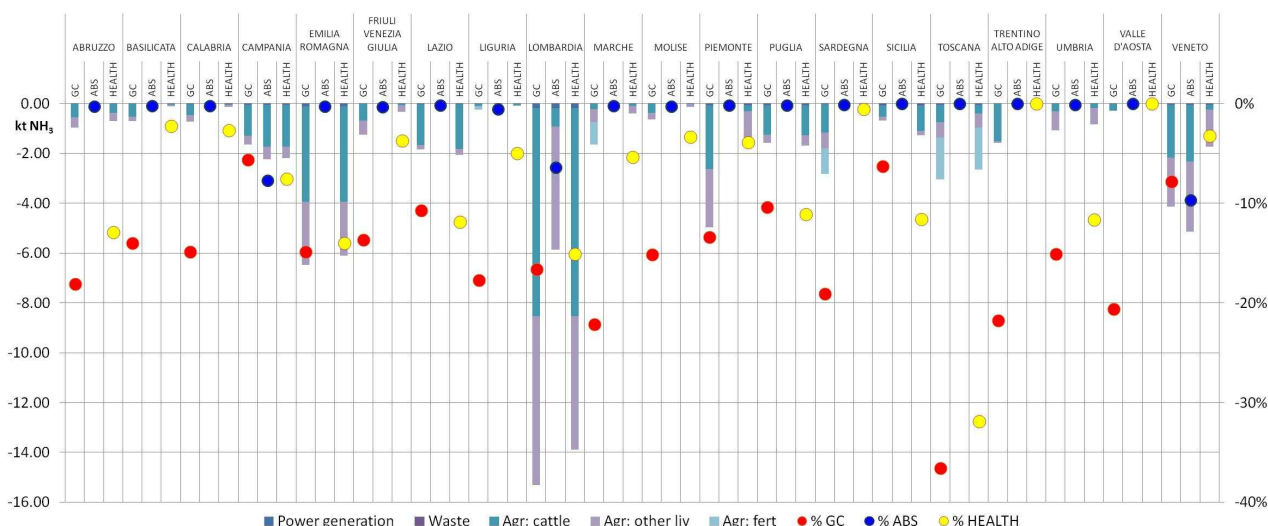


Figure 4 – NH₃ emission reduction relative to the 2030 baseline by region (dots on the right axis) and sector (bars on the left axis) for the HEALTH, GC and ABS scenarios.

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 MTRF.

SCENARIOS	2030 SO ₂ emission reductions respect to Baseline (%)				2030 NO _x emission reductions respect to Baseline (%)				2030 PM _{2.5} emission reductions respect to Baseline (%)			
	GC	ABS	HEALTH	MTRF	GC	ABS	HEALTH	MTRF	GC	ABS	HEALTH	MTRF
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%
SCENARIOS	2030 NMVOC emission reductions respect to Baseline (%)				2030 NH ₃ emission reductions respect to Baseline (%)				Add costs on top BL (€/person)			
	GC	ABS	HEALTH	MTRF	GC	ABS	HEALTH	MTRF	GC	ABS	HEALTH	MTRF
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 MTRF 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/m³ is attained in all grid

1 cells in the ABS scenario, even in the high PM_{2.5} concentration areas such as Milan, the Po valley
 2 and Naples.

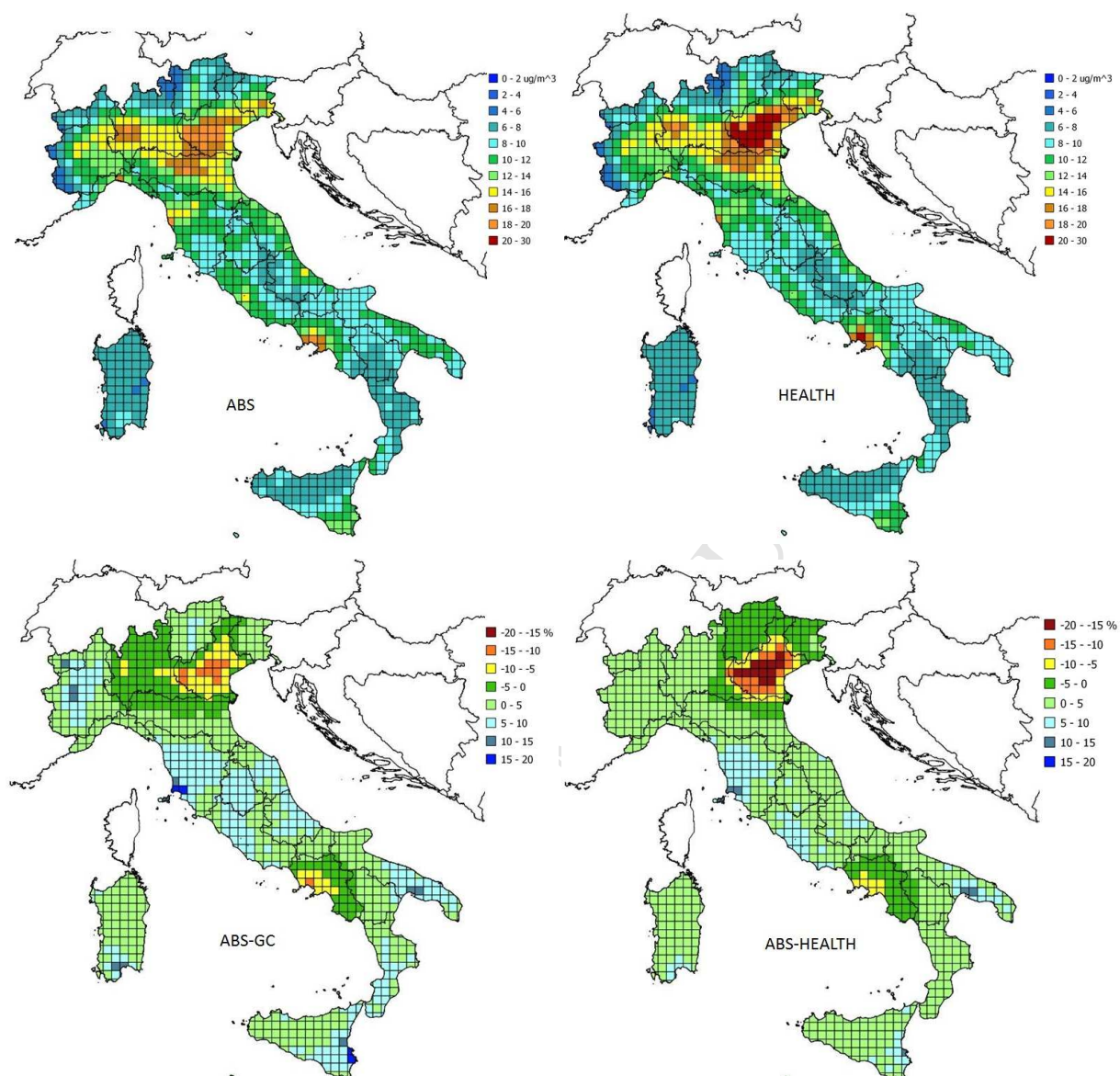
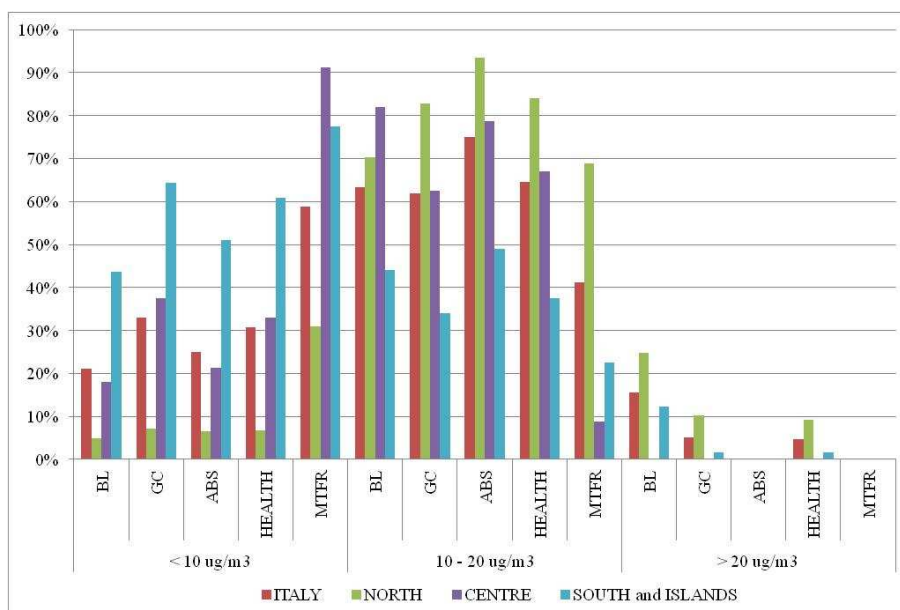


Figure 5 – Annual mean average PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) for the year 2030 in the ABS (top left) and HEALTH scenarios (top right) and concentration differences (in %) between ABS and GC scenarios (bottom left) and between ABS and HEALTH scenarios (bottom right).

9 In contrast, the maximum annual PM_{2.5} concentration in some areas still reaches almost $23 \mu\text{g}/\text{m}^3$
 10 and $24 \mu\text{g}/\text{m}^3$ in GC and HEALTH, respectively, and is thereby up to 15% and 20% higher than in
 11 the ABS scenario (fig. 5). However, in both GC and HEALTH, in most areas the concentration
 12 level would be lower than ABS. Thus, we estimate that the number of people exposed to more than
 13 $20 \mu\text{g}/\text{m}^3$ in GC and HEALTH would be reduced by 66% relative to baseline, and the share of

1 people that can enjoy a level below $10 \mu\text{g}/\text{m}^3$ would rise from 21% in the baseline to 33% (GC) and
 2 to 31% (HEALTH) instead of only 25% in ABS, cf. fig. 6.

3



4

5 Figure 6 – Population exposure (%) for the year 2030 by geographical area in three PM2.5
 6 concentration intervals (less than $10 \mu\text{g}/\text{m}^3$, between $10 \mu\text{g}/\text{m}^3$ and $20 \mu\text{g}/\text{m}^3$, more than $20 \mu\text{g}/\text{m}^3$)
 7 for the three policy scenarios and MTRF.

8

9 At the regional scale, in the 2030 baseline scenario the population in the northern area is largely
 10 exposed to higher PM2.5 concentrations and only 5% of the population is exposed to less than 10
 11 $\mu\text{g}/\text{m}^3$ while 25% of the population is exposed to over $20 \mu\text{g}/\text{m}^3$. For the south and islands this share
 12 is only 12%, while in the central area no part of the population is exposed to more than $20 \mu\text{g}/\text{m}^3$. In
 13 the three policy scenarios, the share of people in the north exposed to less than $10 \mu\text{g}/\text{m}^3$ does not
 14 vary, indicating that all three policy options generally improve higher concentration areas. In
 15 contrast, in the south and centre regions the different target setting options have different
 16 implications for the share of people living in areas exposed to less than $10 \mu\text{g}/\text{m}^3$. Regional results,
 17 reported in Appendix 2 (Supplementary materials), show a large variation among northern regions
 18 and policy scenarios.

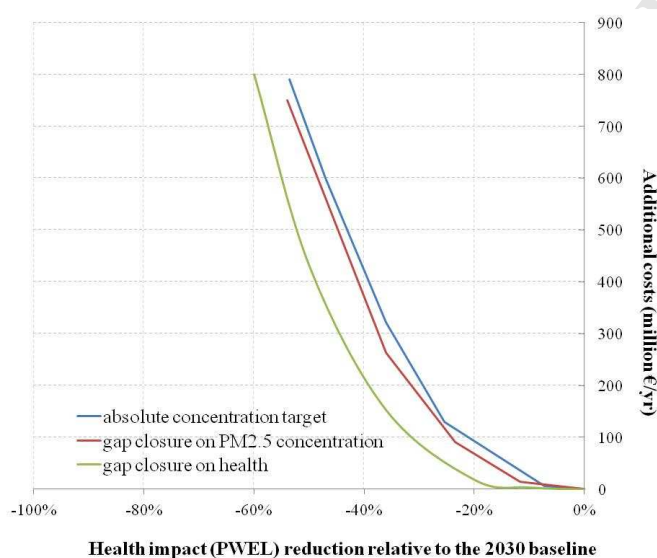
19

20 3.3 Other ambition levels

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

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

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

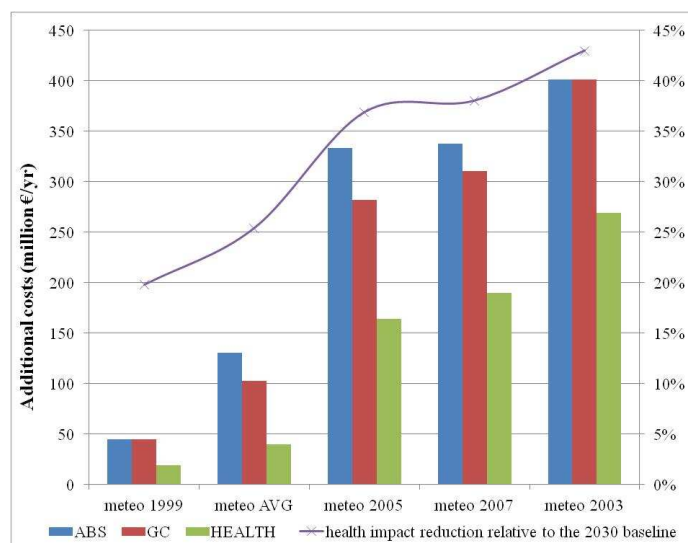


9

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

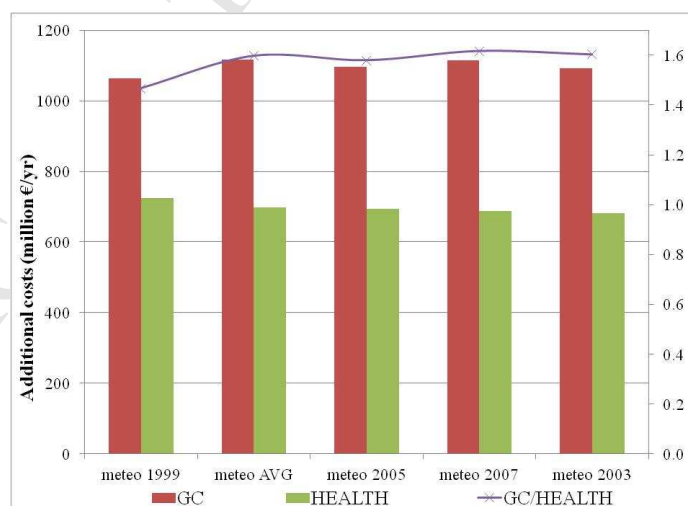
12 The blue curve was generated by setting more and more ambitious absolute concentration targets
 13 (the lowest level that could be achieved in every grid is $16 \mu\text{g}/\text{m}^3$), while the red (green) curve was
 14 generated by increasing the gap closure value from zero to 100% for the PM2.5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

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



3
 4 Figure 8 – Comparison of costs for reaching the same absolute limit value of $22 \mu\text{g}/\text{m}^3$ for the three
 5 different target setting approaches under different meteorological years.

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



11
 12 Figure 9 – Comparison of costs for reaching the same health impact reduction of 60% for the GC
 13 and HEALTH scenarios under different meteorological years.

14

1 4 Conclusions

2 In this paper we have constructed and analysed cost-effective scenarios that achieve either certain
3 air quality standards or health objectives. For the analysis we have implemented and used the Italian
4 version of the GAINS model including an optimization algorithm that is fully consistent with the
5 GAINS-Europe tool, which has been used by policy makers in the design and negotiations of future
6 air pollution control policies. Here we have focused on long-term accumulated exposure to PM_{2.5}
7 concentrations. We have compared three alternative target setting approaches for identifying cost-
8 effective policy options: absolute air quality targets, expressed as limits on annual average PM_{2.5}
9 concentrations; gap closure on PM_{2.5} concentration level in each grid cell, i.e. for each grid cell
10 same progress in the reduction in concentration levels, measured against the potential reduction in
11 each cell; and a gap closure on the total years of life lost of the whole Italian territory. We have
12 specifically compared the cost-effectiveness of the approaches and found that the absolute air
13 quality target is the economically least efficient approach to reducing the overall exposure to PM_{2.5}
14 concentrations, and this is true across all feasible ambition levels and different meteorologies. For
15 the specific case of reaching a universal air quality target of 20 µg/m³ (or equivalent health benefit)
16 we found that setting the absolute air quality target implies additional air pollution control costs of
17 322 million €/yr, while with a gap closure approach on PM_{2.5} concentration (on the YOLL
18 indicator) the same health benefit could be achieved with 264 million €/yr (153 million €/yr).
19 Different target setting approaches also suggest different emission reduction measures to be taken,
20 and this has implications for implementation rules. We also found that an air quality target of 20
21 µg/m³ by 2030 would lead to a very uneven distribution of reduction efforts and costs across the
22 twenty Italian regions. Our analysis shows that substantial economic and health benefits could be
23 gained by exploring alternative policy options for achieving a given set of health objectives. In the
24 future GAINS-Italy could be used more widely to further explore specific portfolios of emission
25 control measures beyond current national and EU legislation.

26
27 **Acknowledgements.** This work is part of the MINNI (Integrated National Model in support to the
28 International Negotiation on Air Pollution) project, funded by the Italian Ministry of Environment,
29 Territory and Sea. The present paper represents one of the main results of LECOP, a laboratory
30 born thanks to the framework agreement between ENEA and Emilia Romagna Region signed in
31 2010 within the ROP ERDF 2007-2013 aimed at establishing the regional High Technology
32 Network. We would like to thank three anonymous referees for constructive comments and
33 suggestions for improvements.

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

ITALY	2005 Emission Inventory	2030 Emission scenario		Change 2005-2030	
		Baseline (kt)	MTR (kt)	Baseline (%)	MTR (%)
Pollutant	kt				
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 MTR scenarios.

ITALY/ 2030 Scenario	2030 Emission reduction respect to the Baseline scenario (%)			
	GC	ABS	HEALTH	MTR
POLLUTANT				
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 MTR.

SCENARIOS	2030 SO ₂ emission reductions respect to Baseline (%)				2030 NO _x emission reductions respect to Baseline (%)				2030 PM2.5 emission reductions respect to Baseline (%)			
	GC	ABS	HEALTH	MTR	GC	ABS	HEALTH	MTR	GC	ABS	HEALTH	MTR
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%
SCENARIOS	2030 NMVOC emission reductions respect to Baseline (%)				2030 NH ₃ emission reductions respect to Baseline (%)				Add costs on top BL (€/person)			
	GC	ABS	HEALTH	MTR	GC	ABS	HEALTH	MTR	GC	ABS	HEALTH	MTR
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

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.