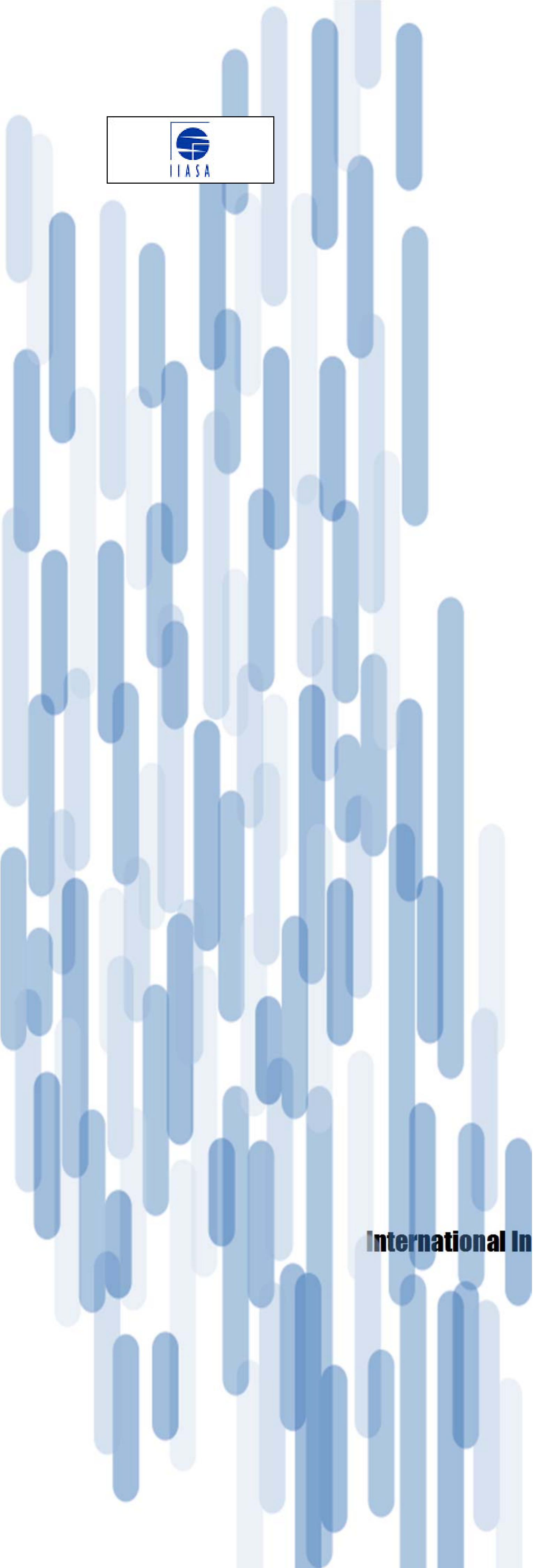

Service Contract on
Monitoring and Assessment
of Sectorial Implementation Actions
(ENV.C.3/SER/2011/0009)

Scenarios of Cost-effective Emission Controls after 2020

TSAP Report #7

Version 1.0

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Executive Summary

Although emissions of most air pollutants are expected to significantly decline in the coming decades, the magnitude of the remaining impacts of poor air quality on human health and ecosystems will still be substantial. Technical and non-technical measures will be still available to reduce emissions and resulting impacts below the 'current legislation' baseline levels.

However, these additional measures come at certain costs. It is estimated that full implementation of all available technical emission control measures would require up to 0.32% of GDP in 2030, and thereby increase total costs of air pollution control by more than 50%.

The GAINS optimization offers a tool for a systematic analysis of the cost-effectiveness of further measures. This report presents a series of illustrative optimization calculations addressing the health and ecosystems impact indicators that have been employed for earlier cost-effectiveness analyses for the 2005 Thematic Strategy on Air Pollution and the 2012 revision of the Gothenburg protocol.

As a first step, a series of calculations determined for each of these endpoints the increase in emission control costs for gradually tightened 'gap closure' targets between the current legislation and the full application of all available technical measures. Costs increase most rapidly for improvements of health impacts (for ozone and PM), while significant progress at comparably low costs is possible for eutrophication and acidification.

In a second step, illustrative joint optimizations for multiple targets have been conducted, aiming at arbitrarily chosen gap closure targets of 25/50/75% for all impact indicators in 2030. The costs of the portfolios of measures that meet these targets range from € 0.3 bn/yr to € 9.9 bn/yr for the most ambitious case.

In a further step, the temporal interactions between emission reductions that have been optimized for a more distant year (e.g., 2030) and potential interim targets for earlier years are discussed. While there are several alternatives for securing temporal consistency of targets over time to avoid regret investments, the choice of the temporal path of environmental ambitions remains a political decision, depending on the weight given to environmental improvements in the near term versus the long-term target.

All calculations presented in this report must be considered as illustrative, since they do not yet include the forthcoming final TSAP baseline scenario that will build on the latest expectations of economic development and energy use.

More information on the Internet

More information about the GAINS methodology and interactive access to input data and results is available at the Internet at http://gains.iiasa.ac.at/TSAP.

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List of acronyms

BAT	Best Available Technology
bbl	barrel of oil
boe	barrel of oil equivalent
CAFE	Clean Air For Europe Programme of the European Commission
CAPRI	Agricultural model developed by the University of Bonn
CH_4	Methane
CLRTAP	Convention on Long-range Transboundary Air Pollution
CO_2	Carbon dioxide
CCS	Carbon Capture and Storage
EC4MACS	European Consortium for Modelling Air Pollution and Climate Strategies
EMEP	European Monitoring and Evaluation Programme
ETS	Emission Trading System of the European Union for CO_2 emissions
EU	European Union
GAINS	Greenhouse gas - Air pollution Interactions and Synergies model
GDP	Gross domestic product
GHG	Greenhouse gases
IED	Industrial Emissions Directive
IIASA	International Institute for Applied Systems Analysis
IPPC	Integrated Pollution Prevention and Control (directive)
kt	kilotons = 10^3 tons
LCP	Large Combustion Plants (directive)
N_2O	Nitrous oxide
NEC	National Emission Ceilings
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
N_2O	Nitrous oxides
O_3	Ozone
PJ	Petajoule = 10^{15} joule
PM10	Fine particles with an aerodynamic diameter of less than 10 µm
PM2.5	Fine particles with an aerodynamic diameter of less than 2.5 µm
PRIMES	Energy Systems Model of the National Technical University of Athens
SNAP	Selected Nomenclature for Air Pollutants; Sector aggregation used in the CORINAIR emission inventory system
SO_2	Sulphur dioxide
TSAP	Thematic Strategy on Air Pollution
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds

1 Introduction

1.1 Scope of this report

As an input for the revision of the EU air quality legislation in 2013, TSAP Report #6 (Amann, Bertok, et al., 2012) analyzed the likely future development of air quality and resulting health and environmental impacts in Europe for the TSAP-2012 baseline emission scenarios that have been presented in TSAP Report #1 (Amann, Borken-Kleefeld, et al., 2012).

While the baseline case will lead to significant improvements in air quality, the magnitude of air pollution impacts and resulting damage will remain substantial. It is estimated that for the baseline in 2030, European population would still suffer a loss of 210 million life years and experience 18,000 yearly premature deaths from high ozone exposure. Biodiversity will remain threatened by excess nitrogen input at 900,000 km^2 of ecosystems, including 250,000 km^2 that are legally protected, inter alia as Natura2000 areas.

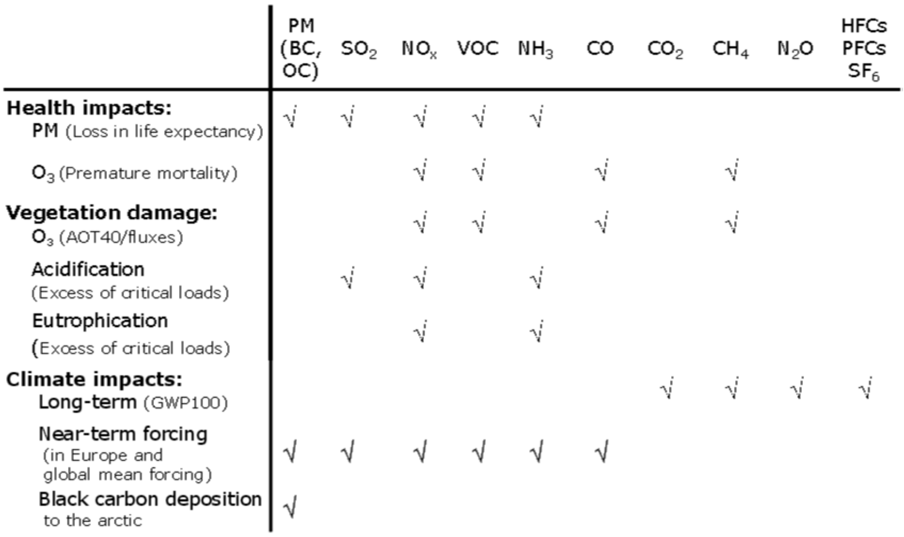
TSAP Report #6 also highlights a substantial scope for additional measures that could alleviate the remaining damage and move closer to the objectives of the Sixth Environment Action Program. By 2030, full application of readily available emission control measures in the EU could reduce health impacts from PM by another 30% and thereby gain more than 55 million life years in the EU. It could save another 3,000 premature deaths per year by lowering ozone concentrations. Further controls of agricultural emissions could protect biodiversity at another 200,000 km^2 of ecosystems against excess nitrogen deposition, including 50,000 km^2 of Natura2000 areas and other protected zones. It could eliminate almost all likely exceedances of PM10 air quality limit values in the old Member States; in the urban areas of the new Member States additional action to substitute solid fuels in the household sector with cleaner forms of energy would be required. Such Europe-wide emission controls would also resolve in 2030 all likely non-compliance cases with NO_2 limit values with the exception of a few stations in Europe, for which additional local measures (e.g., traffic restrictions, low emission zones) would be necessary.

Obviously, such additional measures will involve additional costs, which need to be balanced against their benefits. This TSAP Report #7 explores an approach for developing cost-effective scenarios for emission controls beyond current legislation.

1.2 Methodology

To identify cost-effective measures to further improve air quality in Europe, this report employs the GAINS (Greenhouse gas – Air Pollution Interactions and Synergies) model developed by the International Institute for Applied Systems Analysis (IIASA). The GAINS model (Amann et al., 2011) explores cost-effective multi-pollutant emission control strategies that meet environmental objectives on air quality impacts (on human health and ecosystems) and greenhouse gas emissions. GAINS brings together data on economic development, the structure, mitigation potentials and costs of emission sources, the formation and dispersion of pollutants in the atmosphere and an assessment of environmental impacts of pollution. The model addresses air pollution impacts on human health from fine particulate matter and ground-level ozone, vegetation damage caused by ground-level ozone, the acidification of terrestrial and aquatic ecosystems and excess nitrogen deposition to soils, in addition to the mitigation of greenhouse gas emissions. GAINS describes the interrelations between these multiple effects and the pollutants (SO_2, NO_x, PM, NMVOC, NH_3, CO_2, CH_4, N_2O, F-gases) that contribute to these effects at the European scale (Figure 1.1).

GAINS assesses, for each of the 43 countries in Europe, more than 2000 measures to control emissions to the atmosphere. It computes the atmospheric dispersion of pollutants and analyzes the costs and environmental impacts of pollution control strategies. In its optimization mode, GAINS identifies the least-cost balance of emission control measures across pollutants, economic sectors and countries that meet user-specified air quality and climate targets.



	PM (BC, OC)	SO_2	NO_x	VOC	NH_3	CO	CO_2	CH_4	N_2O	HFCs PFCs SF_6
Health impacts: PM (Loss in life expectancy)	√	√	√	√	√					
O_3 (Premature mortality)			√	√		√		√		
Vegetation damage: O_3 (AOT40/fluxes)			√	√		√		√		
Acidification (Excess of critical loads)		√	√		√					
Eutrophication (Excess of critical loads)			√		√					
Climate impacts: Long-term (GWP100)							√	√	√	√
Near-term forcing (in Europe and global mean forcing)	√	√	√	√	√	√				
Black carbon deposition to the arctic	√									

Figure 1.1: The multi-pollutant/multi-effect approach of the GAINS model to find cost-effective solutions to control air pollution and climate impacts

1.3 Access to detailed data on the Internet

A full technical documentation of the methodology of the GAINS model is available at http://gains.iiasa.ac.at/index.php/ documentation-of-model-methodology/supporting-documentation-europe.

All detailed input data and results for all Parties are accessible rom the online version of the GAINS model (http://gains.iiasa.ac.at/gains/EUN/ index.login?logout=1), Scenario Group 'TSAP_Dec12.

1.4 Structure of the report

The remainder of this report is organized as follows: Section 2 summarizes the scope for further health and environmental improvements beyond the current legislation, which has been presented in detail in TSAP Report #6. Section 3 introduces the optimization approach of the GAINS model as a tool to identify portfolios of emission reduction measures to meet targets for health and environmental improvements at least cost. It also reviews the impact indicators that are used for the optimization runs presented in this report. Section 4 discusses cost-effective emission reductions that would achieve targets for health, ozone, eutrophication and acidification separately. It then introduces optimized scenarios that achieve targets for all these effects simultaneously. For the forthcoming review and revision of the 2005 Thematic Strategy on Air Pollution, a further dimension arises from the time horizon that should be covered by the strategy. The report discusses how the interplay between targets for a longer time horizon, e.g., 2030, and interim targets could be addressed in cost-effective strategies. Conclusions are then drawn in Section 5.

2 Scope for further environmental improvements

As discussed in TSAP Report #6, there is further scope for improvements of the health and environmental impact indicators, both through end-of-pipe emission control technologies and measures that influence the levels of polluting activities. Figure 2.1 displays, for the various effects, the improvements that could be achieved through (a) further technical emission control measures applied to the TSAP-2012 baseline activity projection (based on the PRIMES 2010 Reference energy scenario), and (b) additional improvements that could be attained in the Maximum Control Efforts (MCE) scenario. The MCE scenario assumes, in addition to all end-of-pipe emission controls, strict decarbonisation policies for the energy sector and agricultural production responding to a 'healthy diet' development.

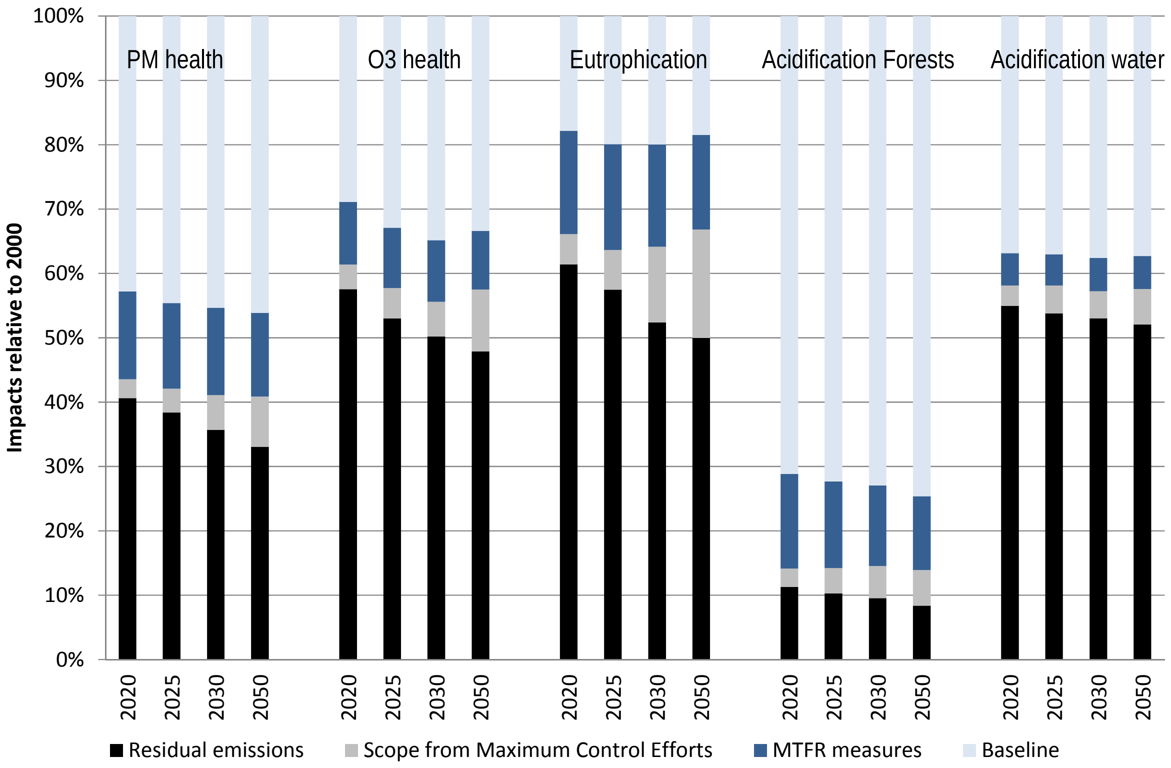


Figure 2.1: The scope for further improvement of the health and environmental impact indicators through MTFR and MCE measures.

While the MTFR scenario offers the larger potential for further environmental improvements in the near term, structural changes in activity and consumption patterns (as outlined in the MCE scenario) provide considerable additional scope for emission reductions, especially in the long-run.

With the analysis restricted to the MTFR measures, it is estimated that costs of a full application of available technical emission control measures increase from € 37 bn/yr in 2020 (0.27% of GDP) to € 53 bn/yr (0.32% of GDP) in 2030. These costs would come on top of the costs of measures that are already included in the current legislation, i.e., for the EU-28 € 84 bn/yr (0.59% of GDP) in 2020, and € 94 bn/yr (0.56% of GDP) in 2030.

Costs incurred by the MCE scenarios have not been quantified.

3 An optimization approach to determine cost-effective emission reductions

In general, additional emission abatement measures will involve additional costs, and an appropriate strategy needs to balance these costs against the benefits from such actions.

The GAINS optimization can be used to determine how emission control costs increase when the ambition for environmental improvements is gradually tightened, e.g., between the 'current legislation' baseline case (i.e., without further measures) and the implementation of all available measures.

To provide a comprehensive picture for a strategic assessment, such an analysis should explore the full range of possible improvements, i.e., in addition to the technical measures of the MTFR scenario also the changes included in the MCE scenarios. However, country details of the presently available MCE/decarbonisation scenario that has been developed for the PRIMES-2010 family of energy projections are not publicly available, and the PRIMES-2012 family of energy projections has not yet been finalized. Thus, the optimization analysis in the current report can only rely on the readily available TSAP-2012 baseline and MTFR scenarios, but cannot address the additional scope offered by modified climate and agricultural policies. Thus, the quantitative results presented in this report can only outline an illustrative way forward to identify cost-optimal steps for the improvement of air quality in Europe. Robust quantitative estimates on achievable environmental improvements, implied emission reduction costs and the distribution of costs and benefits across Member States require another round of calculations with the final set of energy and agricultural scenarios. In particular, there are indications that the new PRIMES-2012 reference scenario will result in lower levels of energy consumption and emissions as a consequence, inter alia, of less optimistic assumptions on future economic development in Europe.

It is clear that not all of the additional measures that are available are also cost-effective. The cost-effectiveness analysis of the GAINS model can identify those measures that attain a large share of the feasible environmental improvements at a fraction of the overall costs of the MTFR scenario.

3.1 Impact indicators

As different measures affect different pollutants, and different pollutants contribute to the different air quality effects to different extent, the cost-effectiveness of a given measure depends on the chosen effect.

Following the concepts that have been employed for the cost-effectiveness analyses for the 2005 Thematic Strategy on Air Pollution and, more recently, for the negotiations on the revised Gothenburg protocol, air quality impacts are represented in the GAINS optimization by the following indicators:

3.1.1 Health impacts from fine particulate matter

The scenarios analysed in this report use as a health impact indicator the 'Years of Life Lost' (YOLL), which are essentially calculated as the product of the number of people exposed times the average concentration of PM2.5 they are exposed to times the concentration/response function. These calculations account only for people older than 30 years.

Target setting and optimization employs the *European-wide* approach, in line with what was used for the TSAP and Gothenburg analyses: At the European scale, first the indicator is calculated for the baseline and MTFR scenarios. The difference between these scenarios is defined as the 'gap', i.e., the feasible space for improvements, and then a 'gap closure' procedure is applied to this gap. In particular, there are no country-specific target values, and the optimization identifies the most-cost-effective solution to reduce health impacts within Europe, independently of the country in which this would occur.

3.1.2 Eutrophication

For eutrophication, the impact indicator accumulates for all ecosystems in a country the total amount of deposited nitrogen that exceeds critical loads (AEE). The gap closure procedure then is applied to this indicator in each country separately. This means that first the AEEs are calculated for each country for the baseline and the EU-wide MTFR scenarios. The gap closure target calls for the same relative improvement of the AEE in each country. Thereby, improvements in local biodiversity are achieved in each country to avoid trading of benefits across Europe and across very different ecosystems. The AEEs are approximated as piece-wise linear functions in the GAINS model so that cost optimization calculations can be performed very efficiently.

However, following common practice to facilitate communication to the general public and decision makers, progress in ecosystems protection is reported in terms of the area of ecosystems where deposition exceeds critical loads. This indicator is calculated ex-post from the optimization results for each country.

3.1.3 Acidification

For acidification, the same concept as for eutrophication is used.

3.1.4 Ground-level ozone

Pending advice from the WHO REVIHAAP project on an improved representation of health impacts from ground-level ozone, the current analysis employs the SOMO35 (sum of daily eight-hour mean ozone over a threshold of 35 ppb) indicator as a proxy for the acute health effects of human exposure. It uses the concentration-response functions that have been used in earlier analyses for the quantification of the associations between ozone exposure and premature mortality. Based on this indicator, the gap closure concept is applied for each country, i.e., the same relative improvement (between baseline and MTFR) needs to be achieved in each country.

Damage from ground-level ozone on forest trees, semi-natural vegetation and agricultural crops will be explored in an ex-post analysis based on the ozone flux approach in cooperation with the Coordination Centre for Effects and the Working Group on Effects. Work to incorporate the quantification of vegetation damage into GAINS based on the ozone flux approach is underway and will allow in the future optimizations targeted to the protection of vegetation.

4 Cost-effective emission reduction scenarios

4.1 Optimizing for single effects

With the effect indicators discussed above, the GAINS optimization has been used to explore for each indicator separately how emission control costs increase between the current legislation baseline (no additional measures, no additional costs) and the maximum feasible improvements offered by the MTFR scenario. For 2030, the resulting relations between the 'gap closure' (between the baseline and the MTFR case) and the associated emission control costs are shown in Figure 4.1.

There is clear evidence that a subset of measures could achieve much of the maximum feasible improvements at a fraction of the costs of the MTFR case. In general, 50% of the possible health improvements could be achieved at 1-2% of the costs of the MTFR measures, and 80% can be realized at 14% of the costs of the full set of measures.

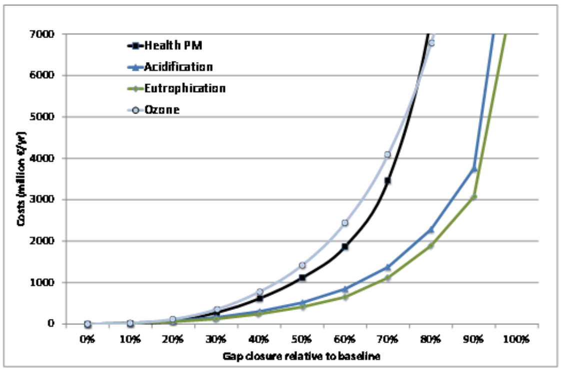


Figure 4.1: Emission control costs for single-effect optimizations that close in the year 2030 the gap between the current legislation baseline and the maximum feasible environmental improvements.

In general, emission control costs increase steepest for the lowering health impacts from ground-level ozone, followed by health impacts from fine particulate matter. For instance, a 50% gap closure for these health related targets would involve costs between € 1.0-1.4 bn/yr. Similar relative improvements for ecosystems-related impacts, i.e., eutrophication and forest acidification, are achievable at only half of the costs.

While the cost curves for ozone, acidification and eutrophication expose similar shapes as in earlier GAINS analyses (e.g., for the revision of the Gothenburg protocol), costs for improving premature mortality from fine particular matter exhibit now a steeper increase. This is caused by the recent inclusion of secondary organic aerosols in the GAINS model, which requires also cuts in VOC emissions for a reduction of ambient PM2.5 levels. Thus, in the new model approach potential reductions of ambient PM2.5 level include measures for VOC emissions, which involve additional costs.

4.2 Optimizing for multiple effects

With the earlier choices on impact indicators and the ways how to set targets across Member States, appropriate ambition levels for the individual effects and their combination into a manageable set of meaningful policy scenarios remain to be decided. Obviously, combining ambition levels for different effect categories requires political value judgment, and cannot be performed in an objective and unambiguous way by scientific models. (In principle, a strict cost-benefit analysis with full monetary quantifications of all health and environmental effects could provide a rational framework for relating ambition levels for different effects; however, in practice a precise monetary quantification of health and ecosystems benefits remains controversial.)

As a starting point, a pragmatic approach has been taken to establish three different sets of ambition levels. For simplicity, a 'low' case combines for all effects their 25% gap closure targets, the 'mid' case the 50% gap closure targets, and the 'high' case the 75% gap closure targets. The GAINS optimization will then determine the portfolios of emission controls that simultaneously meet the targets for all effects at least cost.

Table 4.1: Emission control costs in 2030 for the single effect optimization and the combined optimization for all targets simultaneously (million €/yr)

	Health PM	*Acidi-fication*	*Eutrophi-cation*	*Ozone*	*All targets combined*
Baseline	0	0	0	0	0
25% gap	158	109	86	216	372
50% gap	1069	534	431	1752	2343
75% gap	4994	1764	1477	5238	9982
MTFR	158	109	86	216	53836

Cost-effective portfolios have been identified that meet in 2030 the targets for all four indicators simultaneously. These involve costs of € 0.37 bn/yr for the low case, € 2.34 bn/yr for the mid case, and € 9.98 bn/yr for the high case (**Error! Reference source not found.**), corresponding to 0.002%, 0.014% and 0.059% of GDP.

In the low case, largest emission reductions emerge for PM2.5 and VOC (-22% and -11%, respectively), mainly from the ban of agricultural waste burning. In the mid case, emissions would be reduced by 15 -20% % below the baseline, with larger reductions for PM2.5 (-29%). For the high case, emission of all pollutants are cut by 25-35%. It is noteworthy that even in the high ambition case the cost-effective reductions involve only 70% of the total further mitigation potential for PM and VOC and 80% for NO_x and NH_3, while for SO_2 they include 90% of the total potential. Detailed results for Member States are provided in the Annex.

Table 4.2: Emissions, costs (million €/yr) and impact indicators (million YOLLs, cases of premature deaths, 100- km^2) of the optimized scenarios for the different gap closure targets for 2030

	Baseline	***Low case***	***Mid case***	***High case***	***MTFR***
		25%	*50%*	*75%*	*100%*
	kt	Change to baseline			
SO_2	2242	-3%	-16%	-32%	-36%
NO_x	4066	-6%	-15%	-23%	-29%
PM2.5	1150	-22%	-29%	-35%	-49%
NH_3	3952	-8%	-15%	-24%	-29%
VOC	5574	-11%	-18%	-28%	-40%
Costs	0	372	2343	9982	53836
% of GDP	0.000%	0.002%	0.014%	0.059%	0.320%
YOLLs	209	195	181	166	152
O_3 deaths	18788	17993	17275	16524	15786
Eutro. all	913	862	812	749	701
Eutro N2000	345	330	311	285	261
Acid forests	48	40	31	23	21
Acid N2000	15	12	10	7	7

The series of illustrative cost-effectiveness analyses presented in this report does not include a Europe-wide introduction of further controls for road vehicles in the optimization, inter alia since cost estimates for additional standards have not yet been developed. Work is underway to provide such estimates, so that in the following rounds of analyses these measures could be included in the optimization. However, the analysis includes the potential emission reductions from further measures in this sector in the MTFR scenario. Thus, this measures are considered for the calculation of the gap between baseline and MTFR, and thus for resulting gap closure targets.

Table 4.3 lists the distribution of costs across the different economic sectors for the optimization analysis that did not include further measures for road vehicles.

Table 4.3: Emission control costs in 2030 by SNAP sector of the optimized scenarios for the different gap closure targets (million €/yr)

	Low	***Mid***	***High***	***MTFR***
	25%	*50%*	*75%*	*100%*
Power generation	27	310	1540	2983
Domestic sector	45	722	2300	18463
Industrial combust.	124	445	1110	1748
Industrial processes	31	102	990	3051
Fuel extraction	5	5	173	698
Solvent use	46	409	2457	12101
Road transport	0	0	0	6529
Non-road mobile	0	0	24	1961
Waste treatment	5	10	10	10
Agriculture	89	340	1379	6293
Total EU-28	372	2343	9982	53836

In the low case, about 40% of emission control costs emerge in the industrial sector. In the mid case, the domestic sector bears the highest costs, while in the high case the domestic sector, industry and solvent use share most of the costs.

Given the shape of the cost curves shown in Figure 4.1, in each of these cases measures will be primarily driven by the targets for health impacts, as these involve highest costs. Much of the ecosystems improvements will occur then as a co-benefit of the health targets. Additional measures that would be required to fully achieve the imposed ecosystems targets will be cheap, as costs for these targets are anyway lower than those of the health endpoints.

Conversely, refined analyses could identify additional improvements for eutrophication and acidification that could be achieved at little extra cost in relation to a given gap closure target for health impacts. This is illustrated in Figure 4.2, which shows little changes in the costs of a joint cost-optimal solution for rather large changes in the ambition of eutrophication and acidification targets around the mid (50% gap closure) case. In contrast, costs of the joint solution are most sensitive towards modified ambition levels for ozone.

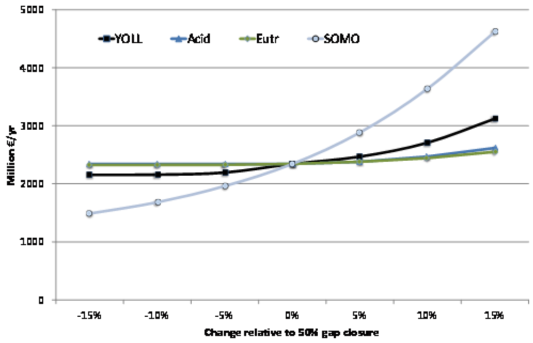


Figure 4.2 : Costs of modifying targets for individual impacts around the mid case, i.e., around a 50% gap closure target

4.3 Cost-effective emission reductions over time

Without pre-emptying a policy decision about the appropriate time horizon for emission reduction strategies, the cost-effectiveness analysis presented above addressed 2030 as a target year. Alternatively, optimization analyses could also be carried out for the nearer future, i.e., for 2020 and 2025.

However, as many of the investment decisions about further emission controls affect long-lived infrastructure, a long-term perspective will help to avoid regret investments that might turn out as in-effective in the long run.

On the other hand, a target year of 2030 is clearly beyond the typical planning cycle of governments. Meaningful interim targets that are coherent with a long-term strategy might help to guide timely investments, which are required to meet the long-term goal. Ideally, such interim targets could also outline a cost-effective pathway towards the long-term targets.

Although the current version of the GAINS model is not designed to address the full dynamics of capital vintage structures, ecological processes and demographic trends, there are various ways how GAINS analyses could inform deliberations about meaningful interim targets.

Essentially, the GAINS optimization determines, for a given set environmental targets, the least-cost constellation of the implementation rates of about 2000 discrete emission control measures in each country. Implementation rates can range from the level specified in the current legislation baseline to the maximum feasible penetration rate that is defined in the MTFR scenario (reflecting constraints on applicability, etc.). The optimal implementation rates are determined within this range for the target year for which the optimization is performed. To derive interim milestones on the way towards these targets, one could interpolate implementation rates for earlier years, starting, e.g., from current implementation rates. In this way, resulting emissions could be calculated for any point in time before the year of the original optimization.

However, there is no guarantee that such a trajectory would indeed indicate the most cost-effective way towards the long-term targets. Alternatively, one could set environmental interim targets for earlier years (in terms of effect indicators), and then perform cost-optimizations for these earlier years. A comparison of the cost-optimized implementation rates for the interim year with those optimized for the final target year should ascertain that implementation rates from these optimized scenarios are internally coherent, i.e., that they do not decline over the technical lifetime of already installed measures. Any such decline would indicate a regret investment, as once built technologies would not be operated for their full technical life time. If such cases emerged, additional constraints in the optimization problem could avoid such inconsistencies in further optimization rounds.

To this end, a first step of such an approach was made by determining cost-effective emission control strategies for gap closure targets in the year 2025. Arbitrarily, three illustrative cases have been developed for 25%, 50% and 75% closures, respectively, of the gap in 2025, for all effect indicators. However, interim targets could reflect political preferences for early or delayed progress towards the final target.

The cost-optimal emission reductions for achieving the various gap closure targets for 2025 were then compared to those for 2030 (Figure 4.3 to Figure 4.7). At least at the aggregated level, cost-optimized emission levels that meet the gap closure targets in 2030 are consistently lower than those for the corresponding gap closure targets of 2025. A possible exception occurs for ammonia emissions, where however also baseline emissions exhibit an increase during this period.

Table 4.4: Emissions, costs (million €/yr) and impact indicators of the optimized scenarios for the different gap closure targets for 2025

	Baseline	*Low*	*Mid*	*High*	*MTFR*
		%25	*50%*	*75%*	*100%*
	kt	Change to baseline			
SO_2	2403	-2%	-14%	-29%	-34%
NO_x	4751	-5%	-13%	-19%	-24%
PM2.5	1201	-21%	-28%	-34%	-46%
NH_3	3920	-8%	-15%	-23%	-29%
VOC	5710	-10%	-18%	-27%	-39%
Costs	0	356	2203	8582	48934
% of GDP	0.000%	0.002%	0.014%	0.055%	0.316%
YOLLs	216	202	188	174	160
O_3 deaths	19487	18707	18011	17276	16550
Eutro. all	929	877	832	777	723
Eutro N2000	353	330	311	285	261
Acid forests	51	42	33	26	22
Acid N2000	16	13	10	8	7

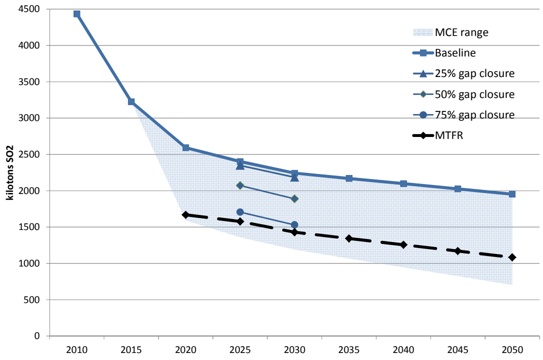


Figure 4.3: Cost-optimal SO_2 reductions in the EU-28 to meet the gap closure targets in 2025 and 2030

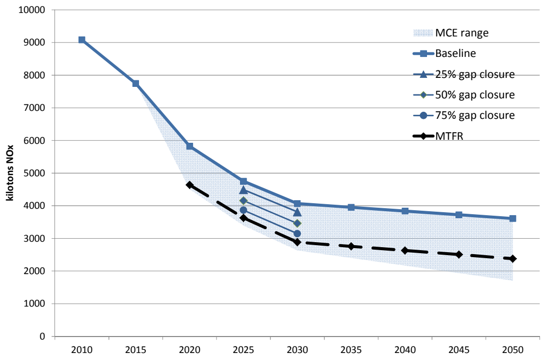


Figure 4.4: Cost-optimal NO_x reductions in the EU-28 to meet the gap closure targets in 2025 and 2030

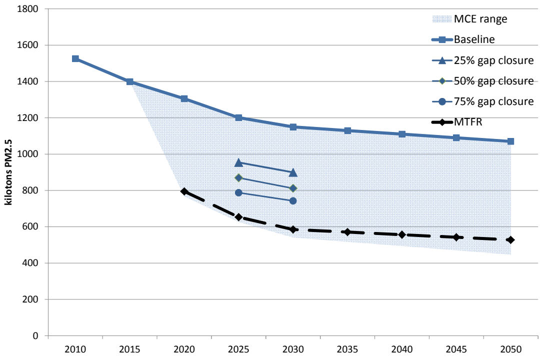


Figure 4.5: Cost-optimal PM2.5 reductions in the EU-28 to meet the gap closure targets in 2025 and 2030

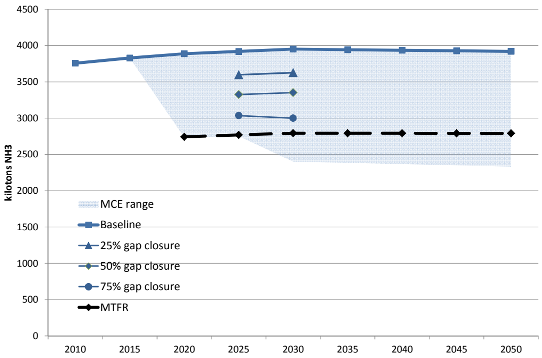


Figure 4.6: Cost-optimal NH_3 reductions in the EU-28 to meet the gap closure targets in 2025 and 2030

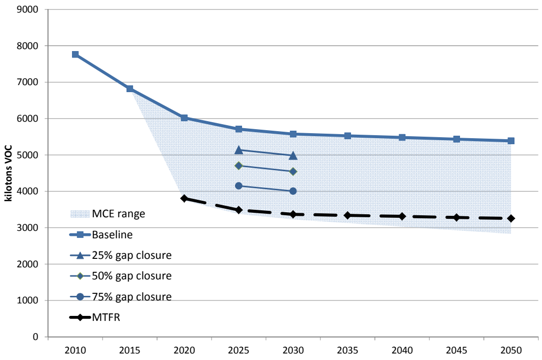


Figure 4.7: Cost-optimal VOC reductions in the EU-28 to meet the gap closure targets in 2025 and 2030

While this illustrative analysis does not reveal obvious inconsistencies for equal gap closures applied to different target years, a final analysis for politically determined combinations of the stringencies of interim and final targets will need to assess the monotony of increasing implementation rates for each measure in each Member States.

5 Conclusions

Although emissions of most air pollutants are expected to significantly decline in the coming decades, the magnitude of the remaining impacts of poor air quality on human health and ecosystems will still be substantial. Further technical and non-technical measures will be available to reduce emissions and resulting impacts below the ‘current legislation’ baseline levels. However, these additional measures come at certain costs.

It is estimated that full implementation of all available technical emission control measures would cost of € 37 bn/yr in 2020 (0.27% of GDP) and € 53 bn/yr (0.32% of GDP) in 2030. These costs would come on top of the costs for measures that are already included in the current legislation, i.e., for the EU-28 € 84 bn/yr (0.59% of GDP) in 2020, and € 94 bn/yr (0.56% of GDP) in 2030.

In addition, emissions of air pollutants and their impacts could be reduced further through climate and agricultural policies, although it is difficult to accurately estimate the net costs of such strategic changes.

As costs of additional measures are significant, their cost-effectiveness and benefits need to be carefully examined. The GAINS optimization offers a tool for a systematic analysis of the cost-effectiveness of further measures.

Continuing earlier practices employed for the cost-effectiveness analyses for the 2005 Thematic Strategy on Air Pollution and the 2012 revision of the Gothenburg protocol, the analysis adopts four types of indicators to represent different dimensions of air pollution impacts:

- For premature mortality attributable to the exposure to fine particulate matter (PM2.5), years of life lost (YOLLs) are used as metric to measure progress beyond the baseline scenario. Improvements in health effects are optimized across Europe (for the least cost solution), irrespective of the country where they are occurring.
- For health impacts caused by the exposure to ground-level ozone, the optimization uses the number of annual premature deaths as the quantitative indicator.
- For eutrophication, the optimization employs excess nitrogen deposition accumulated over all ecosystems in each country as indicator for measuring progress. However, for communication to the public, progress is reported in terms of the ecosystems area that is protected against eutrophication.
- The same concept is applied for acidification.

As a first step, an optimization has been carried out to determine for each of these endpoints the increase in emission control costs for gradually tightened ‘gap closure’ targets between the current legislation and the full application of all available technical measures. It turns out that costs increase most rapidly for improvements of health impacts (for ozone and PM), while larger improvements at comparably low costs are possible for eutrophication and acidification.

In a second step, illustrative joint optimizations for multiple targets have been conducted, aiming at arbitrarily chosen gap closure targets of 25/50/75% for all impact indicators in 2030. The costs of the portfolios of measures that meet these targets range from € 0.3 bn/yr for the low ambition case, over € 2.3 bn/yr for the mid case, up to € 9.9 bn/yr for the most ambitious case. These costs constitute only a small fraction of the costs of the full set of the technically feasible measures (€ 53.9 bn/yr). They account for 0.002% to 0.06% of GDP, while they achieve a major share of the possible environmental improvements.

In a further step, the temporal interactions between cost-effective emission reductions for different points in time are discussed. While there are several alternatives for securing temporal coherence of emission control strategies over time and thereby avoid regret investments, the choice of the temporal path of environmental ambitions remains a political decision, depending on the weight given to environmental improvements in the near term.

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Annex: Results for Member States

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Table 5.1: SO$_2$ emissions for the optimized scenarios by Member State (kilotons)

	Baseline	*Low case*	*Mid case*	*High Case*	*MTFR-EU*	*Baseline*	*Low case*	*Mid case*	*High Case*	*MTFR-EU*
			2025					2030		
Austria	18	18	17	15	15	16	16	16	14	14
Belgium	82	75	71	64	61	80	71	69	62	60
Bulgaria	92	92	89	45	44	91	90	87	43	42
Cyprus	5	5	5	5	2	5	5	5	5	2
Czech Rep.	90	89	83	80	77	81	80	74	70	68
Denmark	11	11	11	10	9	11	11	11	10	9
Estonia	14	14	14	14	11	14	14	14	13	10
Finland	34	34	34	33	29	34	33	33	32	28
France	181	174	162	124	122	173	166	154	119	118
Germany	307	305	299	280	272	281	277	270	250	241
Greece	93	93	93	68	40	82	81	81	57	36
Hungary	59	56	38	32	30	58	55	34	31	30
Ireland	25	25	21	20	18	22	21	18	16	16
Italy	165	161	144	103	93	167	162	145	99	92
Latvia	5	4	4	4	3	4	4	4	4	3
Lithuania	14	14	14	9	7	15	14	14	7	7
Luxembourg	1	1	1	1	1	1	1	1	1	1
Malta	2	1	1	1	0	1	1	1	0	0
Netherlands	46	45	40	35	33	48	47	38	35	33
Poland	412	409	313	273	259	387	384	286	254	241
Portugal	58	57	52	34	30	56	55	43	31	29
Romania	139	134	102	75	71	126	122	88	66	64
Slovakia	40	40	34	21	20	37	37	30	18	17
Slovenia	12	12	10	9	8	10	10	8	7	7
Spain	276	274	240	195	177	248	245	213	165	150
Sweden	26	26	26	26	26	26	26	26	26	26
UK	170	158	139	119	108	145	133	113	87	82
EU-27	2377	2325	2057	1695	1569	2218	2162	1875	1522	1422
Croatia	26	25	15	10	8	24	23	14	8	6
EU-28	2403	2349	2072	1706	1577	2242	2186	1889	1530	1429

Table 5.2: NO$_x$ emissions for the optimized scenarios by Member State (kilotons)

	Baseline	*Low case*	*Mid case*	*High Case*	*MTFR-EU*	*Baseline*	*Low case*	*Mid case*	*High Case*	*MTFR-EU*
			2025					2030		
Austria	76	74	69	64	60	65	64	58	55	50
Belgium	159	159	152	138	118	146	145	139	124	104
Bulgaria	69	69	60	58	56	59	58	50	48	46
Cyprus	11	10	9	8	7	9	8	7	6	6
Czech Rep.	134	122	118	108	102	111	99	97	88	82
Denmark	70	66	63	60	60	61	57	52	49	47
Estonia	19	15	14	11	11	16	13	11	9	9
Finland	101	98	95	86	83	90	86	81	73	71
France	476	449	413	388	359	412	383	350	327	295
Germany	594	585	532	504	454	495	486	437	400	370
Greece	213	210	179	173	163	188	185	152	141	129
Hungary	69	64	60	54	47	59	54	50	44	38
Ireland	61	54	50	46	43	46	39	35	31	28
Italy	564	533	512	470	482	498	472	436	395	373
Latvia	20	19	18	17	17	16	14	13	13	12
Lithuania	26	23	23	22	21	22	20	19	18	18
Luxembourg	13	13	13	12	10	9	9	9	8	7
Malta	3	3	3	3	3	2	2	2	2	2
Netherlands	154	154	154	145	120	136	136	136	128	103
Poland	392	361	353	326	311	340	314	303	274	260
Portugal	91	85	69	65	61	76	71	54	51	47
Romania	151	129	122	110	101	128	107	101	88	80
Slovakia	53	45	44	41	37	47	39	39	35	31
Slovenia	19	18	17	16	15	14	13	12	12	11
Spain	570	530	472	433	413	457	417	356	311	287
Sweden	76	75	67	65	64	70	69	61	60	57
UK	527	494	441	411	380	454	421	369	329	299
EU-27	4708	4457	4121	3835	3599	4028	3781	3431	3121	2859
Croatia	43	35	34	31	31	38	30	28	25	24
EU-28	4751	4492	4156	3865	3630	4066	3811	3459	3146	2883

Table 5.3: PM2.5 emissions for the optimized scenarios by Member State (kilotons)

	Baseline	*Low case*	*Mid case*	*High Case*	*MTFR-EU*	*Baseline*	*Low case*	*Mid case*	*High Case*	*MTFR-EU*
			2025					2030		
Austria	13	12	11	10	9	13	12	11	10	8
Belgium	21	19	18	16	15	20	19	17	15	14
Bulgaria	31	20	19	14	11	29	17	17	12	9
Cyprus	1	1	1	1	1	1	1	1	1	1
Czech Rep.	36	25	22	20	15	33	22	18	17	13
Denmark	21	18	14	13	9	20	16	13	12	7
Estonia	8	6	5	5	4	7	6	5	4	3
Finland	21	20	18	16	11	19	18	17	15	9
France	216	174	168	157	127	212	170	162	153	114
Germany	101	81	78	75	68	99	78	74	71	62
Greece	32	24	21	19	17	30	23	20	18	15
Hungary	21	17	14	13	10	20	16	12	11	9
Ireland	8	7	7	7	6	7	7	7	6	5
Italy	93	79	71	70	65	94	78	71	69	63
Latvia	13	12	10	8	5	12	10	9	7	3
Lithuania	10	6	6	5	4	9	6	6	5	3
Luxembourg	2	2	2	2	2	2	2	2	2	1
Malta	0	0	0	0	0	0	0	0	0	0
Netherlands	17	14	13	13	11	17	14	13	13	11
Poland	168	159	130	120	95	154	144	117	109	78
Portugal	56	32	32	21	17	54	30	27	19	15
Romania	101	61	56	42	28	93	54	48	37	22
Slovakia	11	10	10	8	7	11	9	9	8	6
Slovenia	5	4	3	3	2	5	4	2	2	2
Spain	101	73	67	64	55	97	70	63	60	51
Sweden	21	19	19	18	16	21	20	19	18	16
UK	60	50	46	44	41	59	49	45	43	40
EU-27	1188	946	862	782	649	1138	893	805	738	581
Croatia	12	8	7	5	4	12	7	6	4	4
EU-28	1201	954	869	787	653	1150	899	811	742	585

Table 5.4: NH_3 emissions for the optimized scenarios by Member State (kilotons)

	Baseline	*Low case*	*Mid case*	*High Case*	*MTFR-EU*	*Baseline*	*Low case*	*Mid case*	*High Case*	*MTFR-EU*
	2025					2030				
Austria	69	62	58	53	47	70	63	59	54	48
Belgium	80	78	74	69	66	81	79	75	69	67
Bulgaria	67	64	64	62	60	67	65	64	62	60
Cyprus	6	5	5	4	4	6	5	5	5	4
Czech Rep.	74	69	64	62	60	74	69	64	60	60
Denmark	57	54	51	47	44	57	54	50	49	43
Estonia	14	13	12	10	9	14	13	12	10	9
Finland	33	31	29	28	26	33	31	30	28	26
France	648	588	532	459	422	653	594	537	463	426
Germany	643	561	491	415	339	648	561	494	363	340
Greece	58	53	51	50	47	57	53	51	50	47
Hungary	75	68	64	56	54	74	68	65	54	54
Ireland	118	115	112	108	105	116	113	110	107	104
Italy	382	361	343	329	306	387	367	349	330	310
Latvia	17	16	16	15	14	18	17	16	16	15
Lithuania	51	47	43	38	33	52	47	43	39	33
Luxembourg	7	6	6	6	5	7	6	6	6	5
Malta	3	3	3	2	2	3	3	2	2	2
Netherlands	129	126	123	122	119	129	125	123	122	119
Poland	349	317	282	266	243	362	330	294	275	255
Portugal	73	67	62	56	50	74	68	63	57	51
Romania	129	122	118	112	105	127	120	115	110	102
Slovakia	43	39	39	36	32	44	40	37	33	33
Slovenia	19	18	18	17	16	19	18	18	17	16
Spain	378	335	303	271	232	377	334	302	271	232
Sweden	52	49	47	44	41	52	49	47	46	41
UK	316	303	293	277	270	319	306	294	278	272
EU-27	3889	3570	3301	3013	2751	3921	3599	3327	2977	2774
Croatia	30	27	25	22	19	31	28	26	23	20
EU-28	3920	3598	3326	3036	2770	3952	3627	3353	3000	2793

Table 5.5: VOC emissions for the optimized scenarios by Member State (kilotons)

	Baseline	*Low case*	*Mid case*	*High Case*	*MTFR-EU*	*Baseline*	*Low case*	*Mid case*	*High Case*	*MTFR-EU*
	2025					2030				
Austria	106	97	85	75	62	104	96	86	74	61
Belgium	123	116	106	92	90	124	116	105	92	89
Bulgaria	83	74	73	62	44	74	65	64	55	37
Cyprus	5	5	5	5	3	5	4	4	4	3
Czech Rep.	156	132	107	94	77	148	124	95	86	72
Denmark	69	62	55	47	38	65	59	52	45	36
Estonia	19	17	14	13	11	17	15	13	11	10
Finland	85	80	74	66	53	81	75	69	61	48
France	686	632	582	517	438	674	621	568	499	424
Germany	863	744	691	602	519	849	731	672	585	507
Greece	130	117	105	92	76	124	111	99	85	71
Hungary	94	83	68	62	49	88	78	63	58	47
Ireland	48	45	39	33	27	47	41	38	33	26
Italy	680	636	583	544	466	678	624	572	521	459
Latvia	42	37	30	24	15	38	32	27	22	14
Lithuania	44	39	39	31	22	41	36	36	30	21
Luxembourg	6	5	5	5	4	6	5	5	5	4
Malta	3	3	2	2	1	3	2	2	2	2
Netherlands	151	145	133	121	113	151	146	134	122	112
Poland	401	375	285	253	200	381	353	265	238	182
Portugal	153	136	131	113	90	150	133	128	111	88
Romania	254	209	209	149	99	239	193	189	142	91
Slovakia	50	48	47	40	30	49	47	46	38	28
Slovenia	26	25	18	14	12	24	23	15	13	11
Spain	590	538	509	454	386	586	531	502	446	380
Sweden	112	104	102	91	77	110	103	101	90	76
UK	671	584	558	506	446	664	577	552	497	437
EU-27	5649	5090	4655	4106	3450	5520	4942	4503	3967	3335
Croatia	61	50	48	44	37	54	44	41	38	33
EU-28	5710	5140	4703	4150	3487	5574	4985	4544	4005	3368