"Analysis of air pollutant emission trends for EU energy intensive industry sectors"

Specific Contract N° 090202/2022/881035/SFRA/ENV.C.4 under Framework contract FRA/C.3/ ENV/2021/OP/0017

Final Report

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Abbreviations

AAQD	...	Ambient Air Quality Directives
BAT	...	Best Available Technology
BATC	...	BAT Conclusion
BAT-AEL	...	BAT Associated Emission Level
BREF	...	BAT Reference Document
CAO	...	Clean Air Outlook
CCGT	...	Combined Cycle Gas Turbine
CCS	...	Carbon Capture and Storage
CLE	...	Current Legislation
CL	...	Critical loads
CO_2	...	Carbon dioxide
DRI	...	Direct Reduced Iron
EGD	...	European Green Deal
ELV	...	Emission Limit Values
E-PRTR	...	European Pollutant Release and Transfer Register
ESP	...	Electrostatic Precipitator
FGD	...	Flue Gas Desulphurization
GAINS	...	Greenhouse Gas – Air Pollution Interactions and Synergies Model
GHG	...	Greenhouse gas(es)
HFO	...	Heavy Fuel Oil
IA	...	Impact Assessment
IED	...	Industrial Emissions Directive
IGCC	...	Integrated Gasification Combined Cycle power plant
LCP	...	Large Combustion Plant
MCP	...	Medium Combustion Plant
MS	...	EU Member States
MTFR	...	Maximum Technically Feasible Reduction
NH_3	...	Ammonia
NH_4	...	Ammonium
NGCC	...	Natural Gas Combined Cycle power plant
NMVOC	...	Non-Methane Volatile Organic Compounds
NO_x	...	Nitrogen oxides (NO, NO_2)
O_3	...	Ozone
OCGT	...	Open Cycle Gas Turbine
PM	...	Particulate Matter
PRIMES	...	Price-Induced Market Equilibrium System
PVC	...	Polyvinylchloride
SCR	...	Selective Catalytic Reduction
SO_2	...	Sulphur Dioxide
TSP	...	Total Suspended Particulate Matter
VOC	...	Volatile Organic Compounds (identical to NMVOC in the figures)

1. Introduction

1.1. This report

This is the Final report for Specific Contract N° 090202/2022/881035/SFRA/ENV.C.4 - “Analysis of air pollutant emission trends towards 2050 for EU energy intensive industry sectors”. It summarizes outputs of the Task 1 and Task 2 of the project as outlined in the Inception report (approved by the European Commission DG Env on 2 December 2022), while taking into account conclusions from the project meetings held on 20 December 2022, 20 March, 31 May and 21 June 2023.

1.2. Purpose of project

The purpose of this study is to support the European Commission in the analysis of the air pollutant emission trends from the energy intensive industry sectors in the EU, with a specific focus on the installations covered by the Industrial Emissions Directive (IED)[1]. The emission trends towards 2050 are evaluated under a Baseline and Maximum Technically Feasible Reduction (MTFR) scenario. The analysis allows for an improved understanding of the main drivers behind the air pollutant trends, including macroeconomic and sectoral development of activities as well as assumptions and methodologies used to assess implementation of technology to comply with the existing legislation and available further mitigation potential in the context of planned revisions to the IED[2]. Outputs from this analysis contribute to an improved understanding and better assessment of implications for further policy action to ensure maximized co-benefits from low-carbon transition and air quality improvements.

To address the specific objectives of the study, the outputs include:

Task 1

- Emission trends of SO_2, NO_x, $PM_{2.5}$ and NMVOC projected for the years 2020-2050 in 5-year steps, for each Member State (MS) and at EU level, covering specific sectors under the scope of the IED. These trends are provided for both the Baseline and the MTFR scenario.
- An embedding of the IED sector emissions in the overall air pollutant emission trends including other (non-IED) sectors in the MS and at EU level.

Task 2

- Analysis of the drivers behind the emission trends for the sectors under the scope of the IED, description of the technical assumptions in the modelling framework of the emission control measures including how they relate to the relevant BAT associated emission levels (BAT-AELs), their uptake level, reduction effectiveness and costs, as well as the role of emerging technologies.
- Summary of essential assumptions in generating the scenarios, key sensitivities of the results, and presentation of the findings.

1.3. Policy context

This study is carried out in a specific policy context in the areas of climate mitigation and air pollution control. Therefore, the IED emission projections are analysed here not only in the context of an increased stringency of emission standards but also in the context of likely innovation and radical changes to relevant production systems induced by climate mitigation and wider pollution

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[1] Directive 2010/75/EU of the European parliament and of the Council of 24 November 2010 on industrial emissions.

[2] Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/75/EU. COM/2022/156 final

reduction objectives, and the associated environmental implications this may have. The key EU legislative framework includes:

European Green Deal

The European Green Deal (EGD)[3], approved in 2020, is a set of policy initiatives by the Commission with the goal of making the EU climate neutral by 2050. To support industry towards climate neutrality, the modernisation and decarbonisation of energy-intensive industries is a top priority[4]. This goal is complemented by zero pollution ambition for 2050 'a Healthy Planet for All'. The EGD calls, inter alia, for the EU to better monitor, report, prevent and remedy air, water, soil and consumer products pollution. Air, water and soil pollution should be reduced to levels no longer considered harmful to health and natural ecosystems and that respect the boundaries our planet can cope with. Thus, the EGD has to be seen as integrating climate with broader environmental objectives.

Fit for 55 package

In July 2021, the European Commission adopted a set of proposals (Fit for 55 package) to make the EU's climate, energy, land use, transport and taxation policies fit for reducing net greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels[5]. The package responds to the assessment that without further action and innovation neither the EU's 2030 reduction target nor the goal of becoming climate neutral by 2050 will be reached. Reduction rates need to be increased relative to what was projected until then.

The energy-intensive industries play an important role in the transition towards carbon neutrality, first because their contribution to emissions is significant and without deep emission cuts in these sectors the overall goals and targets cannot be achieved. And second, these industries will need to be the drivers of innovation and modernization of energy technologies and systems that will allow other sectors to achieve their decarbonization goals as well. Major changes will need to be made in the way industry consumes energy and produces its products. New technologies and prototypes for reconfiguring the industrial sectors are already on the horizon, and their potential impact on the environment also needs to be evaluated.

Industrial Emissions Directive

The Industrial Emissions Directive (IED)[6] regulates the pollutant emissions from over 52 000 of the largest EU high-pollution-risk industrial installations and livestock farms. The IED makes the granting of permits for industrial installations conditional on an installation complying with the best available techniques (BAT). In 2020 the Commission concluded that the IED was generally effective in controlling air pollution from industrial activities, and in promoting the use of BAT. However, a number of areas for improvement were identified including the fact that air pollutant emissions from IED installations are still substantial and could be further lowered to reduced adverse environmental impacts. Under the IED, emission limit values are set in permit conditions based on BAT-associated emission levels (AELs) (a numerical range of emission levels based on what is technically achievable for a range of installations). Reviews of permit conditions[7] to inform the revision of the IED found that ELVs were set based on the upper range of the BAT-AEL range in 75-85% of cases (i.e., the lowest ambition level for environmental protection) and resulted in an under-

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[3] COM(2019) 640 final

[4] Communication from the Commission (COM(2020)102). A new industrial strategy for Europe.

[5] COM(2021) 550 final

[6] Directive 2010/75/EU of the European parliament and of the Council of 24 November 2010 on industrial emissions

[7] Eunomia Research & Consulting (2019), "An Assessment of IED Permitting Stringency"

delivery of emission reductions. Moreover, the reviews concluded that the use of Article 18 when setting permit conditions is low.

On 5 April 2022, the Commission adopted proposals[8] for revised EU measures to address pollution from large industrial installations, which concerns the revision of the IED and the revision of the E-PRTR Regulation (to create the Industrial Emissions Portal). One of the goals is to harmonize the IED with climate, energy and circular economy policies. This is based on the insight that emerging technologies and alternative production processes will reduce emissions of greenhouse gases and air pollutants, i.e., offering synergies between multiple policy objectives. Among the proposed changes, the revision of the IED aims to ensure that the whole range of BAT-AELs is used, and that by default ELVs should be set based on the lower range of BAT-AEL to demonstrate the best performance the installation can achieve, unless evidence is provided to justify a less strict ELV[2]. The proposed changes also seek to adapt the permitting process to better support GHG abatement measures to maximise energy efficiency and minimise energy consumption, particularly in energy-intensive installations.

In parallel, the EU is in the process of revising the overall EU legislation on air quality[9], i.e., revision of the Ambient Air Quality Directives (AAQD)[10] (announced under the umbrella of the Zero pollution ambition of the EGD) aims at the closer alignment of the EU air quality standards with the recommendations of the World Health Organization[11]. The Commission also continues to monitor and analyse the prospects for reducing air pollution in the EU with a series of Clean Air Outlooks[12].

Implications for this study

The policy context thus requires evaluating the industrial emission projections in the view of a) the IED and wider legislation addressing emissions of toxic pollutants, and b) within the broader fields of technology innovation and decarbonization driven by the overarching climate neutrality goal. This has implications for how to examine the potential interactions between reducing greenhouse gas and other air pollutant emissions. The success of the decarbonization strategies is crucial, yet emission standards and BAT provisions of a (revised) IED can effectively complement the carbon mitigation goals for energy systems and production processes.

1.4. Scope of the study

This study focuses on the energy intensive industrial sectors that are subject to the IED, for which emissions of SO_2, NO_x, $PM_{2.5}$, and NMVOC are estimated for the period until 2050. Thus, taking as a starting point Annex I IED activities, the sectors covered in this study are listed in Table 1-1 and elaborated further in Annex I (Table 6-1). The scope has been further determined by data limitations identified when assessing comparability of IED Annex I activities with GAINS activities/sectors (e.g., whether it is covered as part of an aggregate or not). Findings from this assessment and sectoral mapping are presented in Table 2-1. Note that specific activities regulated by IED Chapter V special provisions for solvent use (and the corresponding ELVs set in IED Annex VII) are not in the scope of detailed analysis in this work. Rather, the study focuses on the IED activities 2.6 and 6.7 (surface

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[8] Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. COM/2022/156 final

[9] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12677-Revision-of-EU-Ambient-Air-Quality-legislation

[10] https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en

[11] WHO (2021) WHO Global Air Quality Guidelines. https://apps.who.int/iris/handle/10665/345329

[12] https://europa.eu/!Q7XXWT.

treatment activities) for solvents use (and emissions of NMVOC). Limitations regarding the mapping of GAINS activities with IED Chapter V special provisions for solvent use are presented in Table 2-1.

The contribution of these sectors to current and future total MS emission levels is quantified using the GAINS[13] modelling framework described in Section 2.1.1. In Task 1 of this study, two scenarios are analysed - Baseline and the MTFR, both of which reflect the provisions of the EGD and Fit for 55 package[14], and of which the activity projections have been developed by the PRIMES model. The Baseline scenario is broadly consistent with the baseline used in the AAQD impact assessment (IA)[15], however, it includes further revisions introduced during the work in support of the third Clean Air Outlook (CAO3)[16], especially considerations from the consultations with MS held during CAO3 assessment and the proposal to revise the IED with respect to agriculture. The difference between scenarios underlying the CAO3 and AAQD IA are explained in the CAO3 support study[17] and summarized in the Annex of CAO3 COM report[18].

In summary, and as agreed during the inception phase of this project, the Baseline includes representation of the current legislation adopted in the EU (and national legislation that goes beyond, where relevant). In addition, the Baseline assumptions take into account the IED revisions for the agriculture sector that were considered under the CAO3 assessment. Because the implications of the proposals adopted by the Commission for revision of the IED (April 2022)[8] for the energy intensive industries are highly uncertain at this stage, the revised IED and its potential impacts for the projected emission levels is considered in this study in the qualitative terms in the commentary associated with the modelling findings and potential changes to industrial activities in scope of a revised IED are not modelled. Further, the Baseline does not include any further measures that would be necessary to achieve the recently proposed revision of the AAQD.

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[13] http://gains.iiasa.ac.at/models/gains_resources.html

[14] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (2021) 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. COM/2021/550 final. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:550:FIN

[15] Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ambient air quality and cleaner air for Europe (recast). COM/2022/542 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A542%3AFIN#footnote9

[16] Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (2022) The Third Clean Air Outlook. COM/2022/673 final EUR-Lex - 52022DC0673R(01) - EN - EUR-Lex (europa.eu)

[17] Support to the development of the third Clean Air Outlook Specific Agreement 13 under Framework Contract ENV.C.3/FRA/2017/0012 - Final Report (https://circabc.europa.eu/ui/group/cd69a4b9-1a68-4d6c-9c48-77c0399f225d/library/4f014b48-eb5a-417c-88f2-abe6bb0abdc3/details)

[18] Support to the development of the third Clean Air Outlook Specific Agreement 13 under Framework Contract ENV.C.3/FRA/2017/0012 - Annex to the Final Report (https://circabc.europa.eu/ui/group/cd69a4b9-1a68-4d6c-9c48-77c0399f225d/library/04023caa-eee9-4ec3-9200-b9e9b40183ce/details)

Table 1-1: Overview of the scope of this study

nr	*IED activity*	*covered in this analysis*	*pollutants*	*scenarios*	*timeframe*
1	**Energy industries**			**Baseline** **MTFR**	**2020-2050** **2030-2050**
1.1	Combustion	x	SO2, NOx, PM2.5		
1.2	Refining	x	SO2, NOx, PM2.5		
1.3	Production of coke	x	SO2, NOx, PM2.5		
1.4	Gasification or liquefaction	part of aggregate	NMVOC		
2	**Metals production and processing**				
2.1	Metal ore	x	SO2, NOx, PM2.5		
2.2	Pig iron or steel	x	SO2, NOx, PM2.5		
2.3	Processing of ferrous metals	x	SO2, NOx, PM2.5		
2.4	Ferrous metals foundries	x	SO2, NOx, PM2.5		
2.5	Non-ferrous metals	x	SO2, NOx, PM2.5		
2.6	Surface treatment of metals or plastic	x	NMVOC		
3	**Mineral industries**				
3.1	Cement, lime and magnesium oxide	x	SO2, NOx, PM2.5		
3.2	Asbestos	part of aggregate	SO2, NOx, PM2.5		
3.3	Glass	x	SO2, NOx, PM2.5		
3.4	Mineral fibres	part of aggregate	SO2, NOx, PM2.5		
3.5	Ceramic products	part of aggregate	SO2, NOx, PM2.5		
4	**Chemicals industries**				
4.1	Organic	x	NMVOC		
4.2	Inorganic	x	NMVOC		
4.3	Phosphorus-, nitrogen- or potassium-based fertilisers	x	SO2, NOx, PM2.5		
4.4	Plant protection products	part of aggregate	NMVOC		
4.5	Pharmaceutical products	x	NMVOC		
4.6	Explosives	part of aggregate	NMVOC		
5	**Waste industries**				
5.2	(Co-) incineration of waste	part of aggregate	SO2, NOx, PM2.5		
6	**Other activities**				
6.1	Pulp, paper, or wood-based products	x	SO2, NOx, PM2.5		
6.2	Textiles pre-treatment or dyeing	part of aggregate	NMVOC		
6.3	Tanning	part of aggregate	NMVOC		
6.7	Surface treatment	part of aggregate	NMVOC		
6.10	Preservation of wood and wood products	x	NMVOC		

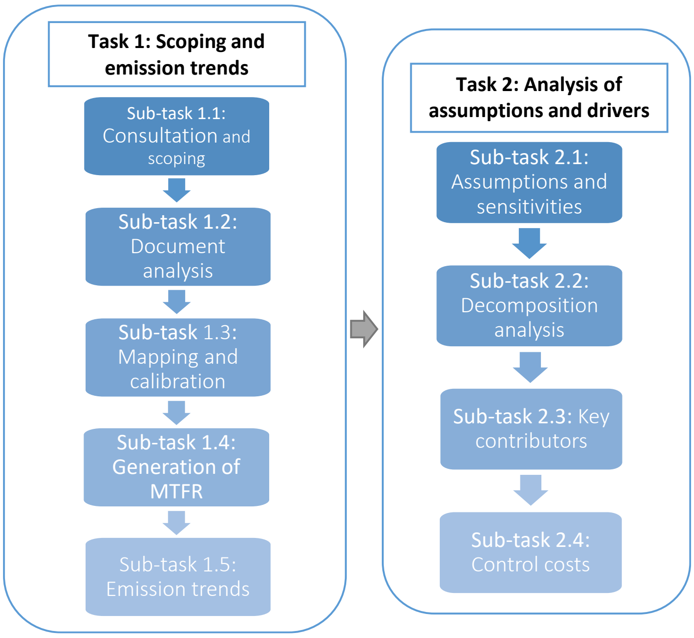
NOTE: orange fields refer to fugitive NMVOC sources not analyzed in detail; combustion emissions from boilers in chemical industries are included (as agreed during progress meetings); see Annex I (Table 6-1) for additional details about sectoral coverage and omissions from other activities.

2. Methodology

2.1. Task 1: Scoping and emission trends

Within this task the projections of air pollutant emissions in the EU towards 2050 have been developed, with a focus on the energy intensive industries under the scope of the IED. Task 1 is split into 5 sub-tasks, the first of which has comprised consultation with the Commission on the exact scoping of the analysis (Task 1.1 is not reported in this report). Task 1.2 involves a) the analysis of relevant documents pertaining to the IED and b) comparison and analysis of legislative drivers and their coverage in the modelling framework. Task 1.3 translates the information collected in Task 1.2 into inputs that are used in the GAINS model. The MTFR scenario for the period 2030-2050 is developed within Task 1.4. Finally, Task 1.5 includes calculation of emission trends towards 2050 for all relevant air pollutants by country and scenario. Results from this task serve as input to the analysis carried out in Task 2. Relations between individual tasks are depicted in Figure 2-1.

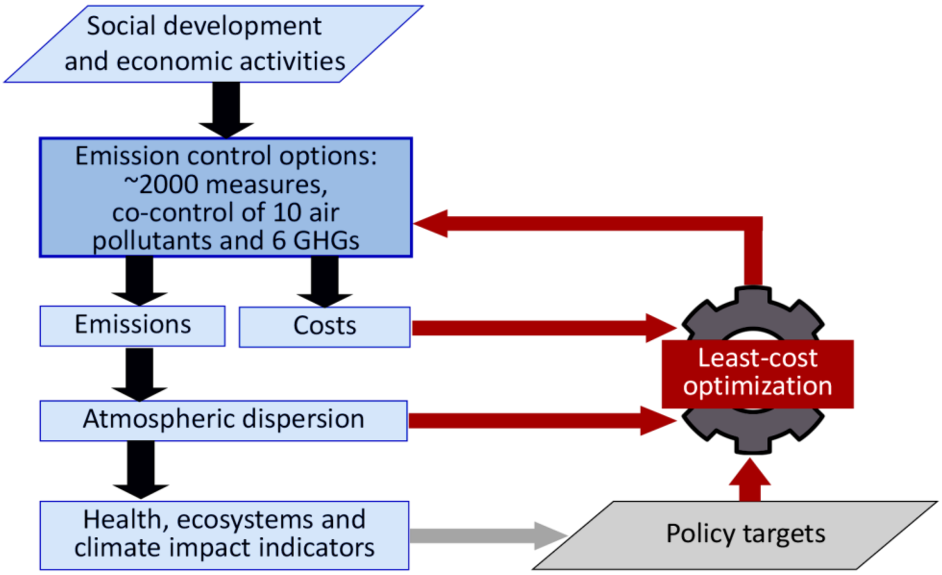
Figure 2-1 Overview flow of sub-tasks under Task 1 and Task 2.



2.1.1 The GAINS modelling framework

The GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) model explores cost-effective multi-pollutant emission control strategies that meet environmental objectives on air quality impacts (on human health and ecosystems) and greenhouse gases. GAINS brings together data on economic development, the structure, control potential and costs of emission sources, the formation and dispersion of pollutants in the atmosphere and an assessment of environmental impacts of pollution (Figure 2-2). The model incorporates databases on energy consumption for each MS, distinguishing about 30 categories of fuels used in relevant economic sectors, and explores for each of the source regions and sectors the effectiveness of more than 2000 measures to control emissions to the atmosphere. The time horizon extends from the year 1990 up to the year 2070.

Figure 2-2 Schematic flowchart of the GAINS model framework.



The model calculates present and future sectoral emissions as a product of activity level (e.g., fuel consumption) and an emission factor. “Raw-gas” unabated emission factors depend on production and combustion technology and for combustion sources also on several fuel quality parameters such as sulphur and ash content of fuels and their calorific values. The abated emission factors account for a removal efficiency of abatement technologies and are used to calculate emissions while considering an application rate of control options over time. Fuel categories in GAINS comprise combustible fuels (coal of different grades, oil products and liquid fuels, natural gas and derived gases, biomass and wastes, hydrogen) and non-combustible fuels (renewables, nuclear, electricity, heat).

The energy and industrial sectors covered in this study include power plants of different characteristics (e.g., subcritical, supercritical, IGCC, with CCS, NGCC), fuel conversion in refineries, industrial furnaces and boilers (split into fuel use for ferrous/non-ferrous metals production, mineral industries, chemicals, paper and pulp production, etc.). Finally, process emissions from industrial activities (iron and steel making, metal smelting, cement kilns, non-metallic products, pulping and others) are calculated based on production levels.

Technologies and measures in GAINS to control emissions from the IED sectors (as well as non-IED sectors) include options ranging from fuel quality upgrades (e.g., low sulphur fuels), combustion modification, to a variety of the flue gas treatments (e.g., Flue Gas Desulphurization, Selective Catalytic Reduction, Electrostatic Precipitators, Fabric Filters, etc.). In the GAINS methodology, the evolution of application rates of control technologies over the modelling period constitutes a scenario-specific control strategy. In technical terms, a control strategy describes which of the emission control options is assumed for a given fuel/sector combination and specifies share of the total capacity (percent of fuel use) to which it is applied. Control strategies are used to simulate the impact of legislation and policies on emissions of a given sector and eventually for each MS or at the EU level. Such emission control strategies are combined in GAINS with a selected activity (energy, agriculture, waste, etc) pathway to form an emission scenario, for which the human health and environmental impacts can then be estimated and further analysed.

In this work, the **Baseline** represents the ‘current legislation’ (CLE) emission scenario, which describes for each MS the expected temporal penetration of the various emission control measures

(BATs) for individual sectors to comply with the applicable legislation. The choice and application level of specific control options, included in the GAINS model, is determined by:

(i) comparing the emission limit values (ELV) specified in legislation and performance of model technologies so that they are achieved for the comparable source-sectors,

(ii) consultations with the MS experts where national emission reporting and experience in actual implementation and performance of measures is discussed and compared to the results of the GAINS model; such consultations between the GAINS team and the MS experts have been carried out several times in the past linked to work on the EU NEC Directive, UNECE Air Convention Gothenburg Protocol, and most recently during the work on CAO3,

(iii) consideration of the differences in the source structure in the model vs sources distinguished in the legislation, including IED. These differences are typically due to age and size distribution, aggregation of several small sources into one category in the model, consideration of fugitive emissions, which are not necessarily considered in the ELVs. An illustration of such differences and more detailed evaluation of mapping of IED Annex I and GAINS sectors is provided in Table 2-1.

The **MTFR scenario**, developed for the period 2030 to 2050, adopts a control strategy assuming full implementation of the most efficient control options while respecting sector, technology, and region-specific application constraints. Such constraints would include technical lifetime of technologies (i.e., no premature/early scrapping of existing capital stock or capacities is allowed in the model), practical limitations of installing or using technology in a given sector or country/region, an example for the latter would include measures in agriculture where stony soils or steep slope fields would not allow to use certain machinery. Typically, considering all these constraints, the potential for further mitigation increases over time as there are less barriers in the longer-term perspective.

2.1.2 Activity projections for IED sectors

Projections of economic activities that underlie calculation of current and future emissions are mainly exogenous inputs to GAINS. In this assessment, the activity projections for the key IED sectors originate from the PRIMES energy systems model (Box 1), which has been used as a tool to develop energy systems scenarios for each MS within the Fit for 55 package process. More specifically we use the ‘MIX 55’ energy scenario developed by PRIMES that the Commission has analysed in recent years in the context of the EGD as well as in the context of air pollution regulations (AAQD, CAO3)[19]. The implementation of the PRIMES energy scenarios in GAINS makes use of a data exchange interface which translates the outputs of the PRIMES model runs into the GAINS data structure. The activity data transferred between the models include detailed energy balances, production volumes by industries, as well macro-economic projections such as GDP and sectoral value added. Some of the specific activity projections used in GAINS for computing emissions (e.g., waste generation, NMVOC-sources) are derived from the PRIMES data by applying trends for selected macroeconomic indicators.

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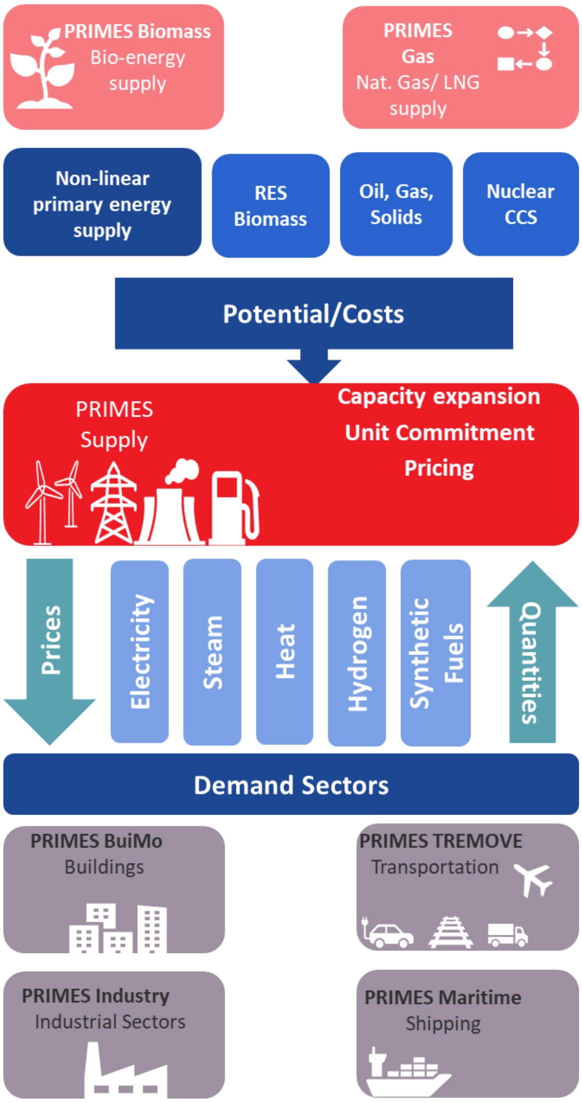
[19] https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en

Box 1: the PRIMES model

The PRIMES (Price-Induced Market Equilibrium System) is a large-scale applied energy system model that provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions. The distinctive feature of PRIMES is the combination of behavioural modelling (following a micro-economic foundation) with engineering aspects, covering all energy sectors and markets. The model has a detailed representation of policy instruments related to energy markets and climate, including market drivers, standards, and targets by sector or overall (over the entire system). It handles multiple policy objectives, such as GHG emission reductions, energy efficiency and renewable energy targets, and also provides a pan-European simulation of internal markets for electricity and gas.

PRIMES offers the possibility of handling market distortions, barriers to rational decisions, behaviours, as well as market coordination issues, and includes a complete accounting of costs (CAPEX and OPEX) and investment expenditure on infrastructure needs. PRIMES is designed to analyse complex interactions within the energy system in a multiple agent – multiple markets framework.

Decisions by agents are formulated based on a microeconomic foundation (utility maximization, cost minimization and market equilibrium) embedding engineering constraints, behavioural elements and an explicit representation of technologies and vintages and optionally perfect or imperfect foresight for the modelling of investments in all sectors. PRIMES is well-placed to simulate medium and long-term transformations of the energy system (rather than short-term ones) and includes non-linear formulation of potentials by type (resources, sites, acceptability etc.) and technology learning.



2.1.3 Task 1.2: Analysis of relevant documents

To examine how the Baseline scenario used in this study captures implementation of the BAT Conclusions under the IED, a mapping exercise was undertaken to link relevant BAT-AEL to GAINS activities. To do this, IED Annex I activities were first mapped to GAINS activities and sectors. The results of this mapping are presented in Table 2-1 together with a brief description of limitations. Note that the focus of this exercise was IED Annex I activities (so as to align with corresponding BAT-AEL). Accordingly, the mapping does not cover the special provisions of the IED which was found to have implications for a limited number of GAINS activities (explained in Table 2-1). As a result of this exercise several gaps have been logged, where an IED activity is not explicitly represented by a corresponding GAINS activity – note also the discussion in previous section on how the legislation is reflected in the GAINS model considering among other ELVs and information from consultations with MS experts.

A further step was undertaken to reflect on potential revisions to the IED. The following activities are noted as being potentially in scope of the IED in future years and not currently captured by GAINS: manufacture of Li-ion batteries, and extraction and treatment of non-energy minerals. It is noted, however, that the emissions (primarily coarse particulate matter; PM>2.5 µm) from (non-coal) mining activities are included in an aggregated GAINS sector 'Other mining: bauxite, copper, iron ore, other'.

Table 2-1: Mapping of IED Annex I activities to GAINS activities and the associated limitations

IED Annex I activity*	GAINS activity	Limitations
1.1 Combustion of fuels in installations with a total rated thermal input of 50 MW or more	• Fuel production & conversion other than in power plants: Combustion • Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal • Industry: other sectors; combustion of brown coal/lignite and hard coal in large boilers (>50 MWth) • Industry: other combustion (all sectors) except fuel consumption in mineral products industry (used only for emissions calculations) • Power & district heat plants with internal combustion engines • Power & district heat plants, new; coal/lignite fired (> 50 MWth) • Power & district heat plants existing, non-coal; for GAS - boilers • Modern power plants (coal: ultra- and supercritical; gas: CCGT) • Power & district heat plants new, non-coal; for GAS - turbines	• GAINS does not distinguish between total rated thermal input
1.2 Refining of mineral oil and gas	• Crude oil and other products - input to refineries • Waste: Flaring in gas and oil industry • Steam cracking (ethylene and propylene production)	• Flaring is only practised in emergency
1.3 Production of coke	• Ind. Process: Coke oven • Storage and handling: Coal	• None identified
2.1 Metal ore (including sulphide ore) roasting or sintering	• Ind. Process: Agglomeration plant - sinter • Ind. Process: Agglomeration plant - sinter (fugitive) • Ind. Process: Agglomeration plant - pellets	• None identified
2.2 Production of pig iron or steel (primary or secondary fusion) including continuous casting, with a capacity exceeding 2,5 tonnes per hour	• Ind. Process: Pig iron, blast furnace • Ind. Process: Basic oxygen furnace • Ind. Process: Cast iron (grey iron foundries) • Ind. Process: Cast iron (grey iron foundries) (fugitive) • Ind. Process: Electric arc furnace • Ind. Process: Pig iron, blast furnace (fugitive) • Ind. Process: Open hearth furnace • Storage and handling: Iron ore	• GAINS does not distinguish between plants with different production capacity
2.5.a Production of non-ferrous crude metals from ore, concentrates or	• Ind. Process: Other non-ferrous metals prod. - primary and secondary • Ind. Process: Aluminium production - primary	• GAINS covers general activities related to production and

IED Annex I activity*	GAINS activity	Limitations
secondary raw materials by metallurgical, chemical or electrolytic processes		processing of non-ferrous metals that do not correlate precisely with IED Annex I • GAINS does not distinguish between plants with different production capacity •
2.5.b Smelting, including the alloyage, of non-ferrous metals, including recovered products and operation of non-ferrous metal foundries, with a melting capacity exceeding 4 tonnes per day for lead and cadmium or 20 tonnes per day for all other metals	• Ind. Process: Other non-ferrous metals prod. - primary and secondary • Ind. Process: Aluminum production - secondary	• GAINS does not distinguish between plants with different production capacity
3.1.a Production of cement clinker in rotary kilns with a production capacity exceeding 500 tonnes per day or in other kilns with a production capacity exceeding 50 tonnes per day	• Ind. Process: Cement production • Storage and handling: Other industrial products (cement, bauxite, coke)	• • GAINS does not distinguish between plants with different production capacity
3.1.b Production of lime in kilns with a production capacity exceeding 50 tonnes per day	• Ind. Process: Lime production	• GAINS does not distinguish between plants with different production capacity
3.1.c Production of magnesium oxide in kilns with a production capacity exceeding 50 tonnes per day.	• Magnesium production and casting	• Emissions from this sector are aggregated in the GAINS category Ind. Process: Production of glass fibre, gypsum, PVC, other. The same applies to the IED activity 3.2
3.3 Manufacture of glass including glass fibre with a melting capacity exceeding 20 tonnes per day	• Ind. Process: Glass production (flat, blown, container glass) • Ind. Process: Production of glass fibre, gypsum, PVC, other	• GAINS does not distinguish between plants with different production capacity

IED Annex I activity*	GAINS activity	Limitations
3.5 Manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain with a production capacity exceeding 75 tonnes per day and/or with a kiln capacity exceeding 4 m3 and with a setting density per kiln exceeding 300 kg/m3	• Ind. Process: Brick production	• GAINS does not distinguish between plants with different production capacity • GAINS does not cover ceramic production more generally
4.1 Production of organic chemicals	• Organic chemical industry, storage • Synthetic rubber production	• IED covers production of organic chemicals more broadly than GAINS
4.2 Production of inorganic chemicals	• Ind. Process: Nitric acid • Ind. Process: Sulfuric acid	• IED covers production of organic chemicals more broadly than GAINS
4.3 Production of phosphorous-, nitrogen- or potassium-based fertilisers (simple or compound fertilisers)	• Ind. Process: Fertilizer production • Storage and handling: N, P, K fertilizers	• IED covers production as well as well storage and handling
4.5 Production of pharmaceutical products including intermediates	• Pharmaceutical industry	• None identified
5 Waste management	• Waste treatment and disposal	• None identified
6.1.a Production of pulp from timber or other fibrous materials; and 6.1.b Production of paper or card board with a production capacity exceeding 20 tonnes per day	• Ind. Process: Paper pulp mills	• GAINS does not distinguish between plants with different production capacity (for paper and card) • Wood based panels not covered by GAINS (IED 6.1.c)
6.3 Tanning of hides and skins where the treatment capacity exceeds 12 tonnes of finished products per day	• Leather coating • Manufacturing of shoes	• GAINS does not distinguish between plants with different production capacity

IED Annex I activity*	GAINS activity	Limitations
6.4.b Treatment and processing, other than exclusively packaging, of raw materials intended for the production of food or feed	• Food and drink industry • Fat, edible and non-edible oil extraction	• GAINS does not distinguish between plants with different production capacity • IED covers broader range of food and feed products than GAINS
6.7 Surface treatment of substances, objects or products using organic solvents, in particular for dressing, printing, coating, degreasing, waterproofing, sizing, painting, cleaning or impregnating, with an organic solvent consumption capacity of more than 150 kg per hour or more than 200 tonnes per year	• Industrial application of adhesives (use of high-performance solvent based adhesives) • Industrial application of adhesives (use of traditional solvent based adhesives) • Winding wire coating • Coating • Printing, offset** • Printing, offset, new installations • Flexography and rotogravure in packaging** • Rotogravure in publication** • Screen printing** • Industrial paint applications - General industry (continuous processes) • Industrial paint applications - General industry • Industrial paint applications - General industry (plastic parts) • Vehicle refinishing** • Coil coating (coating of aluminum and steel) • Degreasing**	• GAINS does not distinguish between plants with different production capacity
6.8 Production of carbon	• Ind. Process: Carbon black production	• None identified
6.10 Preservation of wood and wood products with chemicals with a production capacity exceeding 75 m3 per day other than exclusively treating against sapstain	• Wood coating • Wood preservation (not creosote)	• GAINS does not distinguish between plants with different production capacity
n/a (not mapped)	• Storage and handling: Agricultural products (crops) • Polystyrene processing • Products incorporating solvents	• For the main part, the excluded GAINS activities in this category do not map to IED activities.

IED Annex I activity*	GAINS activity	Limitations
	• Industry: other sectors; combustion of brown coal/lignite and hard coal in small boilers (< 50 MWth) • Power & district heat plants, existing; coal/lignite fired (< 50 MWth) • Construction activities • Mining: Brown coal • Mining: Hard coal • Industrial Process: Briquettes production • Mining: Bauxite, copper, iron ore, zinc ore, manganese ore, other • Industrial Process: Small industrial and business facilities - fugitive • Extraction, processing and distribution of liquid fuels • Extraction, processing, distribution of liquid fuels • Other industrial use of solvents • *Decorative paints application* • Domestic use of solvents (other than paint) • Polyvinylchloride production by suspension process • *Dry cleaning*** • Tyre production • Manufacture of automobiles	• Certain GAINS activities relevant to NMVOC emissions can be mapped to activities regulated by IED Chapter V special provisions for solvent use (and the corresponding ELVs set in IED Annex VII). They have not been included in the mapping owing to the fact that the respective limits originate from the earlier Solvents Directive and have not been revised recently. In many cases the direct link between the AELs and the GAINS categories is not feasible, as well as the units (activities and emission factors) used are not always consistent. The affected GAINS activities are in italics.

Table note: *IED Annex I activities not covered explicitly by GAINS (or are part of aggregate) are IED 1.4 Gasification or liquefaction; IED 2.3 Processing of ferrous metals; IED 2.4 Operation of ferrous metal foundries; IED 2.6 Surface treatment; IED 3.4 Mineral fibres; IED 4.4 Production of plant protection products or biocides; IED 4.6. Production of explosives; IED 6.2 Textiles; IED 6.5 Disposal of animal carcasses; IED 6.6 Intensive rearing of pigs or poultry; IED 6.9 Capture of CO_2 streams; and IED 6.11. Independently operated treatment of waste water (covered in GAINS but excluded in this study as other waste sectors). IED 3.2 Production of asbestos is also not covered but production is banned and therefore obsolete to this exercise. **For these activities, GAINS distinguishes between existing (pre 2000) and new (post 2000) installations where new assume lower process emissions due to primary measures, broader use of low solvent inputs, or different type of operating equipment (e.g., dry cleaning, vehicle refinishing).

Based on the mapping of IED Annex I activities to GAINS activities, relevant BAT-AELs were identified using the BAT-AEL tool[20], searching by IED activity and pollutant. The BAT Tool enables quick access to the BAT-AELs as published in Commission Implementing Decisions under the IED. The purpose of this exercise was to understand the range of likely emissions based on the abatement techniques employed by industry. BAT-AELs are adopted for specific abatement techniques (unlike GAINS which models emissions for the source of pollution, i.e. for the activity rather than the abatement technique). Accordingly, when identifying relevant BAT-AEL for GAINS activities it is necessary to review the source of emission to which the abatement technique applies. Accordingly, the relevant BAT-AEL were identified based on the description in the BAT-AEL tool for both the "BAT-technique/process/system/methodology and/or plant type/fuel/product" and the "Type/Point/Source of emission / Environmental threat". In particular the latter was used to establish the relevance to the GAINS activity.

BAT-AEL often distinguish between the age of an installation. This provides flexibility to the operator to comply with less stringent BAT-AEL according to the technical capabilities of the installation. However, GAINS only distinguishes between the age of plants for combustion plants. Accordingly, only in the case of Combustion of fuels (IED 1.1), was the "age of plant" taken into consideration for the mapping of BAT-AEL to GAINS. In other cases, the full range of applicable BAT-AEL was logged for each GAINS activity (regardless of the age of the installation). The summary information contained in the BAT-AEL Tool sometimes required cross referencing with the BAT Conclusions decision or BAT Reference Document (BREF) to better understand how the BAT-AEL relates to the GAINS activity (Table 2-2).

Table 2-2: BAT Conclusions and supporting material reviewed

Sector	BAT Conclusions / BREF	Year
Ferrous metals	FMP[21]	2022
Food, drink and milk	FDM[22]	2019
Iron and steel	IS[23]	2012
Large combustion plants	LCP[24]	2021
Large volume organic chemicals	LVOC[25]	2017
Non-ferrous metals	NFM[26]	2016
Pulp, paper and board	PP[27]	2014
Refining of mineral oil and gas	REF[28]	2014
Surface treatment of metals and plastics	STM[29] (BREF)	2006

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[20] https://circabc.europa.eu/ui/group/06f33a94-9829-4eee-b187-21bb783a0fbf/library/ba15ecf4-6bac-4e84-a723-fb5f2b12f7b3?p=1&n=10&sort=modified_DESC

[21] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022D2110

[22] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.313.01.0060.01.ENG&toc=OJ%3AL%3A2019%3A313%3ATOC

[23] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2012.070.01.0063.01.ENG

[24] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021D2326

[25] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017D2117

[26] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2016.174.01.0032.01.ENG

[27] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2014_284_R_0017

[28] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2014_307_R_0009

[29] https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/stm_bref_0806.pdf

Sector	BAT Conclusions / BREF	Year
Inorganic chemicals	SIC[30] (BREF)	
Tanning	TAN[31]	2013
Wood-based panels	WBP[32]	2015
Waste incineration	WI[33]	2019
Waste treatment	WT[34]	2018

The challenges resulting from differences in IED and GAINS structure encountered as part of this process are logged below (Table 2-3) together with a description of the mitigation action to address the challenge.

Table 2-3: Challenges and additional criteria applied for mapping BAT-AEL to GAINS activities

Challenge mapping BAT-AEL to GAINS activities	Mitigation action
This exercise resulted in multiple BAT-AEL ranges being allocated to one GAINS activity, where multiple techniques can apply to one source of emission (i.e. the equivalent GAINS activity). **Moreover, it is not meaningful to attempt to achieve a full compliance with AELs in the Baseline for each sectors/activity because many of the existing installations are a subject of exemptions/derogations[35], planned for a phase out, or are operated as a start-up or backup plants (example heavy fuel oil (HFO) power plants).**	[Resolved] To capture the full spectrum, the lowest and highest BAT-AEL ranges were logged. Impact: Where multiple BAT-AELs are aggregated into one sector, this may lead to comparison with applied emission limit values that are less stringent than the average for the sector.
Different BAT-AEL ranges may apply depending on the age of the installation. GAINS distinguishes between power plants built before 2000 ("existing") and after 2000 ("new"), while under the IED, new plants are considered to be built after the publication of respective BATCs. Hence, the definition of "new" and "existing" power plants differs between GAINS and the IED. **Different BAT-AEL apply to new and existing installations across more IED activities.**	[Resolved] BAT-AEL for "existing" installations were applied to all power plants. Impact: Where multiple BAT-AELs are aggregated into one sector, GAINS cannot distinguish between the IED definition of "existing" and "new" installations. ELV for the aggregated GAINS sector is compared to a wider (i.e., potentially less stringent) range of BAT-AELs.

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[30] https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/sic_bref_0907.pdf

[31] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2013.045.01.0013.01.ENG

[32] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2015.306.01.0031.01.ENG

[33] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.312.01.0055.01.ENG&toc=OJ%3AL%3A2019%3A312%3ATOC

[34] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.208.01.0038.01.ENG&toc=OJ%3AL%3A2018%3A208%3ATOC

[35] Member State reporting on the implementation of the IED for 2017 – 2018 showed 133 Article 15(4) derogations were granted across 98 installations operating in 15 Member States (Belgium, Bulgaria, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Portugal, Romania, Spain and Sweden). [Assessment and summary of Member States' reports under Commission Implementing Decision 2018/1135/EU (2021)]

Challenge mapping BAT-AEL to GAINS activities	Mitigation action
Boiler size: BAT-AEL are frequently stratified into more size classes (e.g. 50-100 MW_{th}, 100-300 MW_{th}, >300 MW_{th}) than the GAINS sectors.	[Resolved] The applied BAT-AELs in GAINS reflect the absolute minimum and absolute maximum out of the BAT-AEL range for each sector/fuel combination. Impact: ELV for the aggregated GAINS sector is compared to a wider (i.e., potentially less stringent) range of BAT-AELs.
Installation size is not specified for different types of gas and oil combustion in GAINS, so the GAINS sectors cover installations <50 MW_{th} and >50 MW_{th}.	[Resolved] LCP BAT-AEL are assumed to apply to the following sectors: industrial boilers, other industrial combustion, conversion, power plants and district heating plants. Diesel generator sets assumed to be below applicable installation size (>50 MW_{th}) and ELVs from the Medium Combustion Plant Directive (MCP) were applied. Impact: Some installations <50 MW_{th} may have been allocated (stricter) BAT-AELs than under BATC, despite not needing to comply due to size. Similarly, some diesel generator sets >50MW_{th} may have been excluded from comparison to AELs.
The GAINS and IED distinction between different types of boilers, furnaces, turbines do not always explicitly match.	[Resolved] Sector and fuel combinations were matched to the following combustion types mentioned in the Large Combustion Plant Directive BAT-AEL: - CCGT: Modern power plants + natural gas - OCGT: Power & district heat plants new, non-coal + natural gas - Boilers: all other types of industrial combustion and power plants+ all other fuels Impact: No impact anticipated.
GAINS combines industrial activity with fuel combustion type. This same breadth of fuel types are not covered by BAT-AEL ranges. **In the case of biomass combustion, there are also uncertainties in the SO_2 emission factors (and AELs) that should be considered in the comparison, and that the BATs (such as FGD) would be applicable for cofiring of wood and coal.**	[Resolved] Where fuel type is specified, BAT-AEL ranges were mapped accordingly. GAINS fuel types were grouped in the following way: - Coal and lignite: all brown coal and hard coal grades - HFO or gas oil: Heavy fuel oil, medium distillates - Mixtures of gases or liquids: Natural gas, gasoline and other light fractions of oil, liquefied petroleum gas Impact: No impact anticipated.
Co-firing of waste or biomass is considered separately in GAINS, but BAT-AELs apply to the fuel mixture.	[Resolved] Biomass co-firing is not considered, biomass combustion is only accounted for as a single-fuel activity. BAT-AELs for coal/lignite were applied to waste combustion. Impact: No impact foreseen as the IED (Chapter I, Art. 40) specifies that ELVs may be set by determining fuel-weighted ELVs.

Challenge mapping BAT-AEL to GAINS activities	Mitigation action
Coke: No separate BAT-AELs for coke combustion, while it represents a separate fuel in GAINS.	[Resolved] Applied BAT-AELs for coal/lignite combustion to coke combustion. Impact: No impact anticipated.
Hydrogen: No explicit BAT-AELs are given for combustion of pure H_2; H_2 is part of iron & steel process gas (LCP NO_x BAT 49), combustion from gas-fired combustion units (REF NO_x BAT 34, higher BAT applies when H_2 >50%) and large volume inorganic chemicals: no BAT-AELs (Annex I, 4.2) **In GAINS, hydrogen is represented both as a dedicated H_2 stream and in the GAS category, which includes syngas and natural gas.**	[Resolved] BAT-AELs for process gas are accounted for in industrial boilers run with gas. Impact: No BAT-AELs can be applied to H_2 combustion as none exist, but H_2 combustion in power plants and industry is included in assessing emissions from combustion sources as laid out in Annex I, Sector 1.1. Impact: No impact anticipated.
GAINS calculates annual emissions. Accordingly, where available, annual BAT-AEL ranges were extracted from the BAT-AEL tool. In some cases, no annual BAT-AEL range was available.	[Resolved] Where different averaging periods are used for BAT-AEL ranges a simple adjustment exercise was undertaken to enable comparison with annual average emission concentrations. The adjustment exercise followed the same approach as previously employed by a study for the Commission, essentially assuming that annual averages are 10% lower than monthly averages (Ricardo 2017)[36]. Impact: No impact anticipated.

The results of this mapping are presented in Annex II (grouped by pollutant – BAT-AEL for SO_2 are presented in Table 7-1, BAT-AEL for NO_x in Table 7-2 and BAT-AEL for Dust in Table 7-3).

2.1.4 Task 1.3: Mapping and calibration of control strategies.

In this subtask, the results of Task 1.2 were systematically interpreted in the context of the GAINS model. Using the mapping presented in previous section at the sectoral level, for each relevant IED sector/activity it has been assessed how the current requirements of the IED and BAT conclusions are represented in the GAINS model in the Baseline. In practice, the ranges of BAT-AELs (summarised in Tables 6-1,-2,-3) have been compared to the corresponding average (implied) emission factors for the mapped sector/fuel combinations in GAINS (see an illustrative example of this procedure in Figure 2-3). In addition, the air pollution abatement technologies (primary and secondary) and measures, their uptake and characteristics in GAINS have been reviewed and adjusted if outdated parameters, missing or wrong datapoints have been identified.

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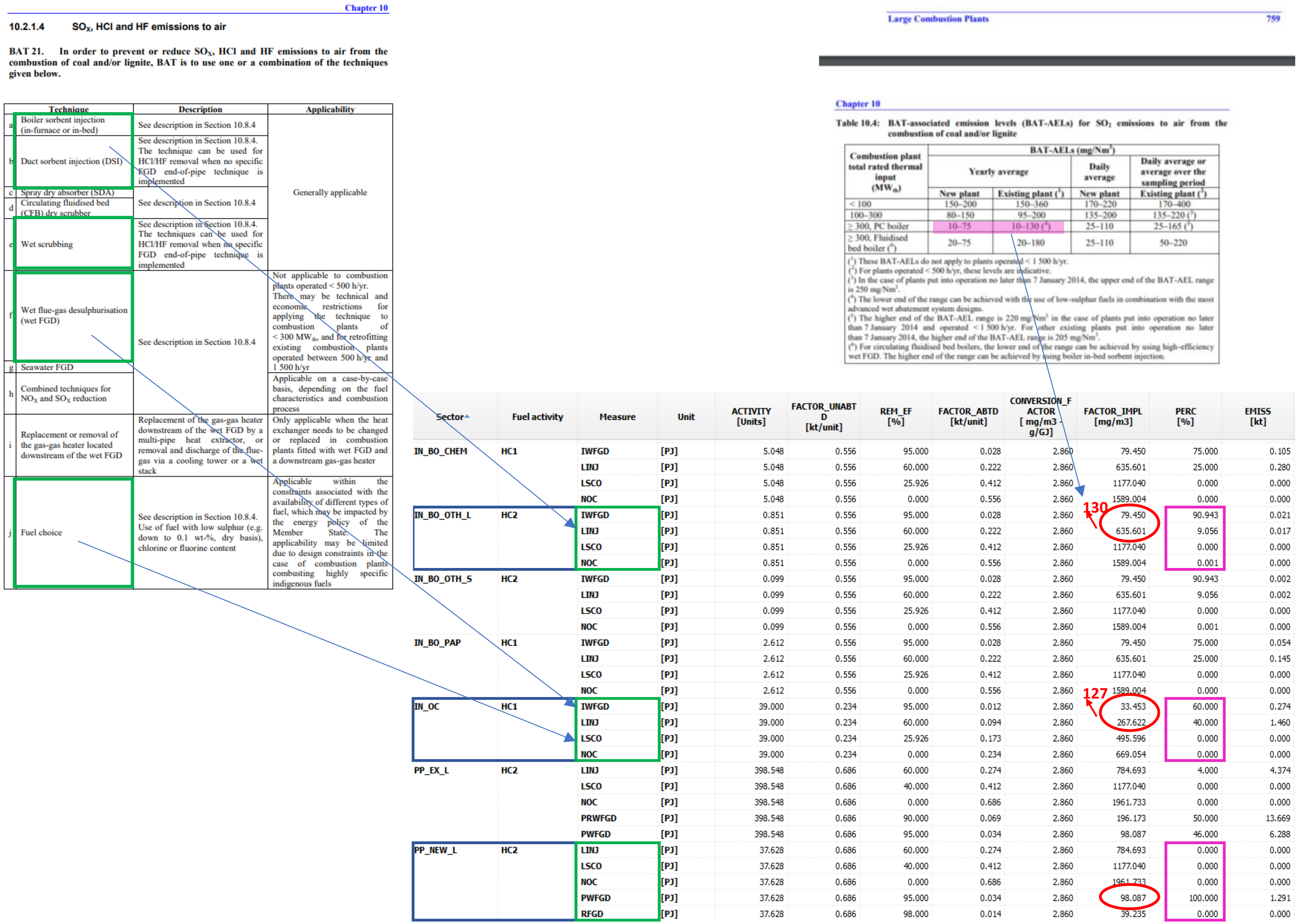
[36] It is noted that Ricardo (2017) explored the option of using the method proposed to the LCP BREF TWG by the Dutch Ministry together with Eurelectric (authors van Aart & Burgers) of deriving monthly emission levels from 0.45*Daily emission level + 0.55*Yearly emission level, using the daily and annual BAT-AELs from the draft BREF. However, that method was found to generate untenable results of IED ELVs when converted to annual averages being lower than the monthly BAT-AELs.
Ricardo (2017) Technical support for developing the profile of certain categories of Large Combustion Plants regulated under the Industrial Emissions Directive. (section 2.4.1) https://circabc.europa.eu/sd/a/f568a5b1-8c7a-475c-8162-a6c47b86ef7f/LCP%20profile.pdf

Figure 2-3. Illustrative example of the mapping and comparison between the GAINS emission factors and information collected from the IED documents.



Chapter 10

10.2.1.4 SO_X, HCl and HF emissions to air

BAT 21. In order to prevent or reduce SO_X, HCl and HF emissions to air from the combustion of coal and/or lignite, BAT is to use one or a combination of the techniques given below.

	Technique	Description	Applicability
a	Boiler sorbent injection (in-furnace or in-bed)	See description in Section 10.8.4	Generally applicable
b	Duct sorbent injection (DSI)	See description in Section 10.8.4. The technique can be used for HCl/HF removal when no specific FGD end-of-pipe technique is implemented	
c	Spray dry absorber (SDA)	See description in Section 10.8.4	
d	Circulating fluidised bed (CFB) dry scrubber		
e	Wet scrubbing	See description in Section 10.8.4. The techniques can be used for HCl/HF removal when no specific FGD end-of-pipe technique is implemented	
f	Wet flue-gas desulphurisation (wet FGD)	See description in Section 10.8.4	Not applicable to combustion plants operated < 500 h/yr. There may be technical and economic restrictions for applying the technique to combustion plants of < 300 MW_{th}, and for retrofitting existing combustion plants operated between 500 h/yr and 1 500 h/yr
g	Seawater FGD		
h	Combined techniques for NO_X and SO_X reduction		Applicable on a case-by-case basis, depending on the fuel characteristics and combustion process
i	Replacement or removal of the gas-gas heater located downstream of the wet FGD	Replacement of the gas-gas heater downstream of the wet FGD by a multi-pipe heat extractor, or removal and discharge of the flue-gas via a cooling tower or a wet stack	Only applicable when the heat exchanger needs to be changed or replaced in combustion plants fitted with wet FGD and a downstream gas-gas heater
j	Fuel choice	See description in Section 10.8.4. Use of fuel with low sulphur (e.g. down to 0.1 wt-%, dry basis), chlorine or fluorine content	Applicable within the constraints associated with the availability of different types of fuel, which may be impacted by the energy policy of the Member State. The applicability may be limited due to design constraints in the case of combustion plants combusting highly specific indigenous fuels

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Table 10.4: BAT-associated emission levels (BAT-AELs) for SO_2 emissions to air from the combustion of coal and/or lignite

Combustion plant total rated thermal input (MW_{th})	BAT-AELs (mg/Nm^3)			
	Yearly average		Daily average	Daily average or average over the sampling period
	New plant	Existing plant (1)	New plant	Existing plant (2)
< 100	150–200	150–360	170–220	170–400
100–300	80–150	95–200	135–200	135–220 (3)
≥ 300, PC boiler	10–75	10–130 (4)	25–110	25–165 (5)
≥ 300, Fluidised bed boiler (6)	20–75	20–180	25–110	50–220

(1) These BAT-AELs do not apply to plants operated < 1 500 h/yr.
(2) For plants operated < 500 h/yr, these levels are indicative.
(3) In the case of plants put into operation no later than 7 January 2014, the upper end of the BAT-AEL range is 250 mg/Nm^3.
(4) The lower end of the range can be achieved with the use of low-sulphur fuels in combination with the most advanced wet abatement system designs.
(5) The higher end of the BAT-AEL range is 220 mg/Nm^3 in the case of plants put into operation no later than 7 January 2014 and operated < 1 500 h/yr. For other existing plants put into operation no later than 7 January 2014, the higher end of the BAT-AEL range is 205 mg/Nm^3.
(6) For circulating fluidised bed boilers, the lower end of the range can be achieved by using high-efficiency wet FGD. The higher end of the range can be achieved by using boiler in-bed sorbent injection.

Sector	Fuel activity	Measure	Unit	ACTIVITY [Units]	FACTOR_UNABTD [kt/unit]	REM_EF [%]	FACTOR_ABTD [kt/unit]	CONVERSION_FACTOR [mg/m3 - g/GJ]	FACTOR_IMPL [mg/m3]	PERC [%]	EMISS [kt]
IN_BO_CHEM	HC1	IWFGD	[PJ]	5.048	0.556	95.000	0.028	2.860	79.450	75.000	0.105
		LINJ	[PJ]	5.048	0.556	60.000	0.222	2.860	635.601	25.000	0.280
		LSCO	[PJ]	5.048	0.556	25.926	0.412	2.860	1177.040	0.000	0.000
		NOC	[PJ]	5.048	0.556	0.000	0.556	2.860	1589.004	0.000	0.000
IN_BO_OTH_L	HC2	IWFGD	[PJ]	0.851	0.556	95.000	0.028	2.860	79.450	90.943	0.021
		LINJ	[PJ]	0.851	0.556	60.000	0.222	2.860	635.601	9.056	0.017
		LSCO	[PJ]	0.851	0.556	25.926	0.412	2.860	1177.040	0.000	0.000
		NOC	[PJ]	0.851	0.556	0.000	0.556	2.860	1589.004	0.001	0.000
IN_BO_OTH_S	HC2	IWFGD	[PJ]	0.099	0.556	95.000	0.028	2.860	79.450	90.943	0.002
		LINJ	[PJ]	0.099	0.556	60.000	0.222	2.860	635.601	9.056	0.002
		LSCO	[PJ]	0.099	0.556	25.926	0.412	2.860	1177.040	0.000	0.000
		NOC	[PJ]	0.099	0.556	0.000	0.556	2.860	1589.004	0.001	0.000
IN_BO_PAP	HC1	IWFGD	[PJ]	2.612	0.556	95.000	0.028	2.860	79.450	75.000	0.054
		LINJ	[PJ]	2.612	0.556	60.000	0.222	2.860	635.601	25.000	0.145
		LSCO	[PJ]	2.612	0.556	25.926	0.412	2.860	1177.040	0.000	0.000
		NOC	[PJ]	2.612	0.556	0.000	0.556	2.860	1589.004	0.000	0.000
IN_OC	HC1	IWFGD	[PJ]	39.000	0.234	95.000	0.012	2.860	33.453	60.000	0.274
		LINJ	[PJ]	39.000	0.234	60.000	0.094	2.860	267.622	40.000	1.460
		LSCO	[PJ]	39.000	0.234	25.926	0.173	2.860	495.596	0.000	0.000
		NOC	[PJ]	39.000	0.234	0.000	0.234	2.860	669.054	0.000	0.000
PP_EX_L	HC2	LINJ	[PJ]	398.548	0.686	60.000	0.274	2.860	784.693	4.000	4.374
		LSCO	[PJ]	398.548	0.686	40.000	0.412	2.860	1177.040	0.000	0.000
		NOC	[PJ]	398.548	0.686	0.000	0.686	2.860	1961.733	0.000	0.000
		PRWFGD	[PJ]	398.548	0.686	90.000	0.069	2.860	196.173	50.000	13.669
		PWFGD	[PJ]	398.548	0.686	95.000	0.034	2.860	98.087	46.000	6.288
PP_NEW_L	HC2	LINJ	[PJ]	37.628	0.686	60.000	0.274	2.860	784.693	0.000	0.000
		LSCO	[PJ]	37.628	0.686	40.000	0.412	2.860	1177.040	0.000	0.000
		NOC	[PJ]	37.628	0.686	0.000	0.686	2.860	1961.733	0.000	0.000
		PWFGD	[PJ]	37.628	0.686	95.000	0.034	2.860	98.087	100.000	1.291
		RFGD	[PJ]	37.628	0.686	98.000	0.014	2.860	39.235	0.000	0.000

The following parameters were updated in the Baseline for individual countries and sectors:

- sulphur content in heavy fuel oil has been revised to assure a compliance with the current fuel quality standards[37] and corresponding BAT conclusions
- emission factors for dust emissions (primarily for coarse particulate matter, i.e., >$PM_{2.5}$) have been adjusted for the cement and lime production
- emission factors for SO_2 emissions have been adjusted for the non-ferrous metals production
- application rates of control technologies[38] have been corrected for the years 2025-2050 in few cases to avoid data gaps or inconsistency in time series.

Figure 2-4 A and B shows a comparison of the implied emission factors for two selected IED activities – coal fired power plants (IED 1.1) and cement production (IED 3.1) - with the corresponding BAT-AELs, indicating a compliance (or non-compliance) with the pollutant specific emission standards in the Baseline scenario. At the EU27 level, the implied emission factor for SO_2, NO_x and dust lay within the upper and lower end of ranges defined by BAT-AELs for coal combustion in power plants. At the country level, there are several cases where the upper end of BAT-AELs is exceeded. This is attributed typically to existing (old) power plants where no investments in emission controls is expected before the end of their lifetime. In such cases, the extent to which planned revision to the IED to set ELVs based on best performance the installation can achieve will unlikely have an effect. In the cement sector, the GAINS emission factors appear also well below the upper limit values for SO_2 and NO_x. The same is concluded for the emission factors for $PM_{2.5}$, although the BAT-AEL ranges are defined for total emissions of dust. For the dust emissions (PM_TSP), the GAINS values are mostly above the corresponding BAT-AELs at the EU27 and MS levels, despite high application rates of BATs in this sector. This finding is discussed in detail in Box 2. It is noted here that the GAINS controls in the Baseline are primarily parametrised to efficiently abate the emissions of $PM_{2.5}$ as a pollutant of the main health concerns, while the GAINS emission factors of dust are associated with a greater level of uncertainty, often linked to the fugitive emission component, when compared to BAT-AELs ranges (see the discussion below).

As can be seen in Figure 2-4, at the country level the aggregated GAINS emission factors change over time (typically with a declining trend), which is attributed to an increase in controlled capacities as well as to the adoption of more efficient technologies towards 2050. It is also recognised that the controls (BATs) in GAINS are generally defined as single-pollutant technologies and while they are typically applied as technology packages (i.e., SO_2, NO_x, particulate matter reduction techniques would be applied to the same installations if required), some additional benefits, e.g., lower particulate matter emissions when flue gas desulfurization is used are not explicitly considered. Therefore, the trend in changes of the implied emission factors can differ by individual pollutants.

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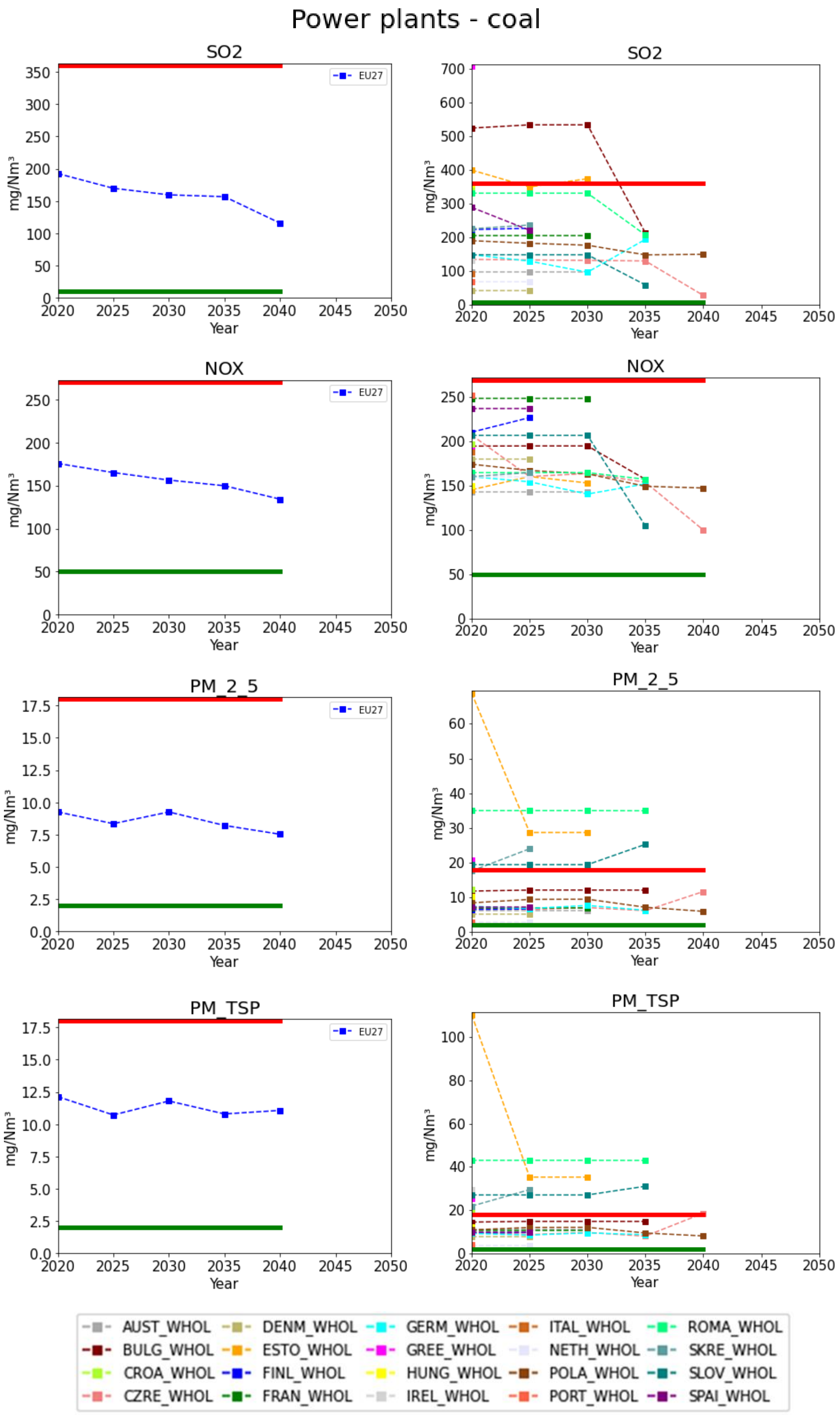
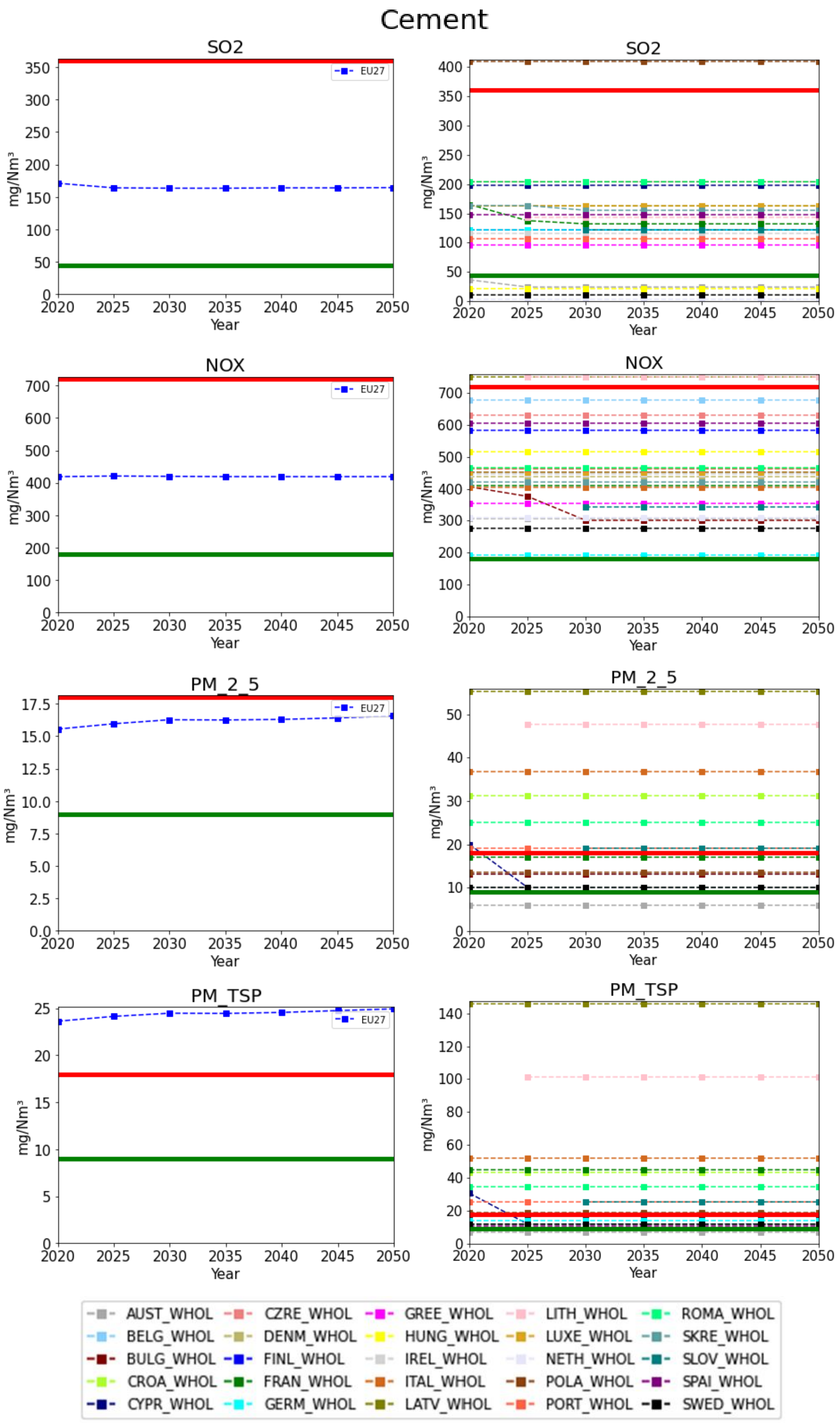
[37] Directive (EU) 2016/802 of the European Parliament and of the Council of 11 May 2016 relating to a reduction in the sulphur content of certain liquid fuels https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32016L0802

[38] Available online (http://gains.iiasa.ac.at/gains/EUN/index.login)

Figure 2-4 Comparison of the GAINS emission factors for coal power plants (upper panel A) and cement production (lower panel B) (2020 – 2050) in the Baseline scenario with the corresponding BAT-AELs (red line – upper end, green line – lower end) (mg/m^3) for the EU27 (blue line) and by MSs.



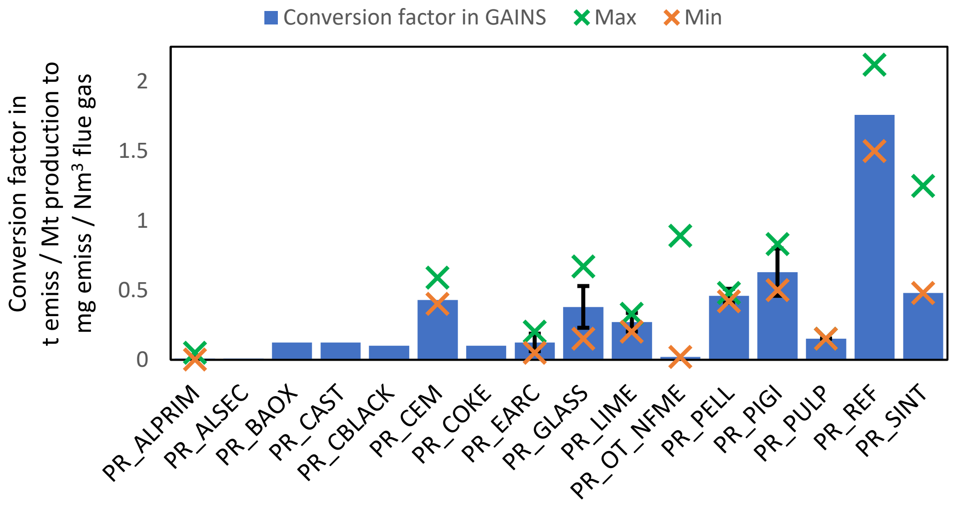


Note: PM_TSP refers to total particulate matter (TSP-total suspended particulate matter) and therefore also includes particles with the aerodynamic diameter larger than $PM_{2.5}$ (> 2.5 um) as well as PM10 (>10 um). In this report it also corresponds to dust, for which the BAT-AELs are provided.

Box 2: Conversion between emission units used in GAINS and the IED BAT-AELs

- BAT-AELs in the IED operate on the installation level and often demand process-specific emission measurements or stack measurements in mg/Nm^3.
- GAINS emissions are calculated on the country level in the EU; sector-specific emission factors are derived from emission guidebooks, national experts or inventories and are representative of average emissions from the sector in the given region. They relate either to the input of energy into a sector (e.g., the amount of a certain fuel used in one type of power station) or to the output (e.g., emissions per Mt of cement, steel, glass, etc. produced).
- GAINS sectors are often aggregates of different processes or process steps (e.g., non-ferrous metal production). They may also include emissions which are not captured in BAT-AELs (e.g., fugitive emissions).
- To compare BAT-AELs to GAINS emission values, emission factors are converted into mg/Nm^3 units. This is done using the average flue gas volumes emitted per (1) PJ of fuel consumed or (2) Mt of product produced from industrial processes, based on the latest available information, such as BREF documents. These conversion factors are not exact numbers but represent the average of a range (see Figure 2-5). Depending on available data, they may be derived from different individual industrial installations, but also different production technologies with varying flue gas volumes, so the resulting conversion factor can only represent the average of a range of possible conversion factors.

Figure 2-5. Ranges of conversion factors – blue bars: conversion factor used in GAINS; green: maximum value for conversion factor found in literature; orange: minimum value for conversion factor found in literature; black bars: 1 standard deviation of average, if available.



NOTES - Literature used: CLM, IS, NFM, PP, REF BREFs, IS, GLS BAT documents, Rentz et al. 1996[39]. Acronyms: PR_ALPRIM - Primary aluminum, PR_ALSEC - Secondary aluminum, PR_BAOX - Basic oxygen furnaces, PR_CAST - Cast iron, PR_CBLACK - Carbon black, PR_CEM - Cement, PR_COKE - Coke, PR_EARC - Electric arc furnaces, PR_GLASS - glass, PR_LIME - lime, PR_OT_NFME - Non-ferrous metals, PR_PELL - Pellet plants, PR_PIGI - Pig iron, PR_PULP - Pulp and paper, PR_REF - Refineries, PR_SINT - Sintering plants.

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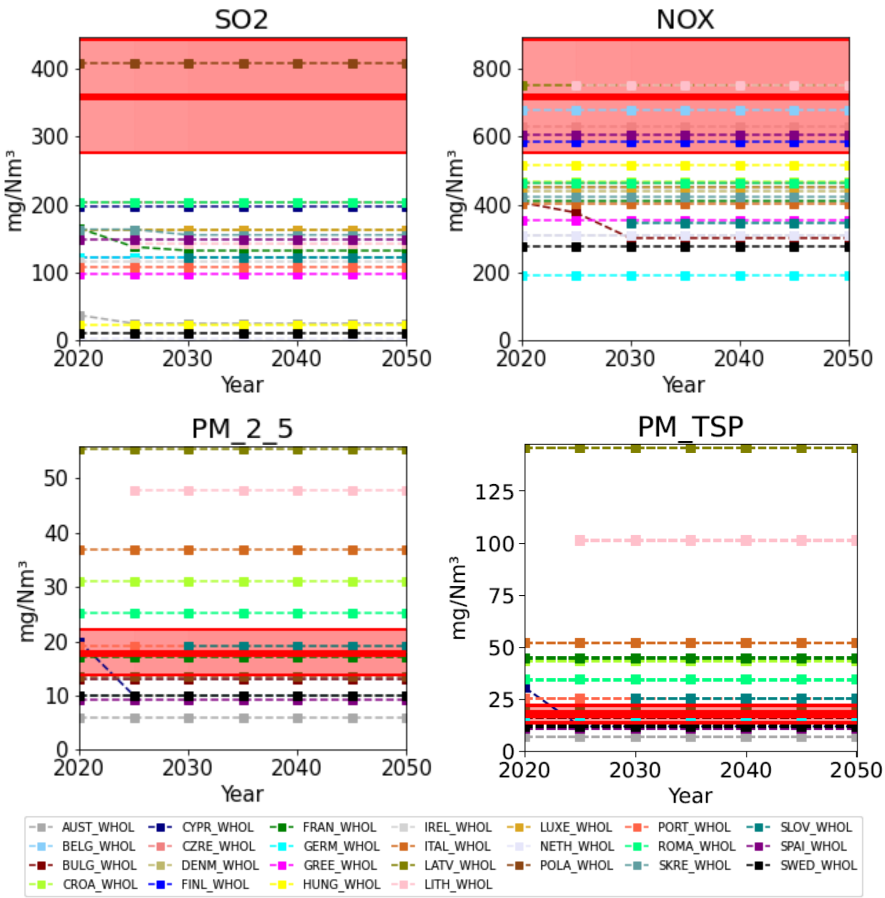
[39] Rentz, O., Sasse, H., Karl, U., Schleef, H. J., & Dorn, R. (1996). Emission control at stationary sources in the Federal Republic of Germany. Vol. 2. Heavy metal emission control.

- The red area in Figure 2-6 represents an example of uncertainty range associated with the use of varying conversion factors to translate the GAINS emission coefficients into the mg/Nm^3 units over the BAT-AEL in the cement industry.
- In some cases, a direct comparison of the converted value to the BAT-AELs is not feasible as the GAINS emissions include fugitives or other emission which would not otherwise be included in an off-gas measurement.

Figure 2-6 An illustration of uncertainty involved in the comparison of the GAINS emission factors to the BAT-AEL values for the cement sector (red area) (mg/m^3).



2.1.5 Task 1.4: Development of the MTFR scenario

An MTFR (maximum technically feasible reduction) scenario has been developed for the period 2030-2050 in 5-year intervals using the GAINS optimization module. This module accesses the full GAINS emission mitigation technology database[40] and identifies for each sector/activity combination a mix of technologies that minimizes the emission of air pollutants, subject to technological constraints. These constraints include, e.g., maximum application rates and capital stock turnover rates that are related to the lifetime of the control technologies, constraining their implementation rates in the short term, but allowing for increasing capacity to be controlled over time. In case two technologies have the same removal efficiency and thus the same emission factor, the GAINS optimization selects the technology with the lower unit cost in order to avoid a tie between two

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[40] Available in the online model (http://gains.iiasa.ac.at/gains/EUN/index.login)

solutions and to ensure reproducibility of results. It is noted that in the current configuration of the model the end-of-pipe techniques for the IED activities are defined as single-pollutant abatement technologies.

The MTFR scenario identifies for each country, sector, pollutant and year, the potential for further reductions beyond the Baseline. Thus, unless the best available technology in the GAINS database is already applied to the maximum feasible extent, the MTFR scenario emissions are lower than the Baseline emissions.

2.1.6 Task 1.5: Emission trends towards 2050

Taking into account updates from Tasks 1.2 – 1.3 and using the GAINS framework, the emission trends for the period 2005-2050 have been computed for the Baseline scenario, and 2030-2050 for the MTFR scenario in 5-year intervals for all pollutants (SO_2, NO_x, $PM_{2.5}$ and NMVOC).

The GAINS model combines exogenous projections – in this case the MIX 55 scenario developed by the PRIMES/CAPRI/GAINS models - of future emission-generating activities (i.e., energy, transport, industrial production, agriculture, waste volumes) with the current emission characteristics (emission factors) in EU MS[41]. GAINS computes future emissions taking account of the penetration of control measures and estimates the potential for additional emission reductions that is offered by several hundreds of abatement technologies available as BAT techniques or their combinations. The emissions are projected at the level of each IED sector in each MS, however, the results also include emissions from other sectors, i.e., transport, agriculture, buildings and other).

Emissions trends are summarized in the Section 3.1, whereby also the past emissions (2005-2015) are included in the results in order to highlight the longer term reduction trends. Both scenarios developed in Task 1 (Baseline and MTFR) have been uploaded to the GAINS database and are accessible[42] through the GAINS online interface upon registration and request (http://gains.iiasa.ac.at/gains/EUN/index.login).

2.2 Task 2: Analysis of assumptions and drivers

The objective of this task was to offer a better understanding of the assumptions and drivers behind the projected air pollutant emission trends computed within Task 1 using the GAINS model for the IED activities. Outcomes are relevant for assessing the effectiveness of the IED in the baseline and for identifying potential priority areas for amendment / focus in future BREF reviews (as well as those where there may be significant structural changes in the future e.g., process changes in response to decarbonization drivers).

Task 2 is structured as follows: **first**, Task 2.1 evaluates major exogenous scenario parameters as well as assumptions compiled under Task 1.2 on the performance of the BATs in the IED sectors and how they relate to BAT-AELs, and provides insights to what extent the projected emissions are robust or sensitive to alternative assumptions. **Second**, driving factors behind the emission trends are examined in Task 2.2 and quantifies how the structural changes in the energy system affect future emission levels versus changes in the implementation rates of BATs following the IED provisions. **Third**, the key contributing IED activities are identified in Task 2.3 both in the Baseline and MTFR

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[41] Amann et al. 2011, Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. https://doi.org/10.1016/j.envsoft.2011.07.012

[42] These scenarios are not in public domain. Access can be granted on request and only to members of the consortium considering confidentiality considerations as discussed during progress meetings and consistent with the agreements and recommendations of the DG-ENV following the AAQD IA and CAO3 work.

scenarios offering insights into which sectors are expected to contribute the most to emission reductions, and are thus the prime target for monitoring the actual implementation of the IED. Identification of the top emission-reducing IED activities in the MTFR scenario offers insights into which sectors should be prioritized in revising pertinent legislation. Finally, the cost of implementation of control measures in the Baseline and MTFR cases has been calculated under Task 2.4.

2.2.1 Task 2.1: Assumptions and sensitivities

This task analyses the main assumptions that have an influence on the emission trends developed in Task 1.5. First, a summary of assumptions about the changes in the energy system that are projected in the Baseline is provided. The achievement of the carbon neutrality target by 2050 and the 55% GHG emission reduction target by 2030, implies significant changes in the technologies used for several energy intensive industries including for example a shift from blast furnace production to direct reduction based on hydrogen for the iron and steel industry. Further, decarbonisation trends are assessed in this context that combine benefits of abating GHG emissions as well as influencing pollutant emissions, namely improved conversion and process efficiency and fuel shifts. A decomposition of carbon emission mitigating factors has been also carried out under this task following the methodology summarised in Annex IX.

Within this task the assumptions about technology characteristics (removal efficiencies) and implementation rates of the emission control measures adopted in the GAINS scenario has been analysed at the level relevant for the IED sectors. As a next step, the assumptions about the effectiveness and performance of the measures implemented in the scenarios have been examined based on the information and data collected in Task 1.2 in order to evaluate how the technologies applied in the model relate to the range of BAT-AELs. For the IED sectors we have constructed a set of sensitivity cases allowing to find out whether the emission factors of the relevant BAT considered in the GAINS model correspond to the lower or upper end of the BAT-AEL range, how they relate to the range and how the emission factors evolve over the time horizon 2020 to 2050.

Finally, the assumptions on the deployment of emerging fuels and technologies in the future energy system have been assessed and a potential impact on the projected emission trends have been examined. Implications of three emerging technologies/fuels are reported: carbon capture utilisation and storage, hydrogen consumption, and ammonia use in the IED sectors.

2.2.2 Task 2.2: Decomposition analysis

To investigate the drivers behind the emission trends calculated in Task 1.5, a decomposition analysis has been carried out that distinguishes the changes in the underlying activity data (production output, energy consumption, and fuel mix) and the changes in implementation rates of emission removal technologies in the Baseline and MTFR scenarios. To disentangle the impacts of autonomous changes in economic growth, structural shifts, or technical innovations from dedicated energy and air-quality policies (including impacts of emerging fuels and technologies), a simplified additive form of the index decomposition analysis has been used[43, 44]. To quantify the relative importance of key determinants of changes in the industrial emission levels, we apply the identity following the evolution of three driving factors: (a) energy intensity; (b) fuel mix; and (c) air-pollution

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[43] Rafaj et al. 2014. Changes in European greenhouse gas and air pollutant emissions 1960–2010: decomposition of determining factors. https://doi.org/10.1007/s10584-013-0826-0

[44] Rafaj et al. 2014. Factorization of air pollutant emissions: Projections versus observed trends in Europe. https://doi.org/10.1016/j.scitotenv.2014.07.013

abatement measures. Formally, emission changes relative to the selected base year (2020) can be described as a result of:

$$\Delta\text{Emissions}=\text{GDP}\cdot\underbrace{\left[\Delta\left(\frac{\text{Energy}}{\text{GDP}}\right)\cdot\Delta\eta\right]}_{\text{(a)}}\cdot\underbrace{\left[\Delta\left(\frac{\text{Emissions}}{\text{Energy}}\right)\right]}_{\text{(b)}}\cdot\underbrace{\left[(1-eff)\cdot\Delta X\right]}_{\text{(c)}}$$

Where the three factors under examination represent:

(i) Temporal change in energy intensity, that is, the Energy consumed per unit of economic output (GDP), which determines the size of energy demand, structure of energy services, and reflects differences in socioeconomic structures, as well as in behavioural patterns. Energy intensity is complemented by the impacts of efficiency improvements of the energy system (Δη), in other words, the efficiency at which primary energy is converted into secondary and final energy.

(ii) The evolution of the fuel mix of different energy forms affects emission intensities, comprising inter-fossil-fuel switch and changes in the fraction of non-fossil fuels in energy supply. Substitution of traditional/combustible fuels by electricity and district heating contributes to this mitigation component on the demand side of the energy system. This component does not apply to the (non-combustion) industrial process activities, and the potential impacts of the innovative techniques (e.g., direct reduced iron (DRI) with H_2) would be indirectly covered in factor (i).

(iii) The changes in aggregated emission factors over time which typically follow the implementation of end-of-pipe measures and fuel quality standards. The resulting emission coefficient reflects the removal efficiency (eff) of a given abatement measure adopted at a specific rate (ΔX).

In our approach, we construct three comparative emission scenarios by sequentially adding the impact of the factors listed above:

$$Emissions^{t} - Emissions^{t-1} = Factor(i+ii)effect + Factor(iii)effect$$

First, an upper limit for emissions is calculated for the hypothetical case in which emission-reduction components (i-iii) are kept at the base-year levels (2020), so that the emission path follows GDP growth. The projected development in energy intensity and efficiency improvements, i.e. based on the PRIMES MIX 55 case, are accounted for in the second scenario, where emission controls are kept unchanged. This scenario also reflects future trends in the share of fuels in key sectors. Although the impact of Factors i and ii can be quantified separately, in this report they have been aggregated into one component. The reason is that a) energy intensity and fuel mix changes occur in parallel in the future energy system and b) some of the projected fuel-switches counteract each other, e.g., emission reductions due to phasing out of coal is partially offset by an increase in biomass combustion. Finally, the contribution of control measures in the third scenario is based on the actual emission trajectories computed in the modelling framework (Task 1.5). This scenario is calculated for both the Baseline and MTFR cases to distinguish the mitigation potential beyond the current legislation.

2.2.3 Task 2.3: Identification of key contributors

In this subtask we have quantified the emission reductions for each IED/activity in absolute terms in the years 2030 and 2050. This allows us to identify the largest contributors to the absolute emission reductions in each MS both in the Baseline and in the MTFR scenario. We have ranked the contributions to reductions in absolute terms and also provide cumulative reductions in order to identify the most “important” contributing sectors/activities to the overall reductions. Such an analysis of the Baseline and MTFR scenarios offers an overview of potential priority areas for further intervention: top-ranked contributing IED activities offer the largest additional potential for reduction.

2.2.4 Task 2.4: Analysis of emission control costs

In Task 2.4, the annual emission control costs over time have been calculated for the Baseline and MTFR scenario with the GAINS model. These costs are calculated at the detailed sectoral level and thereafter are aggregated and reported at the level of IED sectors and at the national level. Cost data are provided in the form of Excel tables, as well as graphically. They cover the cost of end-of-pipe emission control technologies, but not explicitly the costs of changes in the activity data (such as changes in fuel mix or changes in the production processes, such as hydrogen steel).

In GAINS, unit emission reduction costs take into account the initial investment costs (which are annualized using a social discount rate and taking into account the lifetime of the equipment), fixed and variable operating and maintenance cost, such as labour, energy, deposition of wastes, etc. In this way, technology costs may be country-specific. Unit emission reduction costs are assumed to be constant over time, as they are typically mature technologies. Aggregated costs for controlling simultaneously SO_2, NO_x and $PM_{2.5}$ emissions (and separately NMVOC emissions) from the IED sectors are reported in 2015 Euros, which is the current monetary unit used in GAINS.

2.3 Task 3: Summary of findings

In Task 3, a summary of the findings of Task 1 and Task 2, as well as a documentation of the approach and the methodology is provided. Results are presented graphically and numerically, at the MS and EU level. The final report is accompanied by the full set of underlying scenarios, which can be accessed through the GAINS model online interface, as well as by supplementary data tables and graphical output.

3. Results

3.1 Emission projections: Baseline and MTFR results

At the EU level, industrial sectors regulated by the IED represent a significant share of total emission releases (about 70% SO_2, 23% NO_x, 10% $PM_{2.5}$, 25% NMVOC in 2020) and by 2050 this share is projected to increase for all pollutants (80% SO_2, 40% NO_x, 25% $PM_{2.5}$, 30% NMVOC) (see Figure 3-1 and Annex III: Figure 8-1, Figure 8-2, Figure 8-3, Figure 8-4). Compared to 2020, however, the Baseline scenario projects a decline for all pollutants from the IED sectors[45] by 2050. For the EU, this reduction is estimated to be between 30% to 50% for SO_2 and NO_x, and about 10% for $PM_{2.5}$ and NMVOC. Application of the MTFR control strategy in each of the IED sectors by 2050 results in further reductions of more than 70% for SO_2 and NO_x, and nearly 55% for $PM_{2.5}$ and NMVOC (see Figure 3-2).

As shown in Annex IV, Figure 9-1, Figure 9-2, Figure 9-3 and Figure 9-4, the evolution of emission trends differs significantly across EU MS and IED sectors. In total, an increase in the Baseline IED emissions in 2050 relative to 2020 is reported for the following MS:

- SO_2 - Belgium, Luxembourgh (2)
- NO_x – Austria, Belgium, Italy, Luxembourg, Malta (5)
- $PM_{2.5}$ – Belgium, Croatia, Hungary, Italy, Netherlands, Romania, Spain, Sweden (8)
- NMVOC – marginal in Ireland, Latvia, Slovenia (3)

In most of the countries, the **SO_2 emissions** from the IED sector 1 (Energy industries) gradually decline in the Baseline by 2050. Between 2030 and 2050, there is a growing trend reported from this sector, e.g., for Belgium, Hungary or Ireland, associated with a significant increase in the combustion of biomass for power generation. Other activities where an increasing trend is observed are the production of cement and glass (e.g., Belgium, Luxembourgh), non-ferrous-metals smelting, production pulp/paper, and sulfuric acid (multiple countries).

The **NO_x emissions** from combustion sources also decline in the Baseline in most MS by 2050. In some cases (e.g., Italy, Belgium), the rapid growth in the use of biomass in power sector results in an increase in the emissions between 2030-2050. The growing trend in NO_x towards 2050 in Austria is linked with emissions from gas power plants with CCS, indicating a special attention is needed to examine assumptions for this sector and applicable BATs. The non-combustion IED activities with growing NO_x emissions include cement, lime and glass production.

Compared to other pollutants, the IED sectors 2 (Metals production) and 3 (Mineral industries) play a much greater role in the **emission profiles for $PM_{2.5}$**. For many countries the reduction of fine particles from the energy sectors is partially offset by a growing trend in emissions from industrial processes. The key sources that contribute to the modest growth in the $PM_{2.5}$ emissions from

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[45] Non-IED sectors' emissions decline as well driven by implementation of other legislation and by decarbonization of economy. For example, emissions from transport and residential combustion that are important sources of some pollutants decline strongly; for residential combustion biomass use also declines.

industrial process activities comprise cement production, ferrous as well as non-ferrous metals industries.[46]

Emissions of NMVOCs gradually decline between 2020 and 2050 in all MS (with the exception of Ireland, Latvia, Slovenia where a marginal growth is projected). The key emitters (IED 6 – other activities) are the solvents-use sector and industrial applications.

Numerical results for the Baseline scenario (2005-2050) for each pollutant and country (including EU27 totals) are attached to this report as two separate files: 1) emission projections for total IED and non-IED categories, 2) emission projections split by the IED sectors - 1. Energy industries, 2. Metals production, 3. Mineral industries, 4. Chemicals industries, 5. Waste industries, 6. Other activities. The data files also include for all pollutants and EU MSs the estimate of emission reductions induced through the MTFR controls in the years 2030 through 2050. Projected air pollutant trends reported here are examined further by a detailed analysis of underlying assumptions and drivers behind emission changes in Task 2.

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[46] Emissions from the non-coal mining industries was not a special focus of this study being outside of the scope of the existing IED provisions. The GAINS model estimates that in 2020 the $PM_{2.5}$ emissions from this sector are about 1% of the total IED activities, and for PM_TSP about 2.5% of the IED totals.

Figure 3-1 SO_2, NO_x, $PM_{2.5}$ and NMVOC emissions for total IED and non-IED categories in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year) in the EU27.

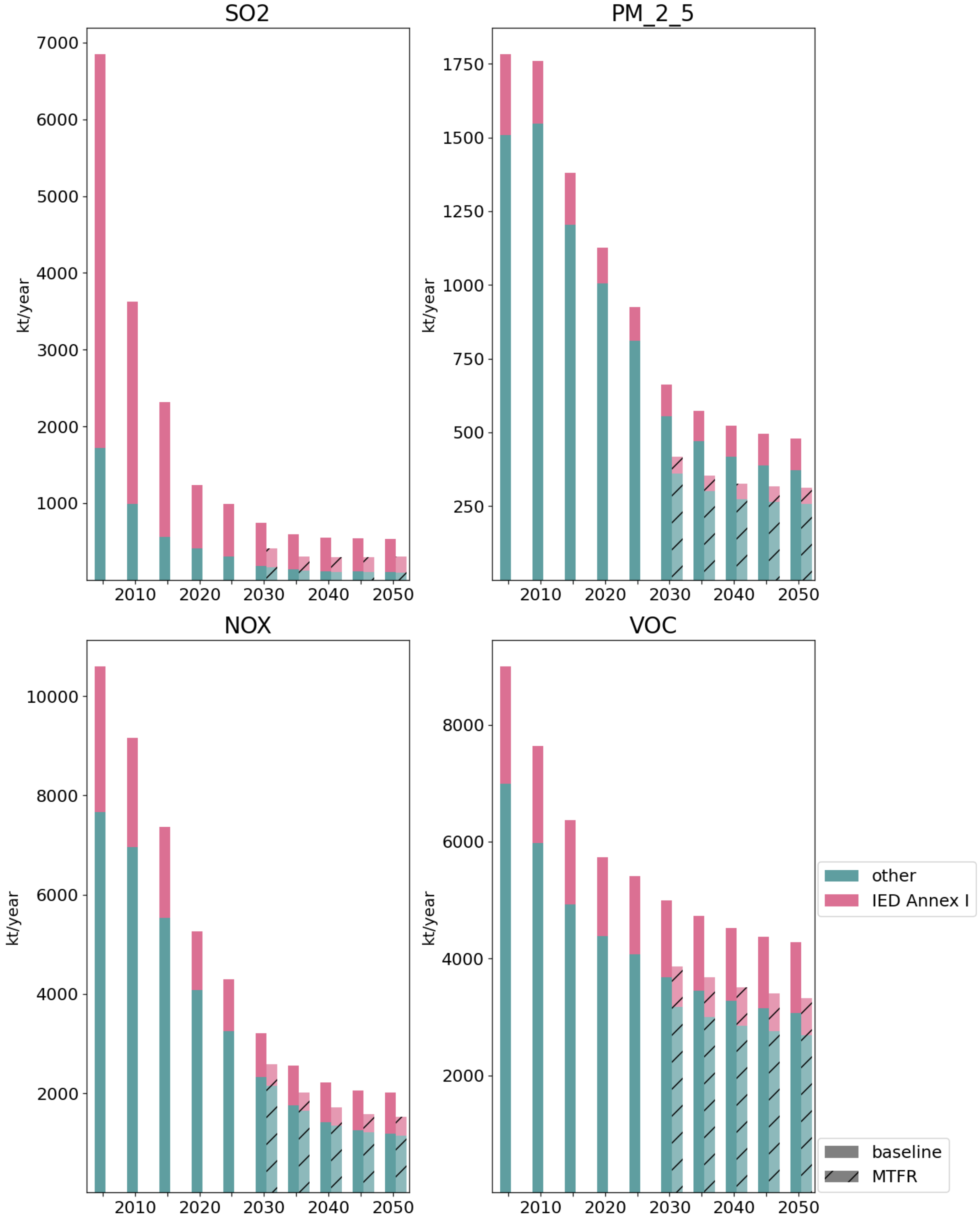
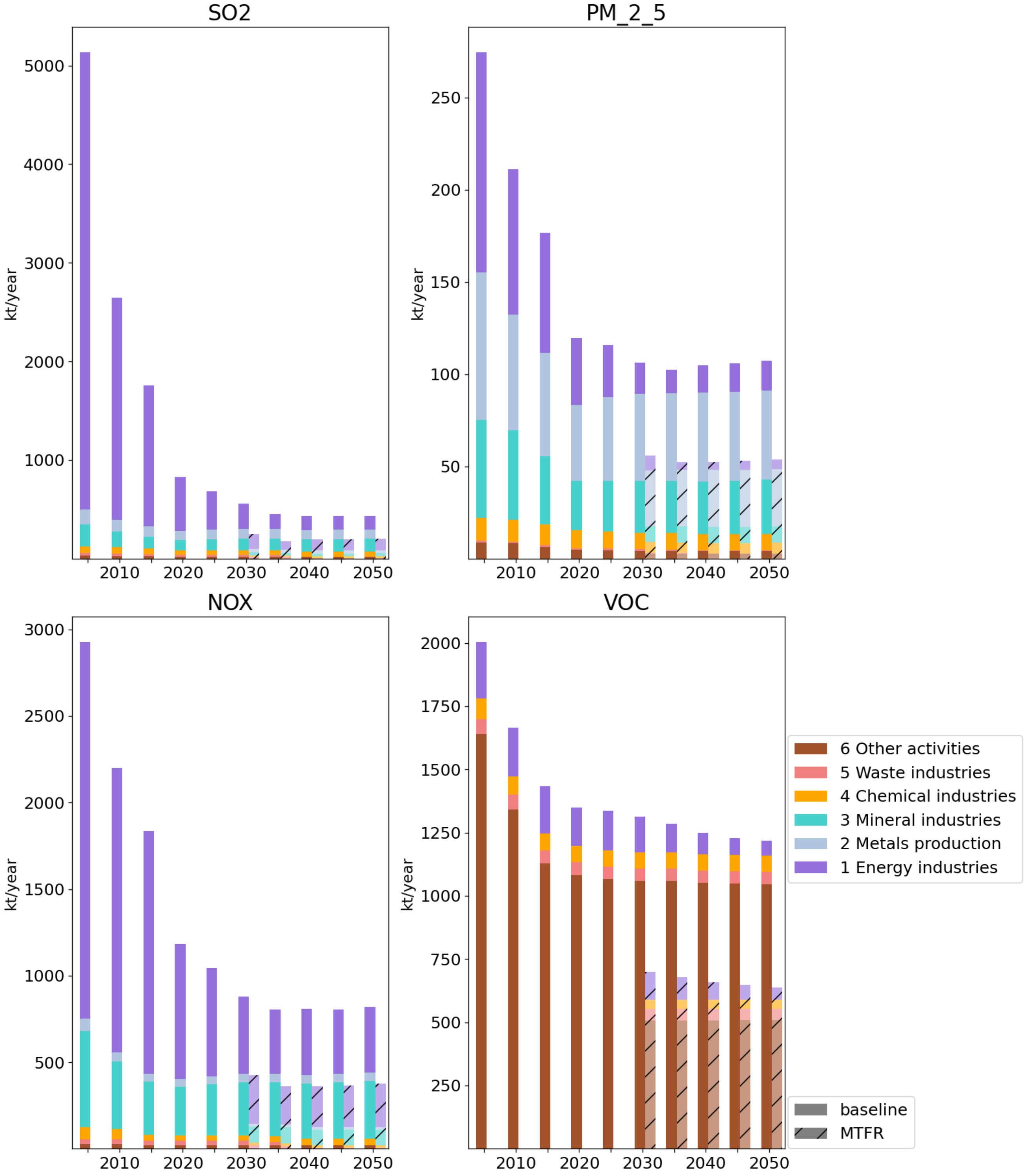


Figure 3-2 SO_2, NO_x, $PM_{2.5}$ and NMVOC emissions by the IED sectors in the Baseline and MTFR scenarios (kt/year) in the EU27.



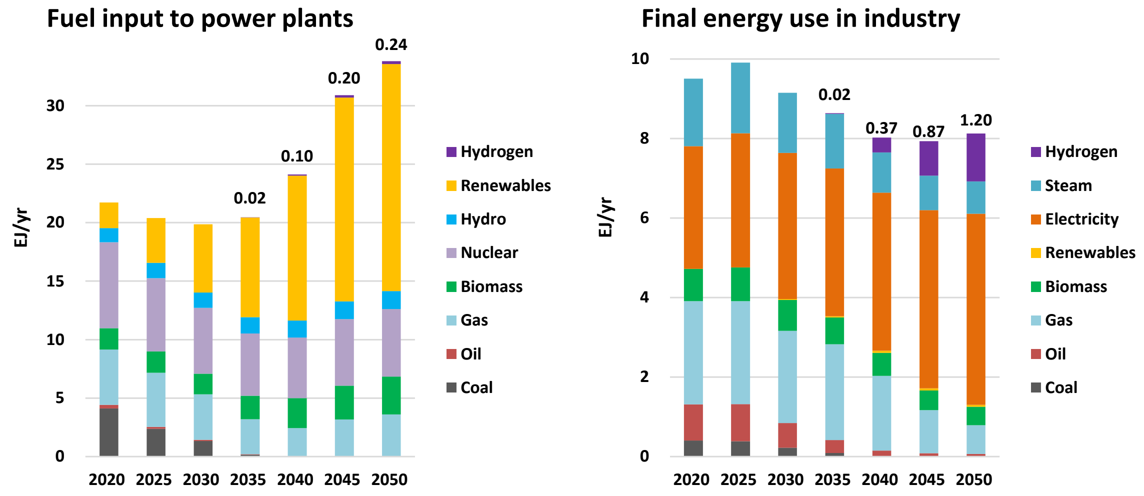
3.2 Impact of assumptions on emission trends and key sensitivities of the results

3.2.1 Evolution of energy consumption in the IED sectors

Emission trends reported in the previous section are largely determined by numerous assumptions on the evolution of the energy system in terms overall energy demand, energy intensity, as well as fuel mix in the IED sectors. The trends for underlying energy projections provided by the PRIMES model in the Baseline are driven by the objectives of the Fit for 55 package, which includes, among others, legislative targets on the transition towards renewable electricity deployment and improvement in the energy efficiency[47]. One of the package goals is to achieve climate neutrality for the EU by 2050, in which fuel substitution in heavy industries plays a substantial role. The proposed revisions to the IED aim to facilitate this package goal with a requirement for IED permit holders to conduct an energy audit or to implement an energy management system pursuant to Article 8 of Directive 2012/27/EU. This in turn has large impacts on the emissions of air pollutants.

As is shown in Figure 3-3, about half of the primary energy input to power and heat generation in the EU27 in 2020 was based on combustion of solid (coal and biomass) and gaseous fuels. By 2050, the share of combustible fuels is reduced to 20%, while coal is phased out and majority of the gas fired power plants are equipped with the CCS technologies. The largest increase in the future fuel mix is projected for renewables such as solar and wind power. Compared to other sources, the direct use of hydrogen for electricity generation is marginal. Decarbonization of the industry sectors by 2050 is reflected in the share of fuels for the final energy consumption (right panel in Figure 3-3). Combustion of fuels (mainly gas and liquids) drops from 50% to 20% in 2050, and is substituted by a rapid growth in the use of electricity, heat, as well as hydrogen. By 2050, the total final energy consumption in industries in the EU27 is projected to decline by 15% relative to 2020.

Figure 3-3 Share of fuel consumption in the power sector and in energy intensive industries in EU27.



3.2.2 Energy efficiency trends in industry and impacts on decarbonization

By 2050, the industry sector is expected to change rapidly in the context of the transition towards net-zero carbon economy. The PRIMES projections assume the continued presence of industrial

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[47] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550

activity within the EU, although there is a general trend towards higher recycling -i.e., less primary production- in the long-term macro-economic trends. In the PRIMES Industry module, the demand for useful energy forms is modelled first with a split into various industrial processes. The demand model links processes to exogenous macroeconomic activity by sector, organises the processes into flows and where applicable formulates substitutions between alternative processes (e.g., electrical vs thermal processing). Then, it models energy production in industry from various types of equipment and technologies (CHPs and boilers). For their operation, the purchase of fuels from the markets and the possible selling of excess fuels to the markets is modelled. PRIMES Industry determines the energy production system intertemporally with simultaneous consideration of heat recovery and horizontal energy efficiency investment.

Substitution possibilities, perfect or imperfect, as well as complementarities play an important role in the modelling of the correspondence between technology and processing types. Penetration of new technologies, energy savings, electrification and the use of alternative fuels are endogenous and dynamic depending on technological progress, prices, standards and policy targets. Perceived costs, uncertainty and risk factors influence costing and decisions, but can vary by scenario. The industrial sectors in PRIMES are split into 9 sectors and 31 subsectors, as well as over 200 different uses. The level of detail allows to account for different mitigation options by use, including understanding where and to what extent electrification is possible, what the effects of fuels shifts and equipment changes are.

As mentioned earlier, the decarbonisation of the industrial sector is a combination of a) fuel switching towards electrification and new fuels, b) energy efficiency gains including heat recovery, and c) changes in industrial output, i.e., shift towards higher recycling levels and lower primary production. In this section, the CO_2 emission trends are decomposed to quantify the relative contribution of different pre-defined factors to the change of one explained variable over the base year (2015) through 2030 and 2050[48]. As depicted in Figure 3-4, until **2030** the **reduction of energy intensity** has the highest impact on the CO_2 emissions reduction because of energy efficiency improvements and structural changes away from energy intensive industrial sectors. Strengthening permit conditions for energy efficiency, as included in the proposed revision to the IED, can help achieve this in the immediate timeframe. On the contrary, in **2050**, the **shift towards electrification, renewables and new fuels** overtakes the mitigation impacts of energy efficiency improvements.

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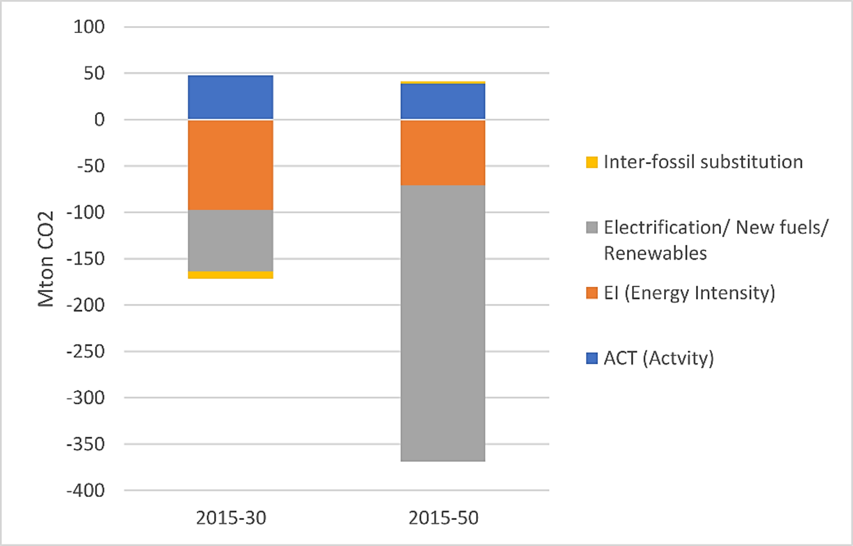
[48] Further details on methodology is provided in ANNEX IX and in Marcucci, A., & Fragkos, P. (2015). Drivers of regional decarbonization through 2100: A multi-model decomposition analysis. Energy Economics, 51, 111-124.

Figure 3-4 Decomposition of CO_2 emissions in Industry



Impacts of different decarbonisation components varies significantly across key industrial subsectors. As shown in Figure 3-5 and Figure 3-6, the improvements in energy efficiency dominate the CO_2 emissions reductions in iron and steel, chemicals and non-metallic minerals sectors until 2030. Contrary, for non-ferrous metals, electrification is already dominant in 2030 and continues to be in 2050. Electrification, new fuels and the shift to renewables has the highest impact on the reduction of CO_2 emissions for the rest of the sectors in 2050 as well. Figure 3-7 shows that for paper and pulp, and other industries (engineering, textiles and leather, food drinks and tobacco and other), until 2030 there is an almost equal contribution of energy efficiency improvements and fuel switches to the reduction of CO_2 emissions. By 2050, similarly to the previous sectors, shifts to electrification, new fuels and renewables have higher mitigation impacts in both sectors.

Figure 3-5 Decomposition of CO_2 emissions in a. Iron and Steel and b. Non-ferrous metals

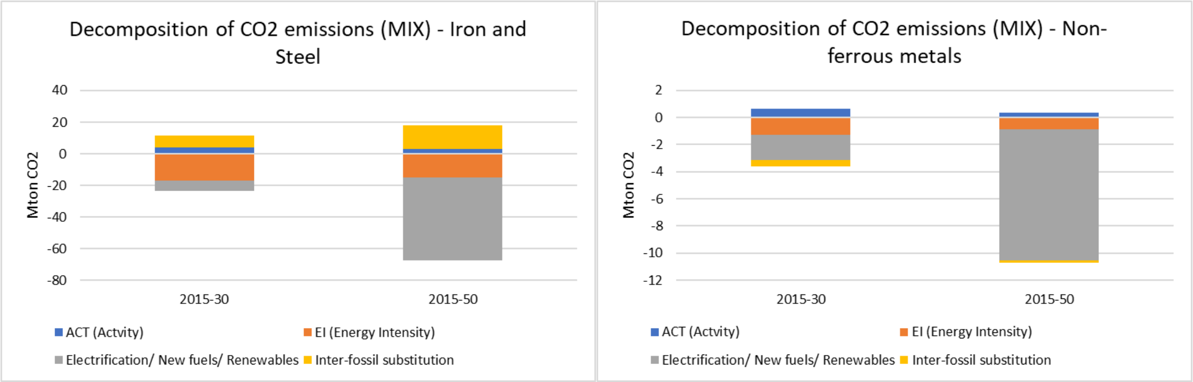


Figure 3-6 Decomposition of CO_2 emissions in a. Chemicals and b. Non-metallic minerals

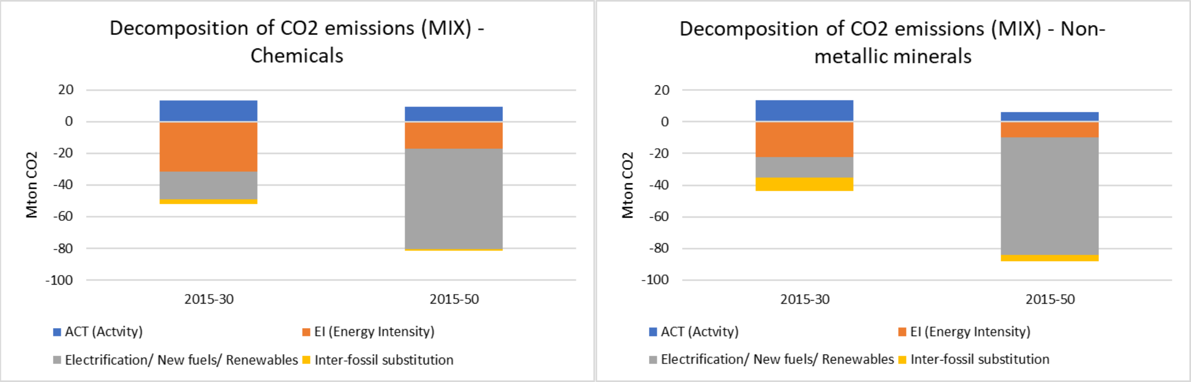
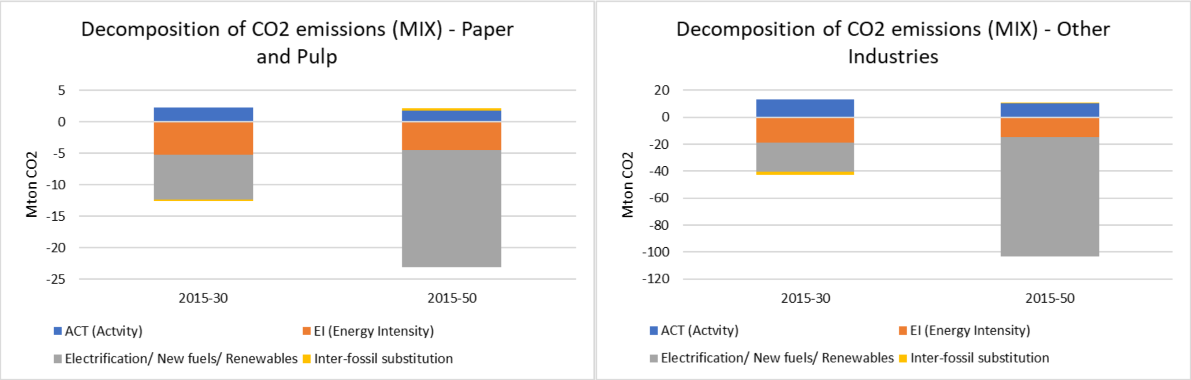


Figure 3-7 Decomposition of CO_2 emissions in a. Paper and Pulp and b. Other Industries



3.2.3 Removal efficiency and application rates of air pollutant emission controls

Besides assumptions about the future energy consumption structure as reported above, another factor that has a decisive impact on the projected emission trends are the assumptions related to the efficiency of emission control options and their application rates over the modelled time horizon. The technology options represented in the GAINS framework correspond to the set of BATs for each pollutant and sector. The following broad group of control options are considered in GAINS:

-treatment of fuels before combustion (e.g., low-sulfur coal and oil products)

-combustion modifications (e.g., sorbent injection, low-NO_x burners)

-treatment of flue gases (e.g., desulfurization, bag filters)

-good practices (mostly for fugitive emissions; storage and handling of fuels/materials)

-measures to control process emissions

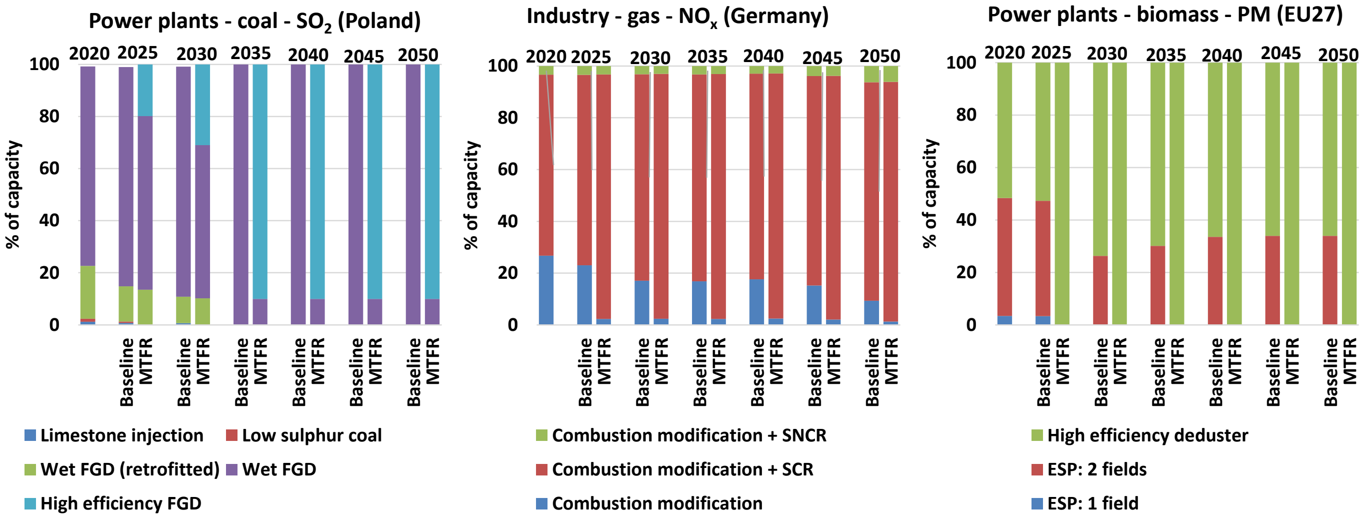
Table 3-1 summarises removal efficiency characteristics of all technologies applied in GAINS to control SO_2, NO_x and $PM_{2.5}$ emissions from the IED sectors. It is noted that a) these efficiencies do not change over time in the model, and b) the control efficiency of low-sulphur fuels depends on the initial sulphur content of the fuel to be replaced. Furthermore, measures to control process emissions are process-specific and depend critically on the type of technology and equipment used. Due to the complexity and in some cases limited availability of data related to industrial process emissions, a more aggregated approach distinguishing three generic stages of SO_2 and NO_x control with different efficiencies and different costs is adopted in GAINS to reflect the overall potential for removing emissions from these sources.

Table 3-1: Removal efficiency of abatement technologies applied in GAINS to control emissions from the IED sectors.

Pollutant	Sector	Abatement technology	Removal efficiency (%)
SO_2	**Combustion (all)**	Low sulphur coal Low sulphur coke Low sulphur fuel oil Low sulphur diesel oil	country specific
	Industry boilers and furnaces	In-furnace control - limestone injection	60
		Industry - wet flue gases desulphurisation (FGD)	95
		High efficiency flue gases desulphurisation	98
	Power and heat	In-furnace control - limestone injection	60
		Power plant - wet flue gases desulphurisation, already retrofitted	90
		Power plant - wet flue gases desulphurisation	95
		High efficiency flue gases desulphurisation	98
	Processes	Process emissions - stage 1 SO2 control	50
		Process emissions - stage 2 SO2 control	70
		Process emissions - stage 3 SO2 control	90
		Good practice in oil and gas industry - flaring	95
NO_x	**Industry boilers and furnaces**	Combustion modification on solid fuels fired industrial boilers and furnaces	50
		Combustion modification and selective non-catalytic reduction on solid fuels fired industrial boilers and furnaces	70
		Combustion modification and selective catalytic reduction on solid fuels fired industrial boilers and furnaces	80
		Combustion modification on oil and gas industrial boilers and furnaces	50
		Combustion modification and selective non-catalytic reduction (SNCR) on oil and gas industrial boilers and furnace	70
		Combustion modification and selective catalytic reduction (SCR) on oil and gas industrial boilers and furnaces	80
	Power and heat	Combustion modification on existing brown coal power plants	65
		Combustion modification and selective catalytic reduction on existing brown coal power plants	80
		Selective catalytic reduction on new brown coal power plants	80
		Combustion modification on existing hard coal power plants	50
		Combustion modification and selective catalytic reduction on existing hard coal power plants	80
		Selective catalytic reduction on new hard coal power plants	80
		Combustion modification on existing oil and gas power plants	65
		Combustion modification and selective catalytic reduction on existing oil and gas power plants	80
		Selective catalytic reduction on new oil and gas power plants	80
		Selective non-catalytic reduction on existing biomass fired power plants	70
		Selective non-catalytic reduction on new biomass fired power plants	70
	Processes	Process emissions - stage 1 NOx control	40
		Process emissions - stage 2 NOx control	60
		Process emissions - stage 3 NOx control	90
		Good practice in oil and gas industry - flaring	95
$PM_{2.5}$	**Industry boilers and furnaces**	Cyclone - industrial combustion	30
		Good housekeeping: industrial oil boilers	30
		Wet scrubber - ind.comb.	93
		Electrostatic precipitator: 1 field - industrial combustion	93
		Electrostatic precipitator: 2 fields - industrial combustion	96
		High efficiency deduster - industrial combustion	99
	Power and heat	Cyclone - power plants	30
		Wet scrubber - power plants	93
		Electrostatic precipitator: 1 field (ESP1) - power plants	93
		Electrostatic precipitator: 2 fields (ESP2) - power plants	96
		High efficiency deduster (HED) - power plants	99.5
	Processes	Cyclone - - industrial process	30
		Wet scrubber - industrial processes	93
		Electrostatic precipitator: 1 field - industrial processes	93
		Electrostatic precipitator: 2 fields - industrial processes	96
		High efficiency deduster - industrial processes	99
		Good practice: storage and handling	10
		Good practice: ind.process - stage 1 (fugitive)	40
		Good practice: ind.process - stage 2 (fugitive)	80
		Good practice in oil and gas industry - flaring	95

The technologies listed above are applied in the GAINS scenarios at different rates in order to simulate implications of policies and emission standards. Choice of technologies and their application rates are year- and country-specific and reflects a stringency of modelled control strategy (e.g., the Baseline CLE assumptions vs. MTFR). Figure 3-8 provides a set of examples of application rates of controls options in the Baseline and MTFR scenarios. Full dataset is available in the online GAINS model, as well as appended as a table to this report.

Figure 3-8 Application rates of SO_2, NO_x and PM controls for the power and industry combustion sectors in Poland, Germany and EU, in the Baseline and MTFR scenarios. Technology codes listed in Table 3-1 above.



In order to examine how the assumptions in GAINS align with the IED provisions, three sensitivity scenarios have been defined and compared to the Baseline and MTFR cases:

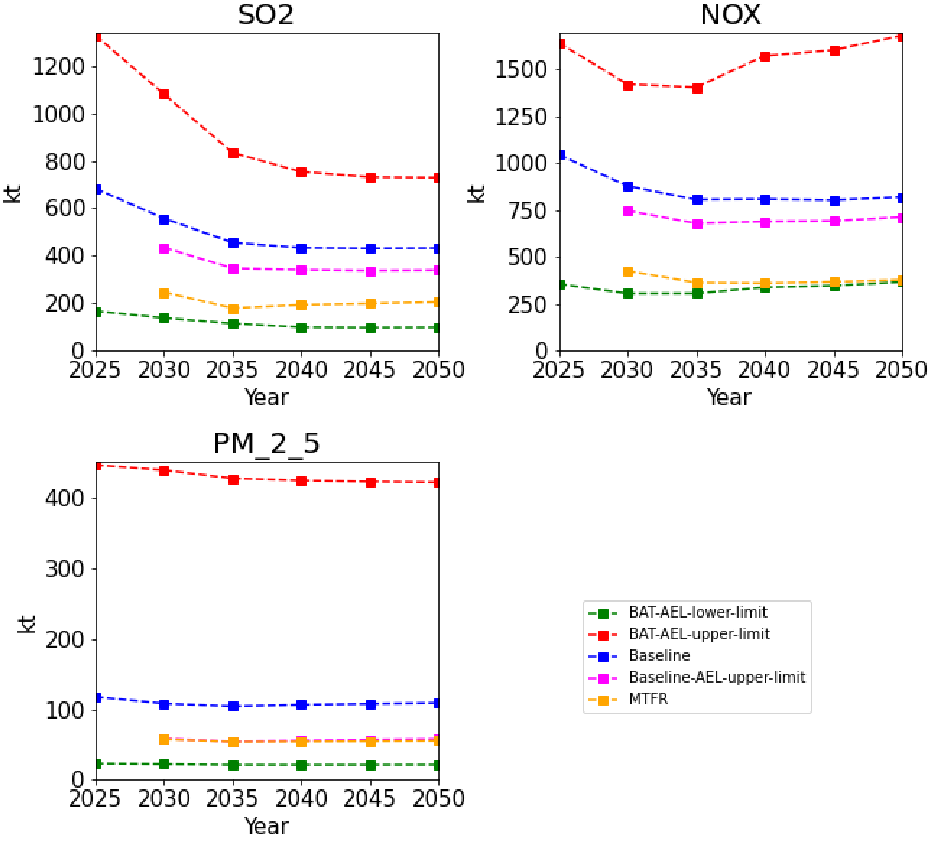
1) a scenario in which all emission factors in the IED sectors are scaled to match the upper range of corresponding emission limits ('BAT-AEL-upper limit'),
2) a scenario in which the lower end of ranges is attained ('BAT-AEL-lower-limit'), and
3) a scenario in which emission factors for only those GAINS sectors that are above the upper end of BAT-AEL in the Baseline are made equal the AEL upper limit ('Baseline-AEL-upper limit').

As shown in Figure 3-9, the total Baseline emissions of SO_2, NO_x and $PM_{2.5}$ are significantly lower than in the 'BAT-AEL-upper-limit' case at the EU27 level, suggesting that for key emitting sources the assumptions in GAINS go beyond the prescribed limit values.

The aggregated emissions of SO_2 and $PM_{2.5}$ in the MTFR scenario are above the 'BAT-AEL-lower-limit' trajectory, while for NO_x the difference between these two cases is only marginal. There are several reasons for this finding. First, the MTFR control strategy assumes a set of technological constraints that limit the adoption of the most efficient techniques to the full extend (see section 2.1.1). The MTFR controls are based on existing technological characteristics of current BATs, without considerations of technological progress that might improve the removal efficiencies. Due to complexities and data availability for several emission sources, some of the technologies are represented in a generic form that might underestimate the actual removal rates achieved in individual process stages (e.g., Table 3-1, high efficiency deduster (HED) represents both baghouse filters and 3-field ESPs that might achieve a higher efficiency depending on the IED activity and fuel type). Further, a combination of BATs (packages of technologies, e.g., ESP+FGD+SCR) applied in particular sequence leads to additional reduction of particulate matter, which is not explicitly modelled in GAINS. Finally, the BAT-AEL ranges as adopted in this exercise (see Table 2-3) do not differentiate between, e.g., age or size of installations for which the MTFR is applied.

As shown further in Figure 3-9, the full enforcement of at least the higher end of BAT-AELs in each IED sector in the 'Baseline-AEL-upper limit' case results for all three pollutants in an emission trajectory below the Baseline levels, whereas the most pronounced difference is observed for the emissions of $PM_{2.5}$. It is reported that the combustion-based IED activities (Sector IED 1) are affected significantly less than aggregated emissions from industrial process activities. This sensitivity scenario suggests an additional abatement potential from the existing legislation, however, the results need to take into consideration a range of uncertainties that is associated with the representation of BAT-AELs in the GAINS modelling approach, as has been elaborated in Section 2.1.4 and Box 2. Furthermore, the additional potential is limited based on the current approach to setting ELVs which are typically set based on the upper range of BAT-AELs (applicable for between 75 and 85% of permit conditions). This additional potential can however be realised by the proposed revision to the IED and the requirement to set ELVs based on the lower range of BAT-AEL by default, unless evidence is provided to justify a less strict ELV (Section 1.3). In addition to better alignment of ELVs with the lower ranges of BAT-AEL, the additional potential identified assumes that derogations do not apply (whereas between 2017 – 2018, 133 Article 15(4) derogations were granted across 98 installations). Thus, to realise the additional potential there is the need to minimise the use of derogations.

Figure 3-9 Evolution of total SO_2, NO_x and $PM_{2.5}$ emissions in the Baseline and MTFR scenarios (EU27) compared to hypothetical projections in which the upper and lower ends of BAT-AELs are attained in each IED sector and MS. Pink line is a scenario in which emission factors for sectors still above the upper end in the Baseline are made equal the AEL upper limit.



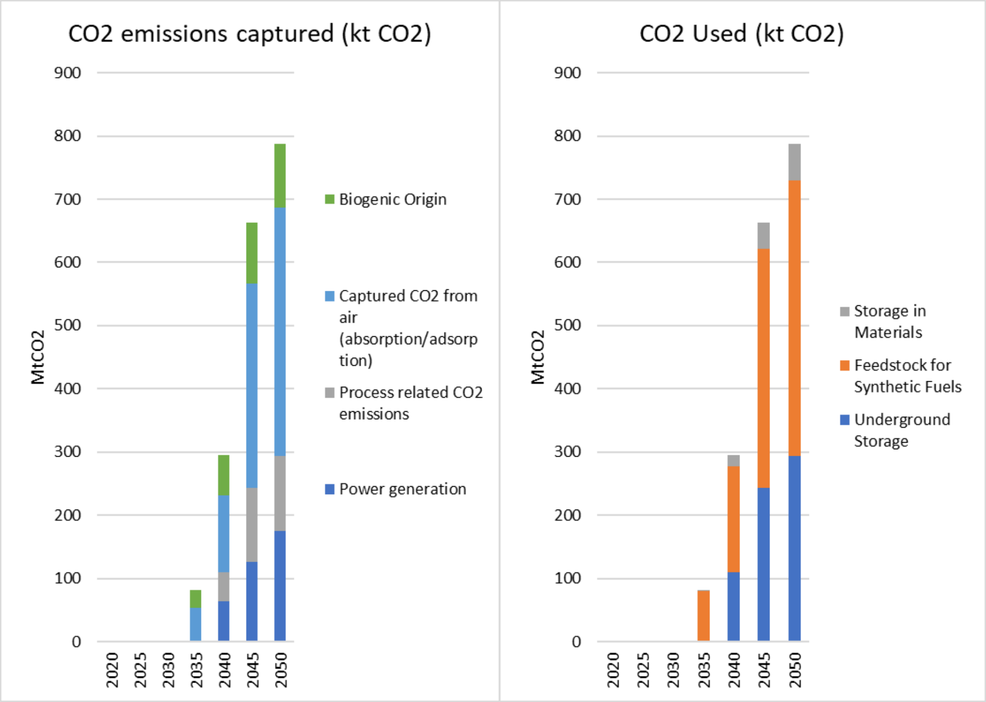
3.2.4 The role of emerging technologies and fuels in the emission trends

Carbon capture, utilization and storage (CCUS)

The PRIMES model includes carbon capture technologies as well as different options to use or store the carbon. Carbon capture occurs in the power generation sector both for fossil fuels as well as for biomass (BECCS) combustion. Further, carbon capture occurs in the scenario results for process-related CO_2 emissions, particularly in iron and steel as well as cement industries (Figure 3-10, left panel). While iron and steel making in the long run is expected to use hydrogen as a reducing agent and therefore reduce needs for carbon capture, in the cement industry CCS is considered as one of the main options to reduce process emissions of CO_2 during the clinker production phase. The PRIMES model also considers Direct Air Capture (DAC) as a mitigation option. Once the carbon is captured, different pathways (Figure 3-10, right panel) can be followed in the PRIMES model[49]:

- Long term underground storage
- Use as feedstock for synthetic fuel production (RFNBOs)
- Use for materials production i.e., storage in materials

Figure 3-10 Carbon capture and use in the Baseline scenario (Source: PRIMES)



Application of carbon capture technology has also an impact on the air pollutant emissions. Figure 3-11 shows the use of gas for power generation in the EU27 countries by 2050, differentiating between combustion with and without CCS. As can also be seen in Figure 3-11, by 2050 nearly all gas fired power plants are projected to be equipped with CCS systems. In GAINS, it is assumed that the power plants with CO_2 capture are constructed as a package together with the most efficient end-of-

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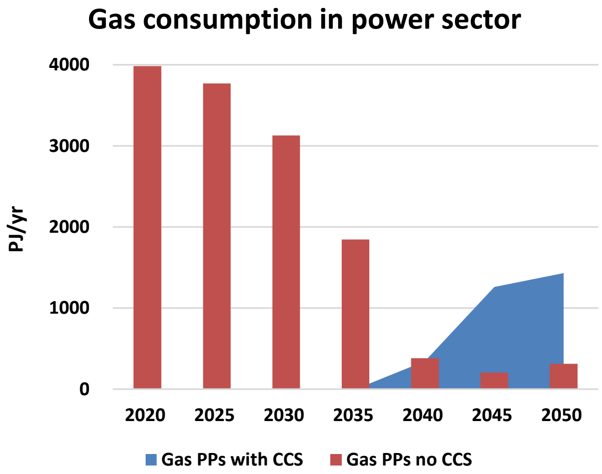
[49] The options for CCUS are currently undergoing revision and updating in the PRIMES model; the results presented here, represent the status quo at the time of the running of the Baseline scenario.

pipe controls for SO_2/NO_x/PM. This assumes that the flue gases have to be cleaned before entering the carbon capture process. Correspondingly the emission factors for the CCS-equipped power plants are significantly lower compared to conventional technologies. Impact of CCS on the air pollutant emissions from the industrial process activities is not explicitly modelled in the current version of GAINS.

Figure 3-11 Consumption of gas in the power plants with and without CCS in the Baseline scenario, EU27 (Source: PRIMES).



Hydrogen

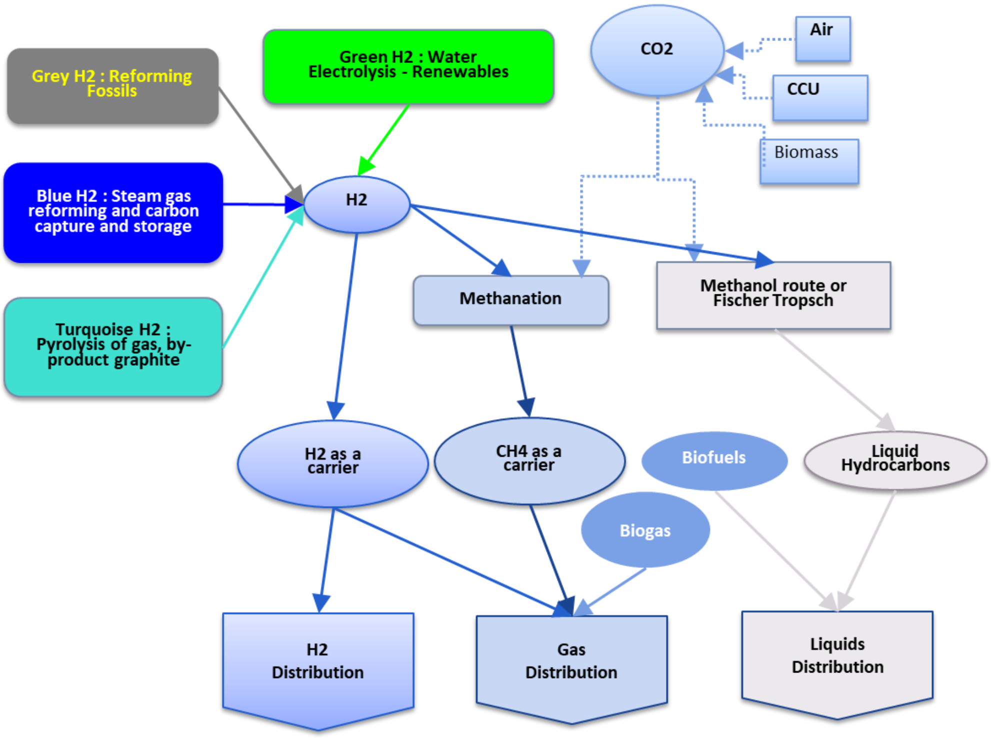
In PRIMES full-scale energy projections, hydrogen is considered as a fuel as well as a feedstock for industrial processes (Figure 3-12). Hydrogen can be used in pure form or blended with methane gas from fossil or renewable origin (natural gas, biomethane, or e-CH4), depending on the sector or subsector. Currently hydrogen is primarily obtained through steam methane reforming (SMR) of natural gas. However, SMR produces CO_2 emissions, and is therefore not an option in a decarbonization context without control measures. For hydrogen production to be compliant with a net-zero scenario the following options exist:

- Green H_2 from renewable or low carbon electricity (according to the latest revision of the Renewable Energy Directive the electricity should be from renewable energy or from low-carbon sources -incl. nuclear if certain conditions are met)
- Steam reforming of natural gas and CCS: no underground storage of CO_2
- Gas pyrolysis producing H_2 and graphite: not yet mature

The PRIMES model considers primarily the first option, as being the most plausible future option for hydrogen production.

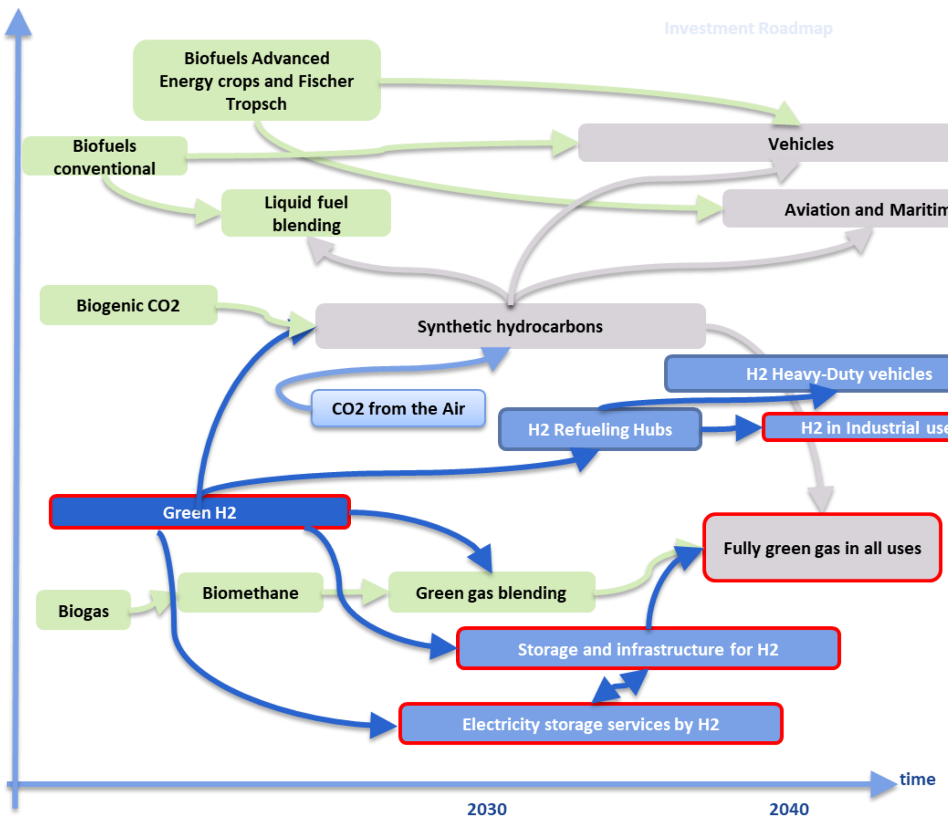
Hydrogen can further be transformed in liquid or gaseous renewable fuels of non-biological origin (RFNBO) through methanation, methanol route, Fischer-Tropsch synthesis. While currently these technologies are not yet mature, they are expected to become available over the next decade. When producing liquid or gaseous RFNBOs also carbon molecules are required, the PRIMES model considered the following two options for CO_2 feedstock: 1) CO_2 capture from air (immature and uncertain technology) and 2) Biogenic CO_2 (feasible but not ready at an industrial scale). In PRIMES, H_2 distribution is possible in pure form where the infrastructure is expected to become available, both within countries and across (EU) borders. Blending into the natural gas grid is feasible in the short term, however regulation and incentives are needed.

Figure 3-12 Schematic overview of the hydrogen pathways in PRIMES (source: E3Modelling)



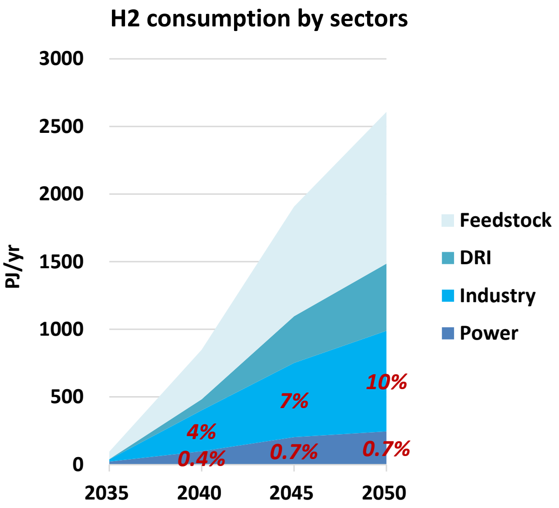
Hydrogen combustion is present in PRIMES for power production and in multiple industry sectors. Over the projection period, additional uses are expected to become available. **Hydrogen in the power generation sector** is primarily used as a longer-term storage option for variable renewable energy sources and to substitute natural gas in gas turbines. The model includes potential use of hydrogen in the power generation sector both in fuel cells as well as in gas turbines in a blended mix with methane gas of different origins (biogenic, e-gas) (Figure 3-13). In the Baseline scenario for economic reasons only gas turbines are used with a hydrogen gas blend; this allows the turbines to be used with multiple blends and a continued use of existing turbines with minor modifications of existing gas turbine power plants which are used primarily for flexibility purposes in the system. In the Baseline all H_2 used for power generation is considered as combusted in a mixture with methane gas reaching a maximum blend of 12% in the EU on average in the projection period. No fuel cells are currently used for power generation.

Figure 3-13 Schematic overview of hydrogen and other (emerging) fuels consumption in PRIMES (Source: E3Modelling)



Hydrogen in the industrial sector has multiple uses: combustion in a gas blend (as in power generation) or as reactor in different industrial processes (Figure 3-14). Currently most of the hydrogen used in industry is derived from on-site SMR. The key sectors using hydrogen are the fertilizer industry (ammonia production), refineries (for the cracking and desulphurization processes), and other minor uses in chemical sectors. In future, in the industrial sectors subject to IED, a strong shift towards higher efficiency and electrification is expected. Therefore, industrial H_2 consumption is expected to occur as a) a direct use of H_2 in chemical reactions (chemicals, iron and steel, clinker production) and b) a blend of hydrogen in gas mix (combusted in industrial CHPs for steam/heat production). All future uses of hydrogen are projected to transform away from SMR towards hydrogen production from electricity through electrolysis.

Figure 3-14 Consumption of hydrogen by sectors in PRIMES (Note: percentage indicates a share of H_2 in total fuel use in power and industry sectors in the Baseline).



As with any other combustion processes, the burning of H_2 is associated with occurrence of NO_x emissions. Information available in the literature indicates that the specific NO_x emission rates depend strongly on the share of hydrogen in the gas mix that is eventually combusted[50] [51] [52]. In the energy scenarios the blending ratios H_2/gas might be sector- and year-specific, which has an impact on the resulting NO_x emission factors. As illustrated in Figure 3-15, a general feature can be anticipated that a higher share of H_2 in the gas-mix results in higher NO_x emissions when compared to the combustion of methane gas. In the current GAINS scenarios (incl. Baseline and MTFR), combustion of hydrogen in the power and industry sectors and the resulting emissions are modelled independently by using generic emission factors of NO_x (i.e., without adjustments of emission factors for natural gas). These emission factors are based on an assumption of low H_2-blending ratios (<10%) and very high efficiencies of NO_x controls applied to the full extend.

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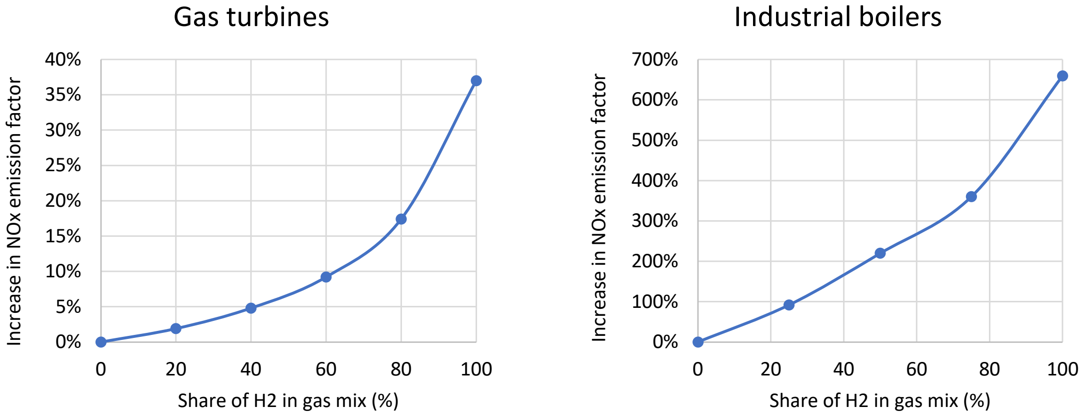
[50] Douglas et al. (2022): NO_x Emissions from Hydrogen-Methane Fuel Blends. Georgia Tech, Strategy Energy Institute, 2022. https://doi.org/10.35090/gatech/65963

[51] Cellek et al. (2018) Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels, International Journal of Hydrogen Energy, Volume 43, Issue 2. https://doi.org/10.1016/j.ijhydene.2017.05.107

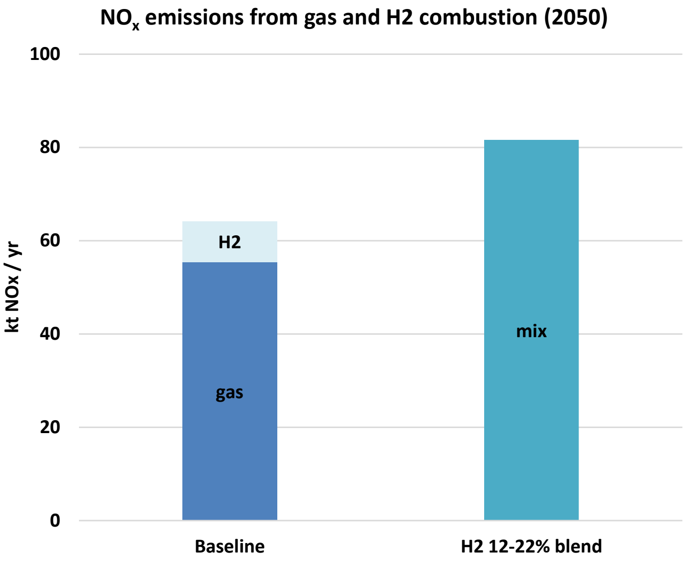
[52] Wright et al. (2022) Emissions of NO_x from blending of hydrogen and natural gas in space heating boilers. Elem Sci Anth, 10: 1. DOI: https://doi.org/10.1525/elementa.2021.00114

Figure 3-15 Change in NO$_x$ emissions from a combustion of different hydrogen-gas fuel blends (Source: 44, 45).



For this project, the existing NO$_x$ emission factors used in GAINS for the gas and H$_2$-consuming IED sectors have been compared to the recent literature data and a sensitivity to the assumed blending ratio H$_2$/gas has been tested. As shown in Figure 3-16, total NO$_x$ emissions from the combustion of gas in power plants (excluding gas engines) and industries in the Baseline is about 55kt NO$_x$ in 2050. In the same year the GAINS model estimates nearly 10kt NO$_x$ that is emitted from burning H$_2$ in the IED sector 1. The sensitivity calculation takes a different approach in which gas and H2 are not combusted separately but assumes average blending ratios of 12% (power plants) and 22% (industry) of H$_2$ in the EU27 gas mix (consistent with the PRIMES values). Applying revised emission factors for gas-mixes from the literature reviews, the NO$_x$ emissions for the same amount of gas and H2 - now burned as a blend - increase by 27% relative to the Baseline in 2050 (column ‘H2 12-22% blend’ in the figure below). It is noted that in this exercise a) adjusted emission factors are based on Source ref. 44 (left panel in Figure 3-15), b) the existing control techniques for natural gas-fired installations are used at the same application rates as in the Baseline also for the H$_2$/gas co-combustion, and c) the hydrogen consumption for Direct Reduced Iron (DRI) is not associated with any increase in the process emissions of NO$_x$.

Figure 3-16 Comparison of the EU27 NO$_x$ emissions from the combustion of methane gas and hydrogen (power sector and industries) in the Baseline (left column) and under revised assumptions on emission factors and H2/gas blending ratios (right column).



Ammonia

The PRIMES model currently does not include ammonia as an energy carrier or a feedstock. Ammonia production is included in the basic chemical sector within the fertiliser industry. It is assumed that future ammonia production will shift from using hydrogen produced through SMR to hydrogen produced from electrolysers. In the current energy balances the H_2 used by the chemical industry is not explicitly visible: in PRIMES however, future use of H_2 by the chemical industry is visible, as the production of H_2 from electrolysis is included in the transformation sector.

There are considerations in literature to use ammonia as a fuel - particularly in the maritime sector[53] [54]. The use of ammonia however requires dedicated or bi-fuel engines for the ships and most importantly requires the development of dedicated infrastructure in the ports, as it is not possible to mix ammonia with other fuels. Similar infrastructure considerations apply for other uses of ammonia as a fuel. However, if the infrastructure issue were solved and the price of ammonia production becomes similar to other e-fuels, then it could be potentially a substitute for any synthetic energy carrier already included in the modelling.

Combustion of ammonia can potentially also have impacts on the emission levels from the IED sectors. Implications of the use of ammonia as a fuel is not modelled in the current version of the GAINS model. The literature sources[55] suggest the atmospheric pollution can occur in two ways: a) ammonia production, storage, and transport might lead to ammonia leaks that besides its toxicity can contribute to secondary $PM_{2.5}$ formation, and b) incomplete ammonia combustion leads to the formation of NO_x emissions. The challenges associated with the use of ammonia as a fuel, e.g., in the gas turbines, include issues such as low flammability/stability, and high NO_x emission. Efficiency of emission controls and potential benefits when using an ammonia/H_2 blend combustion is a subject of ongoing research[56] [57].

3.3 Drivers of emission reductions and emission reduction potentials

As described in Section 2.2.2, a decomposition analysis has been carried out in Task 2 that disentangled the contribution of key drivers behind changes in the air pollutant emission trends. Three counterfactual scenarios have been computed for each pollutant and IED activity in 2030 and 2050 that provide insights on the role of the following factors: a) how much the emissions would grow relative to 2020 in the absence of any mitigating component, b) how much of the emissions decline is due to changing economic structure, efficiency gains and fuel substitutions, and c) how much of the emissions decline is through an adoption of end-of-pipe controls in the Baseline ("2030 CLE effect" in below Figure) and MTFR scenarios ("2030 Additional potential").

As can be seen in Figure 3-17, at the EU27 level the structural changes are the dominating reduction factor for SO_2 and NO_x in 2030 and 2050, whereby the IED sector 1 (Energy industries) is the largest contributor to the emission decline. This result is a combined effect of reduced energy intensity as well as cleaner fuel mix. For $PM_{2.5}$, the reductions due to structural changes are largest for energy

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[53] McKinlay, C. J., Turnock, S. R., & Hudson, D. A. (2021). Route to zero emission shipping: Hydrogen, ammonia or methanol? International Journal of Hydrogen Energy, 46(55), 28282–28297.

[54] IEA. (2021). Net Zero by 2050. IEA, Paris. https://www.iea.org/reports/net-zero-by-2050.

[55] Al-Breiki, M., & Bicer, Y. (2021). Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. Journal of Cleaner Production, 279, 123481. https://doi.org/10.1016/j.jclepro.2020.123481.

[56] Kobayashi et al. (2019) Science and technology of ammonia combustion, Proceedings of the Combustion Institute, Volume 37, Issue 1-109-133, 2019, https://doi.org/10.1016/j.proci.2018.09.029.

[57] Li et al. (2023), Research progress of ammonia combustion toward low carbon energy, Fuel Processing Technology, Volume 248, 2023, https://doi.org/10.1016/j.fuproc.2023.107821.

industries in 2030, while the contribution from other IED sectors (metals and mineral industries) increases significantly by 2050. It is also noted that in some countries (e.g., Ireland, Latvia) the relative increase in the share of biomass and waste combustion (mainly in 2030) counteracts the emission reductions achieved by other (structural) abatement factors. In some cases (e.g., Belgium, Hungary) the production of chemicals has driven growth in emissions.

Emission reductions induced by control technologies are comparatively smaller than for structural change - especially for SO_2 - suggesting that by 2050 the BATs are applied in the Baseline over a relative clean energy and industrial system. At the EU and MS level, the energy industries benefit the most from this abatement component, followed by reductions achieved in the cement manufacturing. The analysis also reveals that there is a large potential for additional reductions from the MTFR measures. By 2050, the largest contributors to the emission reductions in MTFR in the EU are estimated for the mineral industries and metals production (IED sectors 3 and 2), and in some countries also the chemical industry achieves significant reductions under the MTFR scenario assumptions. In general, the decomposition analysis shows large relative differences across MSs in the role of mitigation factors. Results for individual counties are summarised in ANNEX V (Figure 10-1, Figure 10-2, Figure 10-3).

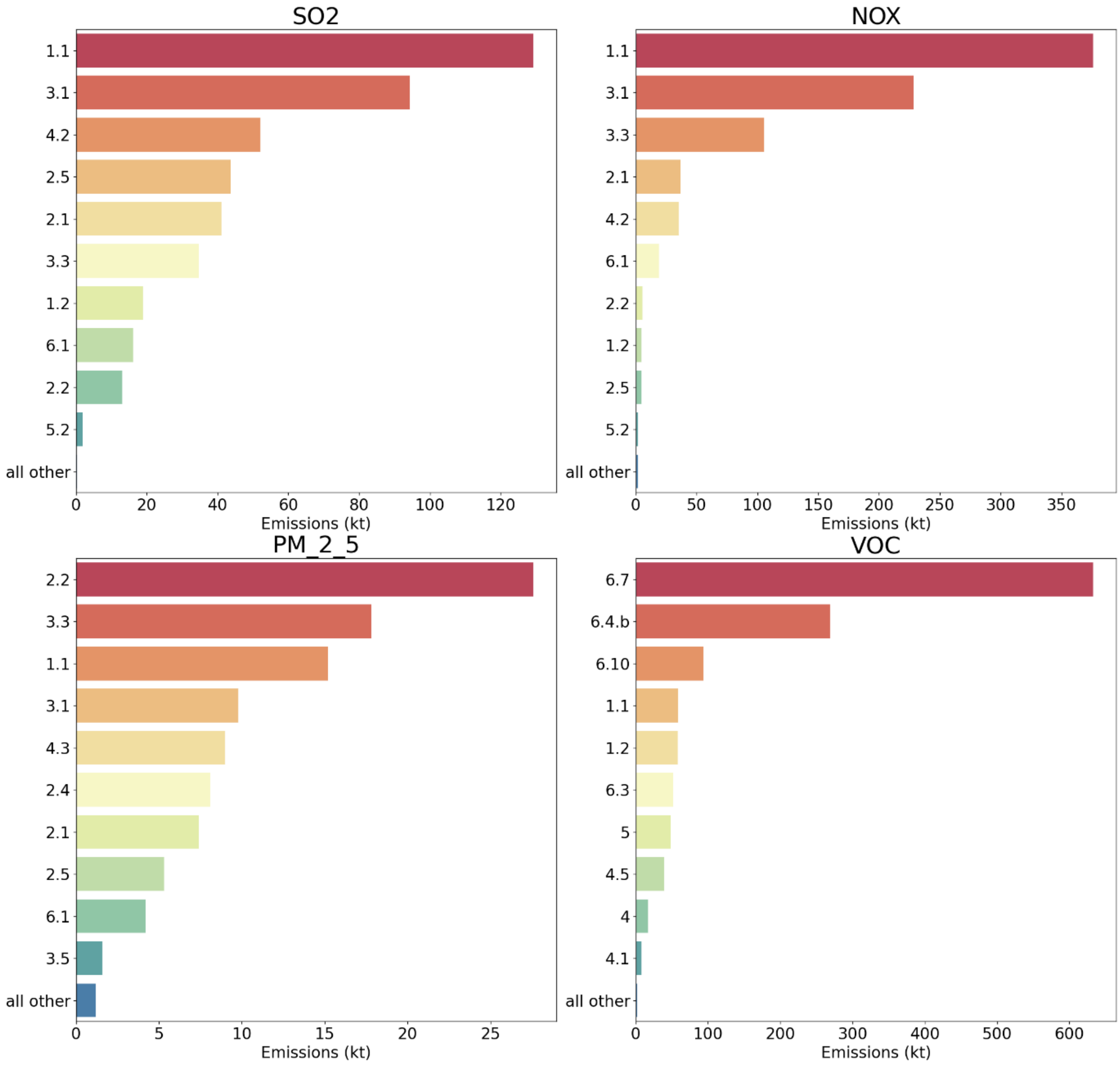
With regard to the effectiveness of the IED to limit air pollution from the heavy industries, it can be concluded that the existing provisions are effective in limiting emissions increase in spite of projected growth in activities. Their successful implementation results in decline of air emissions in the combustion-based IED sectors by 2050. Although the share of emission reductions estimated in the Baseline by the end-of-pipe controls by 2050 is smaller compared to structural changes or a cleaner fuel mix, it needs to be emphasised that much greater reductions than projected in the period 2020-2050 in the IED sectors have already been achieved in the period 2005-2020. As illustrated in Figure 3-2, these reductions represent 80% of SO_2, and 60% of NO_x and $PM_{2.5}$, with the largest reductions for all pollutants achieved in the IED Sector 1 (Energy industries). In that period, the end-of-pipe controls have been the dominant factor in the emission decline. It is also expected that the improved stringency of the revised IED would result in additional reductions quantified in this analysis through the MTFR scenario.

Figure 3-17 Contribution of key mitigation factors to the reductions of SO_2, NO_x and $PM_{2.5}$ by the IED sectors in the Baseline and MTFR scenarios.(Note: IED codes in Table 1-1)

3.4 Key contributing activities

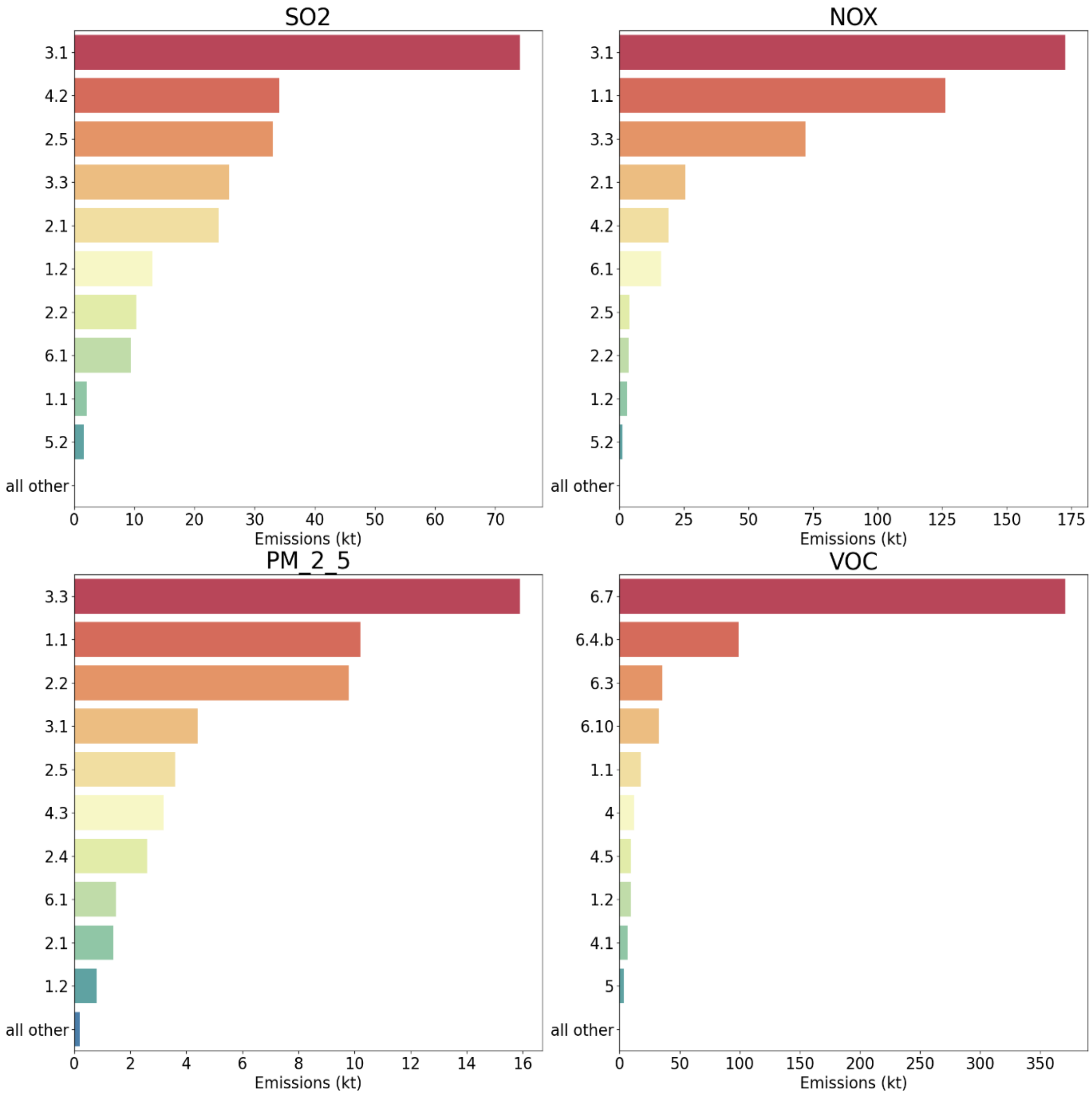
In Task 2.2, the individual IED activities have been ranked for the EU and MSs according to their contribution to the overall emissions in the Baseline (Figure 3-18). In 2050, the top emitter of SO_2 and NO_x in EU27 is the combustion of fuels (biomass and gas) in the energy sector. For SO_2, the other activities include cement plants, chemical industries and non-ferrous metals. For NO_x, mineral-products industries (cement, glass making) contribute by significant shares followed by production of metals and chemicals. For $PM_{2.5}$, combustion in energy industries is ranked below process activities such as steel and glass production but is above production of cement and fertilisers. The top emitters of NMVOC by 2050 in this assessment are surface treatment (solvents) and food production. Results for individual countries are summarised in ANNEX VI (Figure 11-1, Figure 11-2, Figure 11-4, Figure 11-5).

Figure 3-18 Ranking of top IED emitters by activity and pollutant in 2050 in the Baseline (EU27). (Note: IED codes on Y-axis are explained in Table 1-1)



As a next step, the IED activities mapped to the GAINS sectors were ranked by the additional mitigation potential in 2050 computed as a difference between emission levels in the Baseline and MTFR scenarios. As can be seen in Figure 3-19, reductions in cement manufacturing suggest the largest potential for SO_2 followed by the sulfuric acid and non-ferrous metals production. Significant additional abatement potential is also reported for the production of glass, sintering and pelletizing of iron ore. In the case of NO_x, the potential is dominated by mineral industry (cement, glass) and energy combustion (biomass, gas). Glass and steel making are the process activities with the largest potential for reducing $PM_{2.5}$, followed by biomass combustion in energy industries, cement and smelting of non-ferrous metals. The IED activity 6.7 'Surface treatment' (solvents) shows by far the greatest potential for reducing the NMVOC emissions. The ranking of the reduction potential at the country level is provided in Annex VII (Figure 12-1, Figure 12-2, Figure 12-3, Figure 12-4).

Figure 3-19 Ranking of IED activity by the mitigation potential in MTFR by pollutant in 2050 (EU27). (Note: IED codes on Y-axis are explained in Table 1-1)



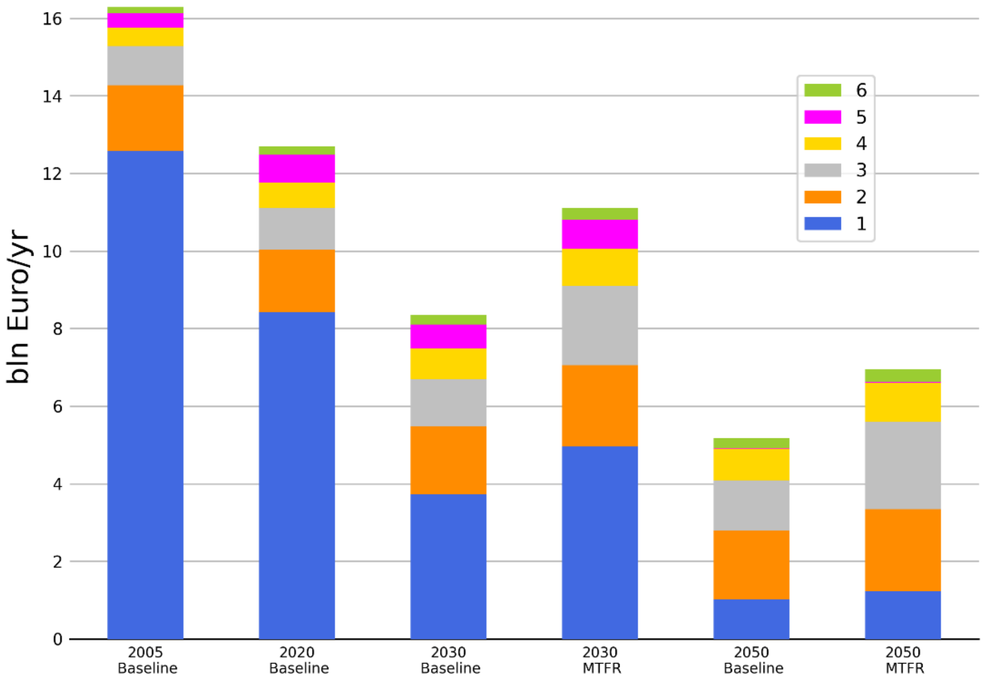
3.5 Trends in emission control costs for the IED sectors

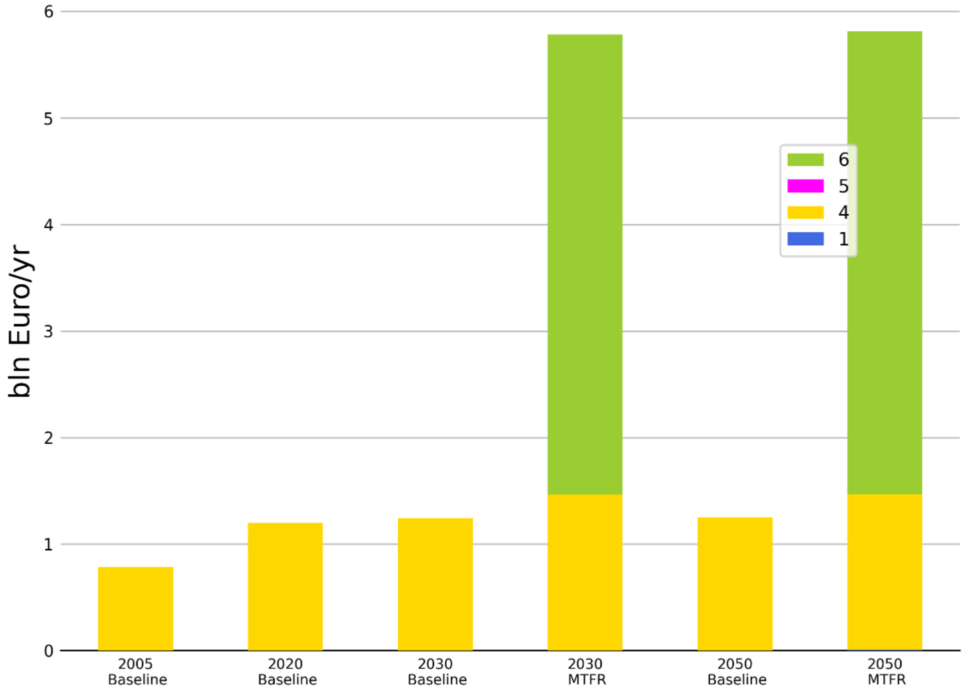
In 2020, the total cost to control emissions of SO_2, NO_x, $PM_{2.5}$ from all IED sectors is estimated at 12.7 billion $Euro_{(2015)}$ in the EU under an assumption of 4% discount rate for the annualization of the investment costs. These costs represent about 20% of the total annual control cost for both IED and non-IED sectors (incl. transport, buildings, etc.), and corresponds to nearly 0.7% of the industrial value added and 0.1% of GDP in 2020.

Similar to the decline in emission trends between 2020-2050, also the control cost decline in the Baseline scenario. By 2030, the total IED-control cost declines by one third, and by 60% in 2050 relative to the year 2020. As shown in Figure 3-20, the largest reduction in annual abatement costs is projected for the energy industries (IED 1) and is associated with the decline in expenditures needed to control pollutants from the fossil-fuels fired installations. In contrary, due to the increases in overall industrial production in some of the sectors and because of increased application rates of controls for industrial processes, the control cost in categories 2-4 slightly increases. Relative to the Baseline in 2030 and 2050, the total cost associated with implementation of the MTFR measures for the IED sectors is by 20-25% higher, whereby the most pronounced increase is reported for the cement and other mineral industries. In 2030, also the MTFR costs to control emissions from energy and combustion related activities are by 25% higher than in the Baseline.

The total NMVOC control cost (both IED and non-IED sectors) decline from nearly 3 bln € in 2020 to about 2.3 bln € in 2050, while the cost for the IED sectors remain rather stable between 2020-2050 (about 1.3 bln €). The MTFR controls of NMVOCs in 2050 are almost four times more costly than in the Baseline (Figure 3-20 – lower chart). Estimates of abatement costs for individual MSs by sectors are reported in ANNEX VIII (Figure 13-1, Figure 13-2), as well as are attached in the table format to this report.

Figure 3-20 Total cost of emission controls for SO_2, NO_x and $PM_{2.5}$ (upper chart) and NMVOCs (lower chart) by the IED sectors in the Baseline and MTFR scenarios in the EU27. (Note: IED codes are explained in Table 1-1)





In Figure 3-21, the total control costs in the IED sectors are compared to the monetised damages induced by the air pollution. The damage costs are calculated using the pollutant specific average marginal cost of impacts on health, forests, crops and materials in the EU[58], while the health impacts are quantified using two metrics for valuing mortality: the value of a life year (VOLY), and the value of a statistical life (VSL). It is reported that the total control cost as well as aggregated damages gradually decline from 2020 to 2050 in the Baseline. The increase in control cost in the MTFR scenario over the Baseline is quantified at more than 6 bln € in 2050. In the same year, the avoided total damage cost due to emission reductions is estimated at 17 bln € and 50 bln € whereby the lower value refers to the VOLY and the higher value to the VSL health-indicators, respectively.

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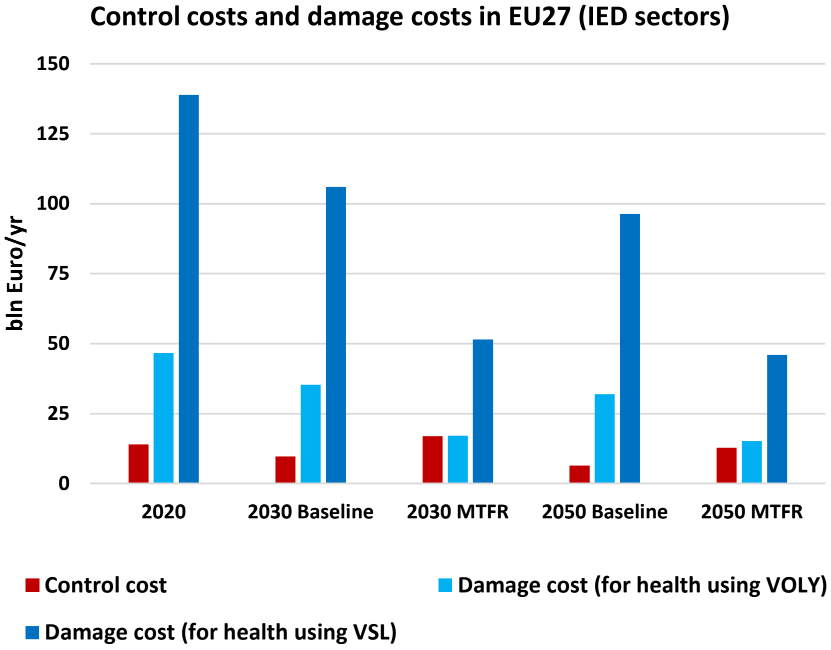
[58] EEA (2020) ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017. https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-04-2020-costs-of-air-pollution-from-european-industrial-facilities-200820132017/@@download/file/ETC-ATNI_2020-4_Task-1222_FINAL_v2_17-08-2021.pdf

Figure 3-21 Comparison of control costs and damage costs for all pollutants and IED sectors in the Baseline and MTFR scenarios in the EU27.



4. Conclusions for the EU energy intensive industry sectors (IED Annex I regulated activities)

Energy industries (IED Annex I - activity group 1)

The IED activity 1.1 (Combustion) has been identified as the largest emitter of SO_2 and NO_x in the Baseline in EU27, and the third largest source of $PM_{2.5}$ in the years 2030 and 2050. Overall, this sector has achieved the largest reductions of SO_2, NO_x and $PM_{2.5}$ in the past, and continues in the declining trend in the future with the decarbonised energy system. It is concluded that the combustion sources in energy industries are efficiently controlled by the existing BATs. However, the use of biomass (and its co-firing) occurs to be a critical source of future emissions in the sector. It is also reported that combustion of hydrogen in various gas mixes for heavy industries and gas power plants with CCS might lead to an increase in the NO_x emissions which will require further attention when defining future ELVs and corresponding BATs. Until 2030, the reduction of energy intensity has the highest impact on the CO_2 emissions reduction because of energy efficiency improvements and structural changes away from energy intensive industrial sectors. Strengthening permit conditions for energy efficiency, as included in the proposed revision to the IED, can help achieve this in the immediate timeframe.

At Member State level, exceedances of the upper end of BAT-AELs are noted but were found to be attributed typically to existing (old) power plants where no investments in emission controls is expected before the end of their lifetime (i.e. more stringent ELVs will not be effective in reducing emissions). To realise the additional mitigation potential identified in this sector requires a better alignment of ELVs with the lower ranges of BAT-AEL, as well as to minimise the use of derogations as proposed under the revised IED.

The IED activity 1.1 remains the top emitter of SO_2 and NO_x also in the MTFR case whereas further mitigation potential exists especially for the emissions of NO_x and $PM_{2.5}$. Compared to other IED sectors, Energy industries are associated with the largest costs to control emissions of SO_2, NO_x and $PM_{2.5}$ in the period 2005-2030.

Metals production and processing (IED Annex I - activity group 2)

Metals production and processing is one of the IED sectors which shows an increasing Baseline emissions trend in the period 2020-2050. Compared to IED 1, also the past reductions for all emissions are less pronounced (about -40-50% between 2005-2020).

The IED activity 2.2 (Pig iron and steel production) is the largest Baseline emitter of total $PM_{2.5}$ in the years 2030 and 2050. It is expected that a gradual shift – driven by the carbon mitigation policies - from the use of coke in the integrated steelworks (basic oxygen furnaces) towards electricity-based processing (electric arc furnaces) as well as to the direct reduction of iron using hydrogen will have a strong air pollution reducing effect, namely for $PM_{2.5}$ and sulphur emissions. Smelting and processing of non-ferrous metals (both primary and secondary) is another IED activity that is projected to increase its share in the future emissions profile under the climate policy and related shifts towards the renewable power generation sector, energy storage and a new infrastructure.

The comparison with emissions under the upper BAT-AEL limit show that the application of the lower range has the most pronounced impact for the emissions of $PM_{2.5}$, indicating that the extent to which planned revision to the IED to set ELVs based on best performance the installation can achieve may have a significant effect.

For iron and steel, the reduction of energy intensity has the highest impact on the CO_2 emissions reduction until 2030 because of energy efficiency improvements, whereas for non-ferrous metals, electrification is already dominant in 2030 and continues to be in 2050. As previously noted, strengthening permit conditions for energy efficiency, as included in the proposed revision to the IED, can help achieve this in the immediate timeframe.

The IED activities 2.2 and 2.5 show also significant potential for reductions of SO_2 and $PM_{2.5}$ by 2050 under the MTFR assumptions. By 2050, Metals production is projected to have the largest air pollution abatement cost among all IED sectors in the Baseline.

Mineral industry (IED Annex I - activity group 3)

The IED has been very effective in mitigating emissions of key pollutants from the Mineral industries between 2005-2020, whereby a reduction of 50% is reported in this period. From 2020 to 2050, however, the emissions in this sector are projected to grow again, mainly due to increased production activities. The IED activity 3.1 (Cement, lime and magnesium oxide) is the second largest source of SO_2 and NO_x by 2050 in the Baseline, while the Glass making (IED 3.3) is the second top emitter of $PM_{2.5}$. Compared to other IED industries, the cement industry is one of key contributors to the modest growth in the $PM_{2.5}$ emissions.

Similar to IED 2, the application of the BAT-AEL lower range has the most pronounced impact for the emissions of $PM_{2.5}$, indicating that the provisions of the revised IED may have a significant abating effect in this sector. By 2030, it is projected that the energy efficiency improvement is a key factor for the CO_2 emissions reductions in Mineral industries, also supporting the air pollutant reductions targeted by the revised IED.

By 2050, the cement and glass manufacturing activities show also the largest mitigation potentials for SO_2 and NO_x (IED 3.1) and for $PM_{2.5}$ (IED 3.3) under the MTFR scenario. Relative to other IED sectors, Mineral industries suggest the highest control costs associated with the MTFR controls in 2050. Because of the growing emission trends and a large potential to reduce future emissions of SO_2, NO_x and $PM_{2.5}$, the IED 3 could be considered among priority sectors for the review of the BATC under the revised IED.

Chemical industry (IED Annex I - activity group 4)

At the EU level, Chemical industries constitutes relatively smaller source of SO_2, NO_x and $PM_{2.5}$ emissions, contributing by 5%, 3% and 8% respectively to the totals in 2020. It is also noted that the relative contribution will likely limit the overall impact the planned revision to the IED to set more stringent ELVs based on the lower range of BAT-AEL may have. The three IED activities in Chemical industries that were analysed in this report include the manufacturing of sulfuric and nitric acid (IED 4.2) and the production of fertilisers (IED 4.3). By 2050 the SO_2 and NO_x emissions from IED 4 are projected to increase by 20%, and for $PM_{2.5}$ to decline by 7% relative to current levels. By 2050, production of sulfuric acid is the third largest emitter of SO_2 in both Baseline and MTFR scenarios and this activity also shows the second largest SO_2-abatement potential (after cement production). Production of fertilisers is potentially important activity for limiting future emissions of $PM_{2.5}$.

Until 2030, the reduction of energy intensity in chemical industries has the highest impact on the CO_2 emissions reduction because of energy efficiency improvements. Strengthening permit conditions for energy efficiency, as included in the proposed revision to the IED, can help achieve this in the immediate timeframe.

Waste management (IED Annex I - activity group 5)

In this study, the IED 5 sector is limited to the emissions from the activity 5.2 – (Co-)incineration of waste, and more precisely, to the incineration of waste for the energy recovery. This activity is strictly regulated under the existing IED (see IED Annex VI). Current emissions of the pollutants under examination are comparatively smaller than from the IED activity 1.1 (Combustion) and decline significantly by 2050 (about -90% between 2020-2050 for SO_2, NO_x and $PM_{2.5}$). Regulations to address air pollutants from Waste industries will remain important under the future waste management practices.

Other activities (IED Annex I - activity group 6)

It is estimated that the IED sector 6 is currently responsible for about 80% of the NMVOC emissions from all IED sectors, followed by the Energy industries (11%). In the period 2005-2020, about one third of the NMVOC emissions have been abated due to the IED regulations, whereas an additional drop by 3% is projected by 2050 in the Baseline. The IED activity 6.7 (Surface treatment) – primarily the use of solvents – is a dominant source in this sector in the years 2030 and 2050 in the Baseline and MTFR scenarios, followed by the activity 6.4.b (Food production) and 6.1 (Pulp and paper). Abatement of NMVOC in the category IED 6.7 also suggests the largest potential (60%) for further mitigation under the MTFR assumptions in the year 2050.

5. Summary

This report summarizes outputs of Task 1 and Task 2 of this project. In Task 1, the updated projections of emissions of SO_2, NO_x, $PM_{2.5}$ and NMVOC for the years 2020-2050 have been calculated for the Baseline and the MTFR scenarios at the EU level and for each MS covering all economic sectors and activities with a special focus at sectors regulated by IED. The scenarios take into account information collected from the BAT conclusions for individual IED activities, that have been mapped to the GAINS structure such that the BAT-AELs can be compared to the aggregated emission factors in the years up to 2050.

At an aggregated level for the EU27 it can be concluded that the Baseline assumptions reflect well the existing IED regulations for the key sectors driving the future emission trends. There have been cases identified where the BAT-AELs are exceeded for some of the GAINS sectors. While the amount and total contribution of the exceeding combustion-related emission sources appears rather marginal, a higher number of exceedances occur for the PM emissions from industrial processes. However, we note that the analysis of the BAT conclusions confirms numerous uncertainties and challenges when comparing the emission factors in GAINS against the legislated limit values since they are based on different principles.

At the EU level, the total emissions from the IED sectors decline rapidly mainly due to air pollutant reductions achieved in the energy industries. At the same time, emissions from industrial processes are projected to increase at various rates, whereby the key contributing activities are the mineral industries such as cement, lime and glass production, sulfuric acid production, as well as ferrous and non-ferrous metals production. At the country level, results of this analysis suggest that the rapid growth in the combustion of biomass for the electricity generation without additional abatement measures might contribute to the overall increase in the SO_2 and NO_x emissions.

In Task 2, the emission trends have been examined in order to quantify in detail the factors that determine the projected emission trajectories. The data collected in Task 1 has been utilized in a sensitivity assessment to find out how the emission trends relate to the attainment of sector specific BAT-AELs. The main conclusion from the sensitivity calculations is that for key emitting sources the assumptions in GAINS in the Baseline go beyond the prescribed limit values. The full enforcement of at least the upper end of BAT-AEL ranges in every ‘non-complying’ IED activity results in an additional abatement potential that can be expected from the existing legislation, most notably for the $PM_{2.5}$ emissions from industrial process activities. Under the Baseline assumptions and considering the uncertainty ranges, this potential is interpreted as an impact of combination of measures such as the full enforcement and elimination of exceptions and derogations. It is also noted that there is additional potential associated with an adoption of the revised IED rules, which, among others, would require the permits for operators are set based on the strictest possible BAT-AELs consistent with the lowest emissions achievable by applying a respective BAT in the installation. The greatest potential in achieving the lower range of BAT-AELs is noted for $PM_{2.5}$ (notably for the metal and mineral IED sectors).

A decomposition analysis of drivers of emission changes - specifically the impact of economic restructuring, efficiency gains, fuel switches and dedicated end-of-pipe measures – reveals that the processes associated with the decarbonisation of the industry and electricity sectors play a much greater role in the air pollution reductions between 2020-2050 than the emission controls applied in the Baseline. Fuels switches towards renewables and non-combustible energy forms combined with a lower energy intensity in most of the IED sectors result in an energy system with a lower overall emission intensity than in 2020. However, some of the carbon mitigation options, e.g., the growing use of biomass, offset some of the mitigation gains induced by a cleaner fuel mix.

In this respect it is also important to pay attention to assumptions and implications of pollution controls for emerging technologies and fuels, e.g., CCS or H_2, that may have important impacts on emission profiles driven by low-carbon transitions of the economy. Our results strongly indicate that the large deployment of power installations with CCS will need to be associated with adequate air pollution controls. Similarly, large deployment of prospective fuels such as hydrogen and ammonia might be associated with an effect on air pollution. The parametric analysis of assumptions on the H_2/gas blending ratios used for combustion and emission controls suggests a significant increment in NO_x with a growing H_2-share in the gas mix in the case when existing abatement techniques are applied.

Low carbon transitions have strong impacts on the resulting air pollution control cost. In the Baseline scenario, costs to control SO_2/NO_x and $PM_{2.5}$ are projected to drop by two-thirds in the period 2020-2050, which is primarily driven by a phaseout of fossil fuels and lower investments required to control pollutants from the combustion-based energy industries. On the other hand, growing trend in some of the industrial production activities in combination with an increased application rates of controls result in a moderate growth of abatement costs for industrial processes (IED 2-4). At an aggregated level, the increase in total cost induced by the MTFR controls relative to Baseline is offset by the benefits due to avoided air pollution related damage cost.

The ranking of top emitters among the IED activities in 2050 identified the combustion of fuels in the energy sector as the largest individual source of SO_2 and NO_x emissions. Other top sources include cement and glass manufacturing, metals production and chemical industries. For $PM_{2.5}$, industrial processes that belong to top emitters comprise steel, glass, cement as well as combustion of biomass. In terms of the mitigation potential incurred by the MTFR controls, mineral industry (cement, glass) shows the most significant space for additional reductions for all pollutants, followed by chemical industries and metals production (SO_2, $PM_{2.5}$). Large abatement potential for NO_x and $PM_{2.5}$ is also reported for biomass combustion in energy industries. For NMVOCs, the IED activity 'Surface treatment' is a top emitter in 2050 and also shows the largest reduction potential.

6. Annex I - IED Annex I activities coverage in GAINS

Table 6-1: Overview of the IED Annex I activities and the GAINS sectors covered in this study

nr	*IED activity*	*explicit GAINS sector*	*aggregated GAINS sector*	*covered in this analysis*
1	**Energy industries**			
1.1	Combustion	x		x
1.2	Refining	x		x
1.3	Production of coke	x		x
1.4	Gasification or liquefaction		x	x (part of aggregate)
2	**Metals production and processing**			
2.1	Metal ore	x		x
2.2	Pig iron or steel	x		x
2.3	Processing of ferrous metals	x		x
2.4	Ferrous metals foundries	x		x
2.5	Non-ferrous metals	x		x
2.6	Surface treatment of metals or plastic	x (NMVOC)	x (fugitive)	x (part of aggregate)
3	**Mineral industries**			
3.1	Cement, lime and magnesium oxide	x		x
3.2	Asbestos		x	x (part of aggregate)
3.3	Glass	x		x
3.4	Mineral fibres		x	x (part of aggregate)
3.5	Ceramic products		x (incl. bricks)	x (part of aggregate)
4	**Chemicals industries**			
4.1	Organic	x (NMVOC)	x	x (part of aggregate)
4.2	Inorganic	x (NMVOC)	x	x (part of aggregate)
4.3	Phosphorus-, nitrogen- or potassium-based fertilisers	x		x
4.4	Plant protection products		x	x (part of aggregate)
4.5	Pharmaceutical products	x (NMVOC)	x	x (part of aggregate)
4.6	Explosives		x	x (part of aggregate)
5	**Waste industries**			
5.1	Disposal or recovery of hazardous waste			
5.2	(Co-) incineration of waste	x		x
5.3	Disposal/recovery of non-hazardous waste	x		x
5.4	Landfills	x		x (CH4, time permitting)
5.5	Temporary storage of hazardous waste			
5.6	Underground storage of hazardous waste			
6	**Other activities**			
6.1	Pulp, paper, or wood-based products	x		x
6.2	Textiles pre-treatment or dyeing		x	x (part of aggregate)
6.3	Tanning		x	x (part of aggregate)
6.4	Slaughterhouses, food products and milk		x	x (part of aggregate)
6.5	Disposal of animal carcasses		x	x (part of aggregate)
6.6	Rearing of poultry or pigs	x		x (NH3, time permitting)
6.7	Surface treatment		x	x (part of aggregate)
6.8	Production of carbon			
6.9	Capture of CO2 streams			
6.10	Preservation of wood and wood products	x (NMVOC)	x	x (part of aggregate)
6.11	Independently operated treatment of waste water	x		
	Newly proposed activities 2022			
3.6	Extractive industry installations	x		x
2.7	Manufacture of lithium-ion batteries (large scale)			
6.5	Larger-scale cattle farming, additional pig & poultry farms	x		x (CH4, NH3 time permitting)

NOTE: gray fields, in the rightmost column, refer to the waste and agricultural sectors excluded from the scope (during the inception phase); orange fields refer to fugitive NMVOC sources not analyzed in detail; NMVOC from combustion is included (as agreed during progress meetings); green fields are sectors covered only partially or as a part of aggregate.

7. Annex II - BAT-AEL ranges mapped to GAINS activities

Table 7-1: BAT-AEL ranges mapped to GAINS activities for SO_2

			BAT_AELs range (mg/Nm3)			
Activity_label	**Sector_label**	**IED activity**	**lower end**	**higher end**	**BAT-AEL reference**	**Comment**
Hard coal, lignite	Fuel production & conversion other than in power plants: Combustion	1.1	10	360	LCP BAT 21	maximum range
Heavy fuel oil	Fuel production & conversion other than in power plants: Combustion	1.1	35	175	LCP BAT 29	maximum range for boilers
Medium distillates	Fuel production & conversion other than in power plants: Combustion	1.1	35	175	LCP BAT 29	maximum range for boilers
Other biomass and waste fuels	Fuel production & conversion other than in power plants: Combustion	1.1	10	360	LCP BAT 21	apply coal BAT techniques
Heavy fuel oil	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	35	175	LCP BAT 29	maximum range for boilers
Medium distillates	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	35	175	LCP BAT 29	maximum range for boilers
Other biomass and waste fuels	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	10	360	LCP BAT 21, PP BAT 21	apply coal BAT techniques
Hard coal, lignite	Industry: other sectors; combustion of brown coal/lignite and hard coal in large boilers (>50 MWth)	1.1	10	360	LCP BAT 21	maximum range
Hard coal, lignite	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	10	360	LCP BAT 21	maximum range
Heavy fuel oil	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	35	175	LCP BAT 29	maximum range for boilers
Medium distillates	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	35	175	LCP BAT 29	maximum range for boilers
Other biomass and waste fuels	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	10	360	LCP BAT 21	apply coal BAT techniques
Hard coal, lignite	Power & district heat plants, new; coal/lignite fired, large units (> 50 MW th)	1.1	10	360	LCP BAT 21	maximum range
Heavy fuel oil	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	35	175	LCP BAT 29	maximum range
Medium distillates	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	35	175	LCP BAT 29	maximum range
Other biomass and waste fuels	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	10	360	LCP BAT 21	apply coal BAT techniques
Hard coal, lignite	Modern power plants (coal: ultra- and supercritical; gas: CCGT)	1.1	10	360	LCP BAT 21	maximum range
Heavy fuel oil	Power & district heat plants new, non-coal; for GAS - turbines	1.1	35	175	LCP BAT 29	maximum range
Medium distillates	Power & district heat plants new, non-coal; for GAS - turbines	1.1	35	175	LCP BAT 29	maximum range
Biomass fuels	Power & district heat plants new, non-coal; for GAS - turbines	1.1	10	100	LCP BAT 25	maximum range
Other biomass and waste fuels	Power & district heat plants new, non-coal; for GAS - turbines	1.1	10	360	LCP BAT 21	apply coal BAT techniques
Hard coal, lignite	Power & district heat plants, new; coal/lignite fired, large units (> 50 MW th)	1.1	10	360	LCP BAT 21	maximum range
No fuel use	Ind. Process: Aluminum production - primary	2.5.a	2.5	15	NFM BAT 69	unit: kt/t Al
No fuel use	Ind. Process: Aluminum production - secondary	2.5.b	2.5	15	NFM BAT 69	unit: kt/t Al
No fuel use	Ind. Process: Cement production	3.1.a	45	360	CLM BAT 21, 47, 65	
No fuel use	Ind. Process: Coke oven	1.3	180	450	IS BAT 49	
No fuel use	Ind. Process: Glass production (flat, blown, container glass)	3.3	90	180	GLS BAT 23	
No fuel use	Ind. Process: Lime production	3.1.b	45	360	CLM BAT 21, 47, 65	
No fuel use	Ind. Process: Nitric acid	4.2	n.a.	n.a.		
No fuel use	Ind. Process: Other non-ferrous metals prod. - primary and secondary	2.5	45	450	NFM BAT 49, 120, 142, 143	maximum range of all BATs
No fuel use	Ind. Process: Pig iron, blast furnace	2.2	n.a.	180	IS BAT 65	
No fuel use	Ind. Process: Paper pulp mills	6.1	5	50	PP BAT 21	maximum range
No fuel use	Crude oil and other products - input to refineries	1.2	90	1080	REF BAT 26	maximum range
No fuel use	Ind. Process: Agglomeration plant - sinter	2.1	90	450	IS BAT 21	maximum range
No fuel use	Ind. Process: Agglomeration plant - pellets	2.1	90	450	IS BAT 22	maximum range
No fuel use	Ind. Process: Sulfuric acid	4.2	n.a.	n.a.		

Table 7-2: BAT-AEL ranges mapped to GAINS activities for NO_x

			BAT_AELs range (mg/Nm3)			
Activity_label	**Sector_label**	**IED activity**	**lower end**	**higher end**	**BAT-AEL reference**	**Comment**
Natural gas, derived gases	Fuel production & conversion other than in power plants: Combustion	1.1	10	100	LCP BAT 44	maximum range for boilers
Gasoline and LPG	Fuel production & conversion other than in power plants: Combustion	1.1	10	100	LCP BAT 44	maximum range for boilers
Hard coal, lignite	Fuel production & conversion other than in power plants: Combustion	1.1	50	270	LCP BAT 20	maximum range
Heavy fuel oil	Fuel production & conversion other than in power plants: Combustion	1.1	45	270	LCP BAT 28	maximum range for boilers
Medium distillates	Fuel production & conversion other than in power plants: Combustion	1.1	45	270	LCP BAT 28	maximum range for boilers
Biomass fuels	Fuel production & conversion other than in power plants: Combustion	1.1	40	225	LCP BAT 24	maximum range
Other biomass and waste fuels	Fuel production & conversion other than in power plants: Combustion	1.1	40	270	LCP BAT 20, 24	min LCP BAT 24, max LCP BAT 20
Natural gas, derived gases	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	10	100	LCP BAT 44, 49, 56	maximum range for boilers
Gasoline and LPG	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	10	100	LCP BAT 44, 49, 57	maximum range for boilers
Heavy fuel oil	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	45	270	LCP BAT 28	maximum range for boilers
Medium distillates	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	45	270	LCP BAT 28	maximum range for boilers
Biomass fuels	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	40	225	LCP BAT 24	maximum range
Other biomass and waste fuels	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	40	270	LCP BAT 20, 24, PP BAT 22	min LCP BAT 24, max LCP BAT 20
Hard coal, lignite	Industry: other sectors; combustion of brown coal/lignite and hard coal in large boilers (>50 MWth)	1.1	50	270	LCP BAT 20	maximum range
Natural gas, derived gases	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	10	100	LCP BAT 44	maximum range for boilers
Gasoline and LPG	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	10	100	LCP BAT 44	maximum range for boilers
Hard coal, lignite	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	50	270	LCP BAT 20	maximum range
Heavy fuel oil	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	45	270	LCP BAT 28	maximum range for boilers
Medium distillates	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	45	270	LCP BAT 28	maximum range for boilers
Biomass fuels	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	40	225	LCP BAT 24	maximum range
Other biomass and waste fuels	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	40	270	LCP BAT 20, 24	min LCP BAT 24, max LCP BAT 20
Hard coal, lignite	Power & district heat plants, new; coal/lignite fired, large units (> 50 MW th)	1.1	50	270	LCP BAT 20	maximum range
Natural gas, derived gases	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	10	100	LCP BAT 44	maximum range for boilers
Gasoline and LPG	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	10	100	LCP BAT 44	maximum range for boilers
Heavy fuel oil	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	45	270	LCP BAT 28	maximum range for boilers
Medium distillates	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	45	270	LCP BAT 28	maximum range for boilers
Biomass fuels	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	40	225	LCP BAT 24	maximum range
Other biomass and waste fuels	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	40	270	LCP BAT 20, 24	min LCP BAT 24, max LCP BAT 20
Natural gas, derived gases	Modern power plants (coal: ultra- and supercritical; gas: CCGT)	1.1	10	50	LCP BAT 44, 49	maximum range for CCGT
Hard coal, lignite	Modern power plants (coal: ultra- and supercritical; gas: CCGT)	1.1	85	270	LCP BAT 20	maximum range for existing PPs
Heavy fuel oil	Power & district heat plants new, non-coal; for GAS - turbines	1.1	45	270	LCP BAT 28	maximum range for boilers
Biomass fuels	Power & district heat plants new, non-coal; for GAS - turbines	1.1	40	225	LCP BAT 24	maximum range
Other biomass and waste fuels	Power & district heat plants new, non-coal; for GAS - turbines	1.1	40	270	LCP BAT 20, 24	min LCP BAT 24, max LCP BAT 20
Natural gas, derived gases	Power & district heat plants new, non-coal; for GAS - turbines	1.1	15	50	LCP BAT 44	maximum range for OCGT
Hard coal, lignite	Power & district heat plants, new; coal/lignite fired, large units (> 50 MW th)	1.1	50	270	LCP BAT 20	maximum range
No fuel use	Ind. Process: Aluminum production - primary	2.5.a	n.a.	n.a.	NFM BAT 13	
No fuel use	Ind. Process: Aluminum production - secondary	2.5.b	n.a.	n.a.	NFM BAT 13	
No fuel use	Ind. Process: Cement production	3.1.a	180	720	CLM BAT 19	maximum range
No fuel use	Ind. Process: Coke oven	1.3	315	585	IS BAT 49	
No fuel use	Ind. Process: Glass production (flat, blown, container glass)	3.3	90	720	GLS BAT 17	
No fuel use	Ind. Process: Lime production	3.1.b	90	450	CLM BAT 45	maximum range
No fuel use	Ind. Process: Nitric acid	4.2	n.a.	n.a.		
No fuel use	Ind. Process: Other non-ferrous metals prod. - primary and secondary	2.5	63	135	NFM BAT 141	
No fuel use	Ind. Process: Pig iron, blast furnace	2.2	n.a.	90	IS BAT 65	
No fuel use	Ind. Process: Paper pulp mills	6.1	50	400	PP BAT 22, 29, 36	max and min of all BATs
No fuel use	Crude oil and other products - input to refineries	1.2	27	360	REF BAT 24	
No fuel use	Ind. Process: Agglomeration plant - sinter	2.1	108	450	IS BAT 23	range depends on technologies
No fuel use	Ind. Process: Agglomeration plant - pellets	2.1	108	450	IS BAT 23	range depends on technologies
No fuel use	Ind. Process: Sulfuric acid	4.2	n.a.	n.a.		

Table 7-3: BAT-AEL ranges mapped to GAINS activities for Dust

			BAT_AELs range (mg/Nm3)			
Activity_label	**Sector_label**	**IED activity**	**lower end**	**higher end**	**BAT-AEL reference**	**Comment**
Heavy fuel oil	Fuel production & conversion other than in power plants: Combustion	1.1	2	20	LCP BAT 30	maximum range
Medium distillates	Fuel production & conversion other than in power plants: Combustion	1.1	2	20	LCP BAT 30	maximum range
Biomass fuels	Fuel production & conversion other than in power plants: Combustion	1.1	2	15	LCP BAT 26	maximum range
Other biomass and waste fuels	Fuel production & conversion other than in power plants: Combustion	1.1	2	18	LCP BAT 22	maximum range
Hard coal, lignite	Fuel production & conversion other than in power plants: Combustion	1.1	2	18	LCP BAT 22	maximum range
Heavy fuel oil	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	2	20	LCP BAT 30	maximum range for boilers
Medium distillates	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	2	20	LCP BAT 30	maximum range for boilers
Biomass fuels	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	2	15	LCP BAT 26	maximum range
Other biomass and waste fuels	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal	1.1	2	18	LCP BAT 22	maximum range
Hard coal, lignite	Industry: other sectors; combustion of brown coal/lignite and hard coal in large boilers (>50 MWth)	1.1	2	18	LCP BAT 22	maximum range
Heavy fuel oil	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	2	20	LCP BAT 30	maximum range
Medium distillates	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	2	20	LCP BAT 30	maximum range
Biomass fuels	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	2	15	LCP BAT 26	maximum range
Other biomass and waste fuels	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	2	18	LCP BAT 22	maximum range
Hard coal, lignite	Industry: other combustion (all sectors) except fuel consumption in mineral products industry	1.1	2	18	LCP BAT 22	maximum range
Hard coal, lignite	Power & district heat plants, new; coal/lignite fired, large units (> 50 MW th)	1.1	2	18	LCP BAT 22	maximum range
Heavy fuel oil	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	2	20	LCP BAT 30	maximum range
Medium distillates	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	2	20	LCP BAT 30	maximum range
Biomass fuels	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	2	15	LCP BAT 26	maximum range
Other biomass and waste fuels	Power & district heat plants existing, non-coal; for GAS - boilers	1.1	2	18	LCP BAT 22	maximum range
Heavy fuel oil	Power & district heat plants new, non-coal; for GAS - turbines	1.1	2	20	LCP BAT 30	maximum range
Medium distillates	Power & district heat plants new, non-coal; for GAS - turbines	1.1	2	20	LCP BAT 30	maximum range
Biomass fuels	Power & district heat plants new, non-coal; for GAS - turbines	1.1	2	15	LCP BAT 26	maximum range
Other biomass and waste fuels	Power & district heat plants new, non-coal; for GAS - turbines	1.1	2	18	LCP BAT 22	maximum range
Hard coal, lignite	Power & district heat plants, new; coal/lignite fired, large units (> 50 MW th)	1.1	2	18	LCP BAT 22	maximum range
No fuel use	Ind. Process: Aluminum production - primary	2.5.a	1.8	4.5	Multiple BAT apply	same ranges
No fuel use	Ind. Process: Aluminum production - secondary	2.5.b	1.8	4.5	Multiple BAT apply	same ranges
No fuel use	Ind. Process: Basic oxygen furnace	2.2	9	45	IS BAT 76 I,II	
No fuel use	Ind. Process: Brick production	3.5	n.a.	n.a.		
No fuel use	Ind. Process: Briquettes production	1.3	n.a.	n.a.		
No fuel use	Ind. Process: Cast iron (grey iron foundries)	2.4	0.9	13.5	IS BAT 61 II	
No fuel use	Ind. Process: Carbon black production	6.8	1.8	9	NFM BAT 178	
No fuel use	Ind. Process: Cement production	3.1.a	9	18	CLM BAT 16,42,43	
No fuel use	Ind. Process: Coke oven	1.3	n.a.	45	IS BAT 44-II	
No fuel use	Ind. Process: Electric arc furnace	2.2	n.a.	4.5	IS BAT 44-II	
No fuel use	Ind. Process: Fertilizer production	4.3	n.a.	4.5	IS BAT 88-I	
No fuel use	Ind. Process: Glass production (flat, blown, container glass)	3.3	9	18	GLS BAT 16-I, 22-I	
No fuel use	Ind. Process: Open hearth furnace	2.2	n.a.	n.a.		
No fuel use	Ind. Process: Lime production	3.1.b	9	18	CLM BAT 16,42,43	also in PP BAT 27
No fuel use	Ind. Process: Other non-ferrous metals prod. - primary and secondary	2.5	1.8	4.5	NFM BAT 119, 140, 158, 171	
No fuel use	Ind. Process: Production of glass fiber, gypsum, PVC, other	3.3	9	18	GLS BAT 16-I	
No fuel use	Ind. Process: Pig iron, blast furnace	2.2	n.a.	9	IS BAT 64	
No fuel use	Ind. Process: Paper pulp mills	6.1	9	36	PP BAT 23	
No fuel use	Crude oil and other products - input to refineries	1.2	9	45	REF BAT 25-I	maximum range
No fuel use	Ind. Process: Agglomeration plant - sinter	2.1	0.9	36	IS BAT 20	maximum range
No fuel use	Ind. Process: Agglomeration plant - pellets	2.1	0.9	36	IS BAT 20	maximum range
No fuel use	Storage and handling: Agricultural products (crops)	n.a.	n.a.	n.a.		
No fuel use	Storage and handling: Coal	1.3	9	18	IS BAT 43	
No fuel use	Storage and handling: Iron ore	2.1	n.a.	n.a.		
No fuel use	Storage and handling: N,P,K fertilizers	4.3	n.a.	n.a.		
No fuel use	Storage and handling: Other industrial products (cement, bauxite, coke)	3.1.a	n.a.	n.a.		
No fuel use	Waste: Flaring in gas and oil industry	1.2	n.a.	n.a.	REF BAT 56	good practice

8. Annex III - Emission trends for the IED and non-IED sectors

Figure 8-1 SO_2 emissions by the sum of IED and non-IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)

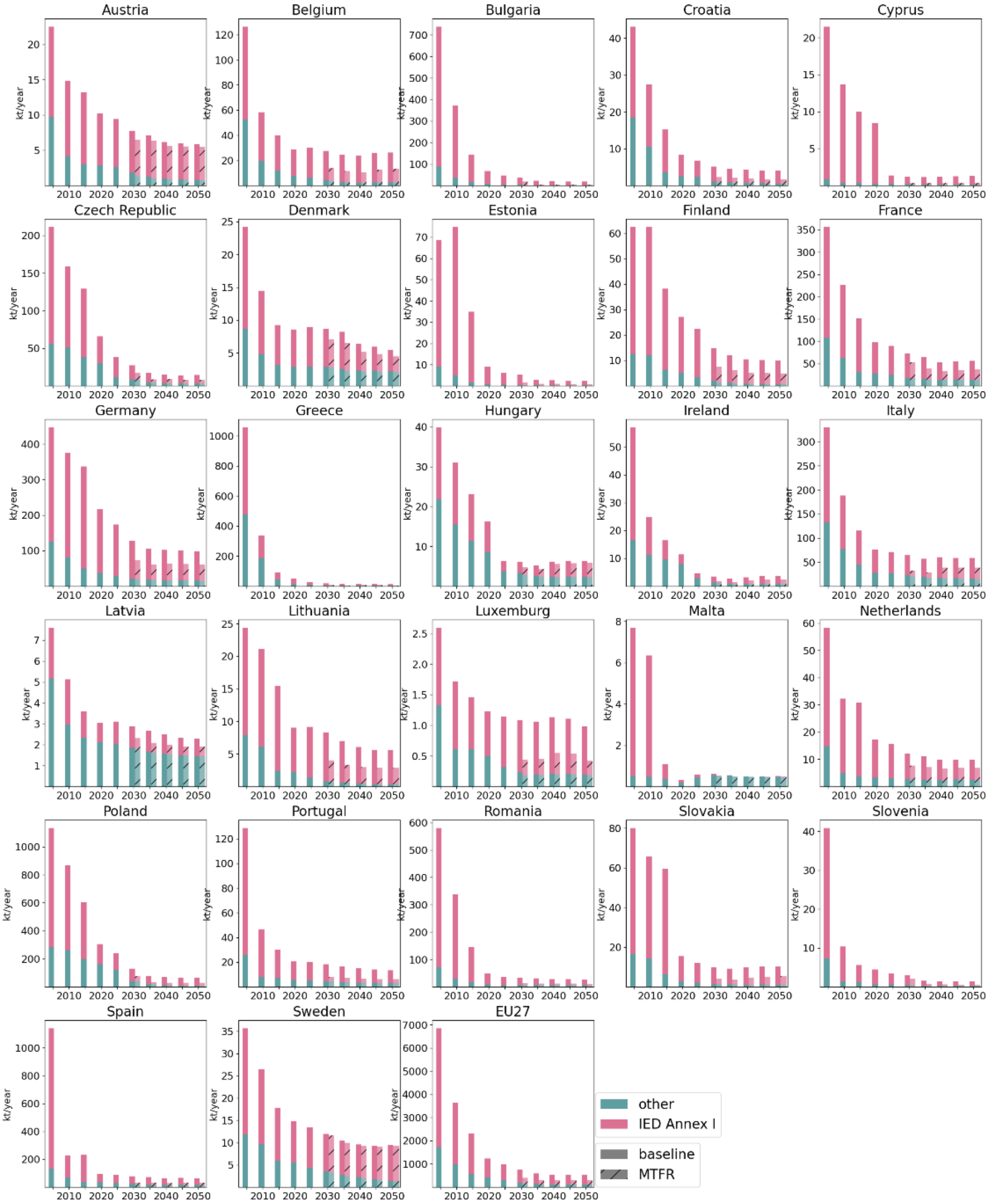


Figure 8-2 NO_x emissions by the sum of IED and non-IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)

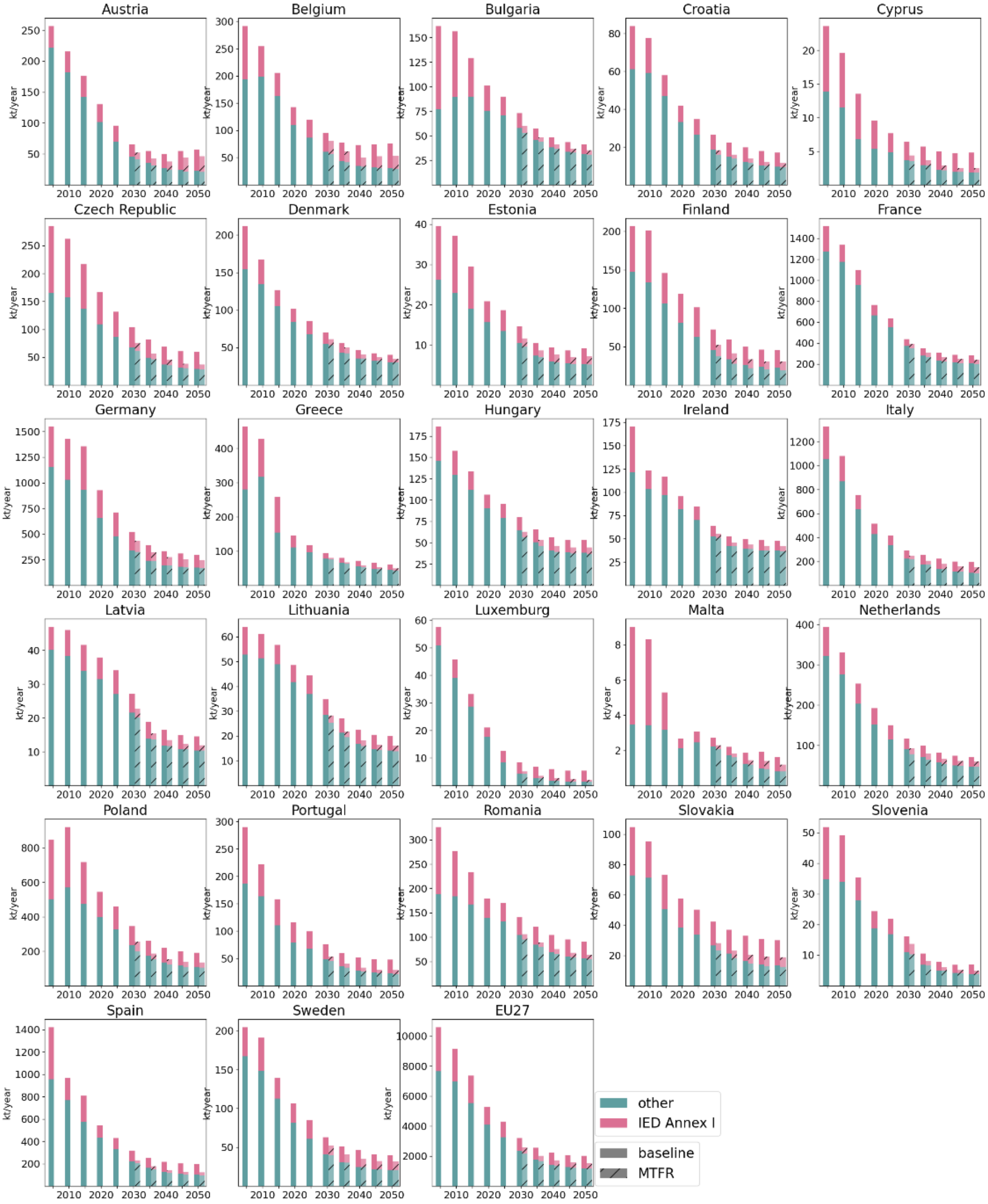


Figure 8-3 PM$_{2.5}$ emissions by the sum of IED and non-IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)

Figure 8-4 NMVOCs emissions by the sum of IED and non-IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)

9. Annex IV - Emission trends by the IED sectors

Figure 9-1 SO₂ emissions by the IED sectors in the Baseline and Maximum Technicaly Feasible (MTFR) scenarios (kt/year)

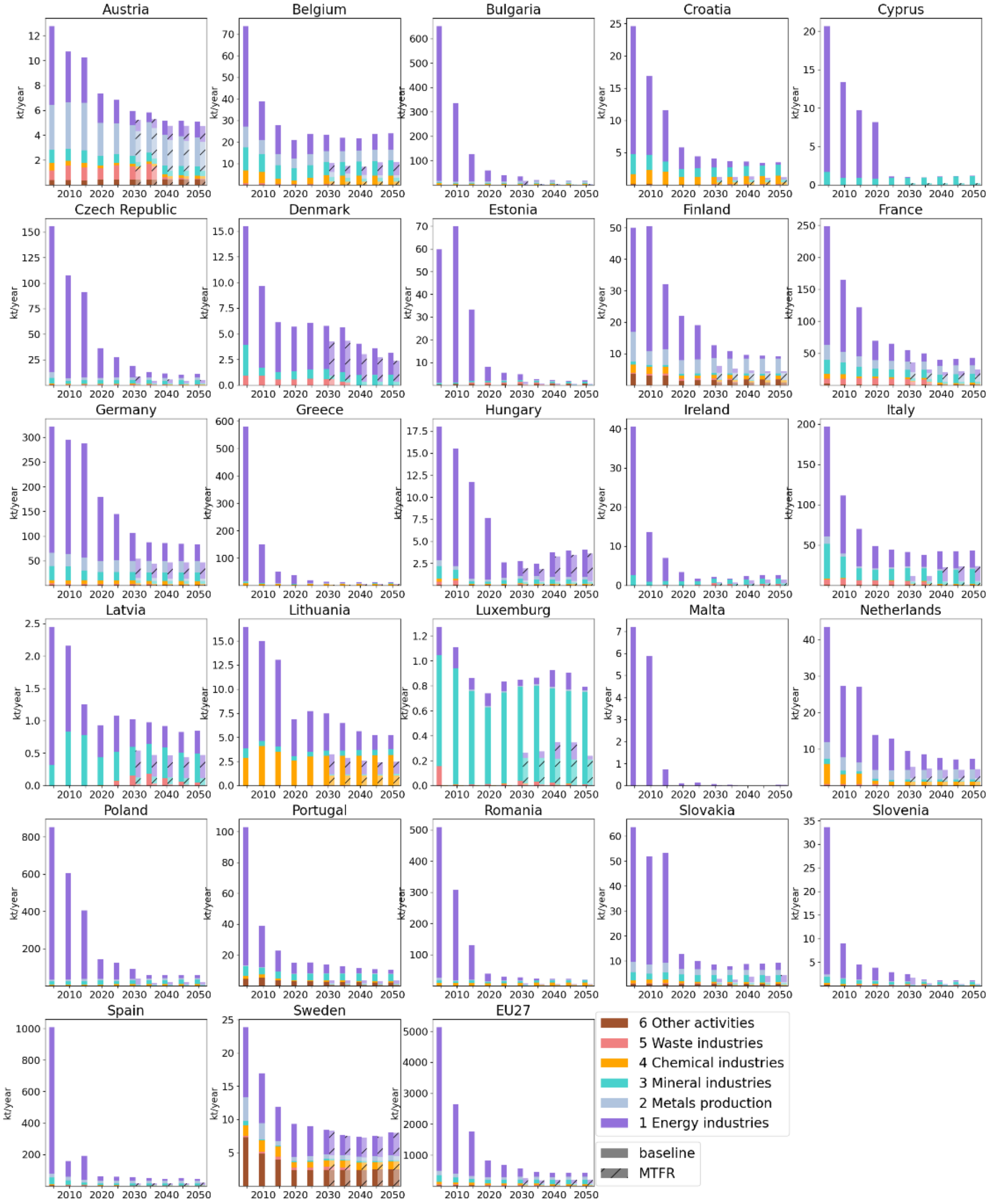


Figure 9-2 NO$_x$ emissions by the IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)

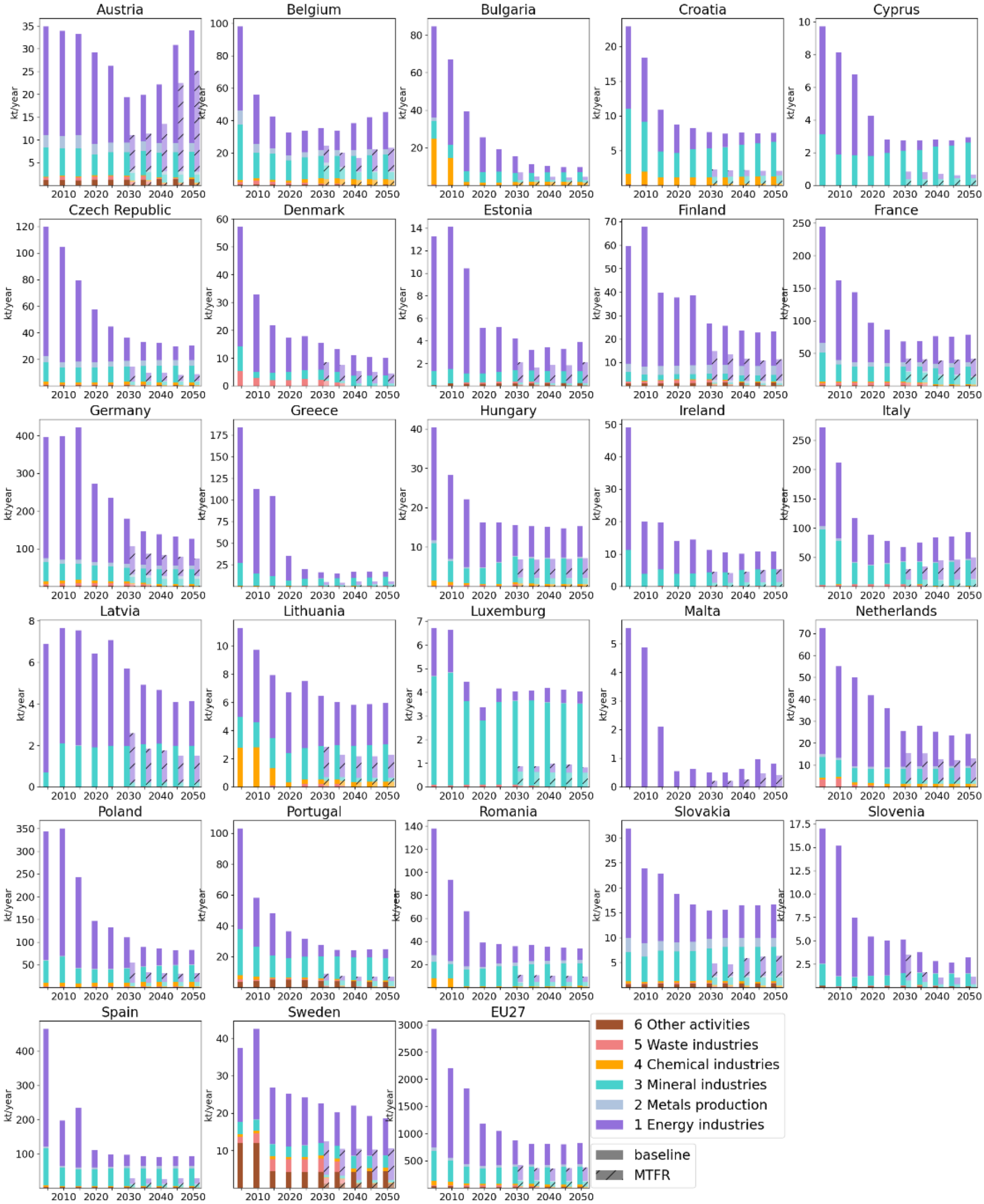


Figure 9-3 PM$_{2.5}$ emissions by the IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)

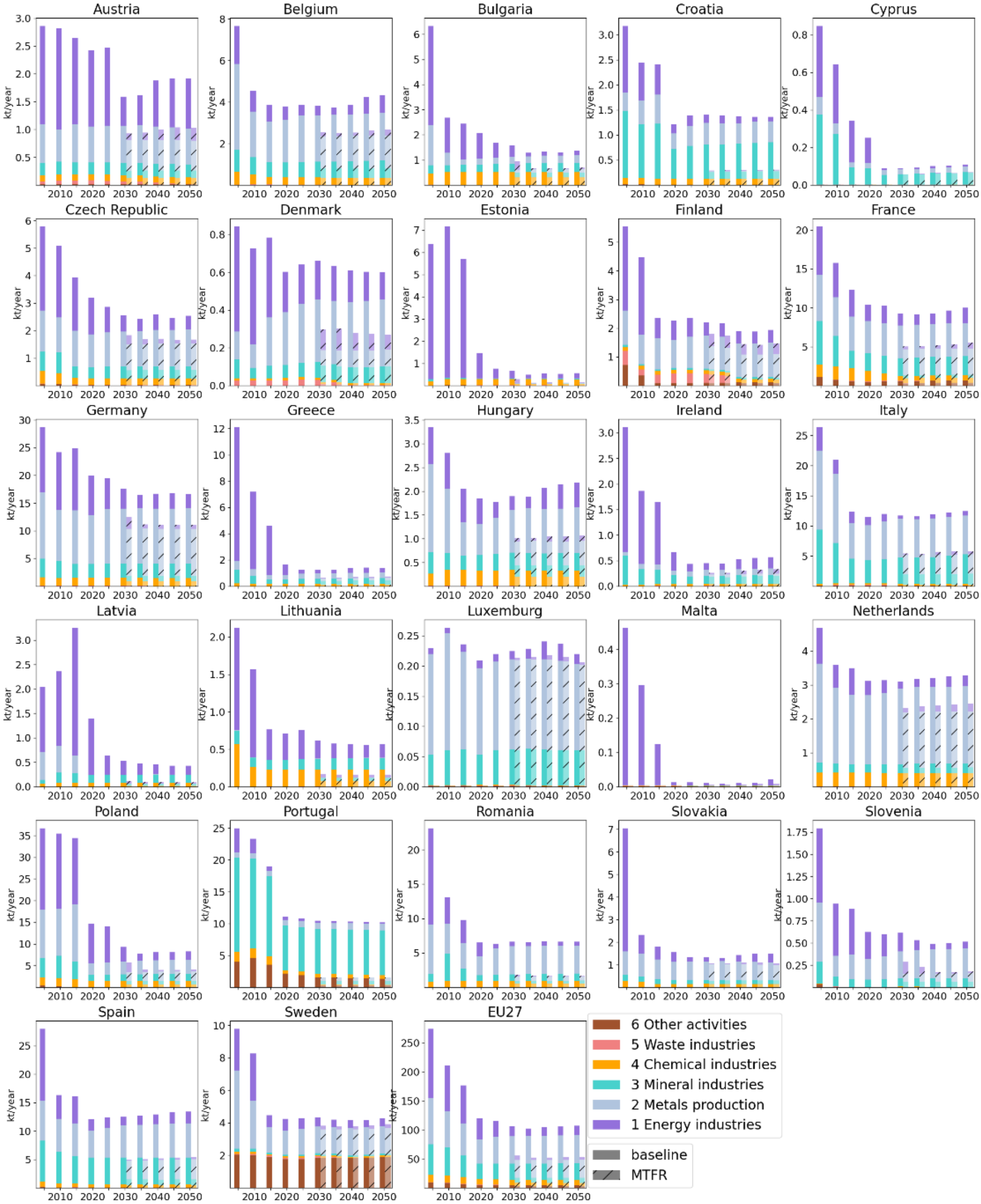
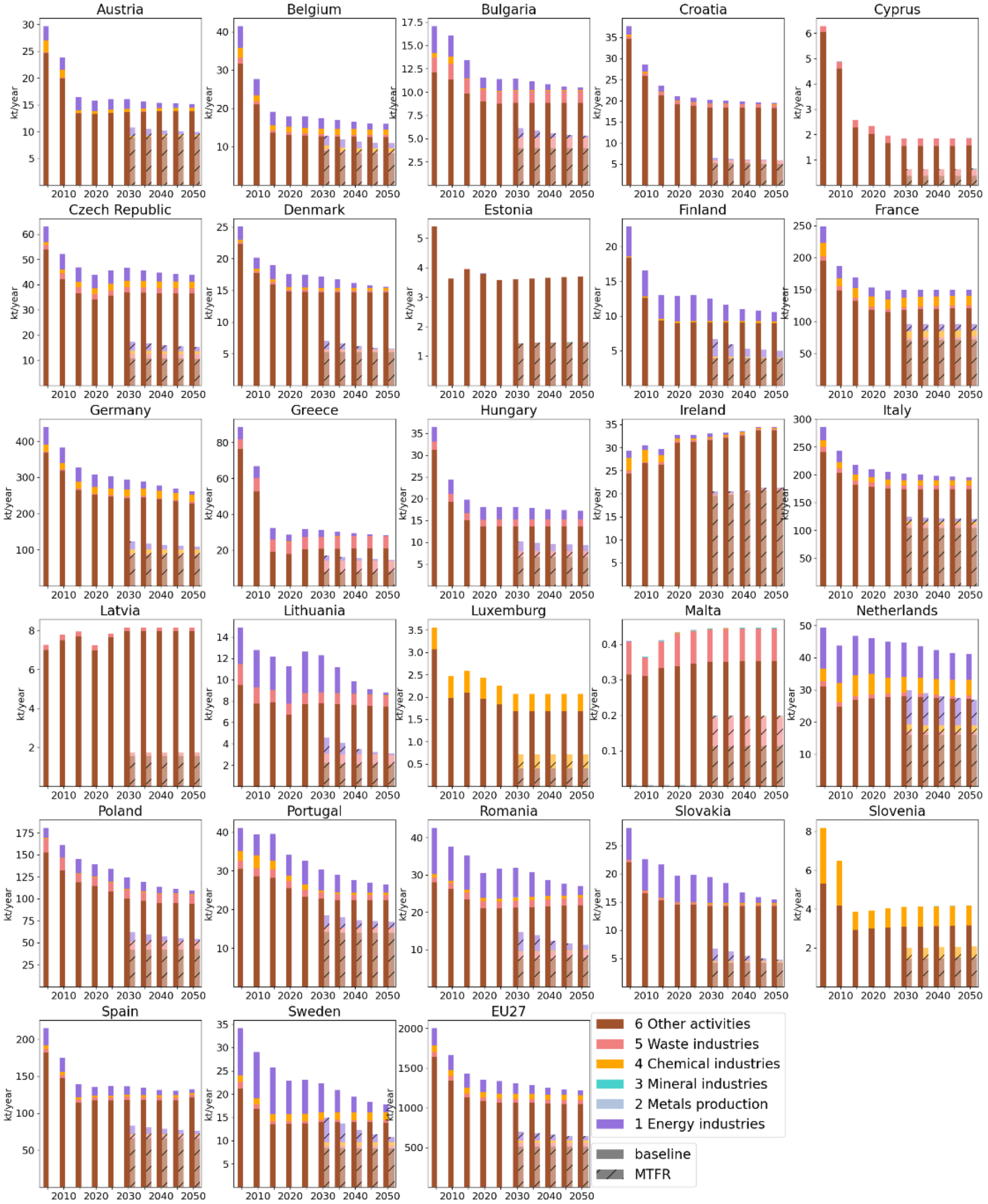


Figure 9-4 NMVOCs emissions by the IED sectors in the Baseline and Maximum Technically Feasible (MTFR) scenarios (kt/year)



10. ANNEX V – Decomposition of emission mitigation factors

Figure 10-1 Contribution of key mitigation factors to the reductions of SO_2 by the IED sectors in the Baseline and MTFR scenarios. (Note: IED codes in Table 1-1)

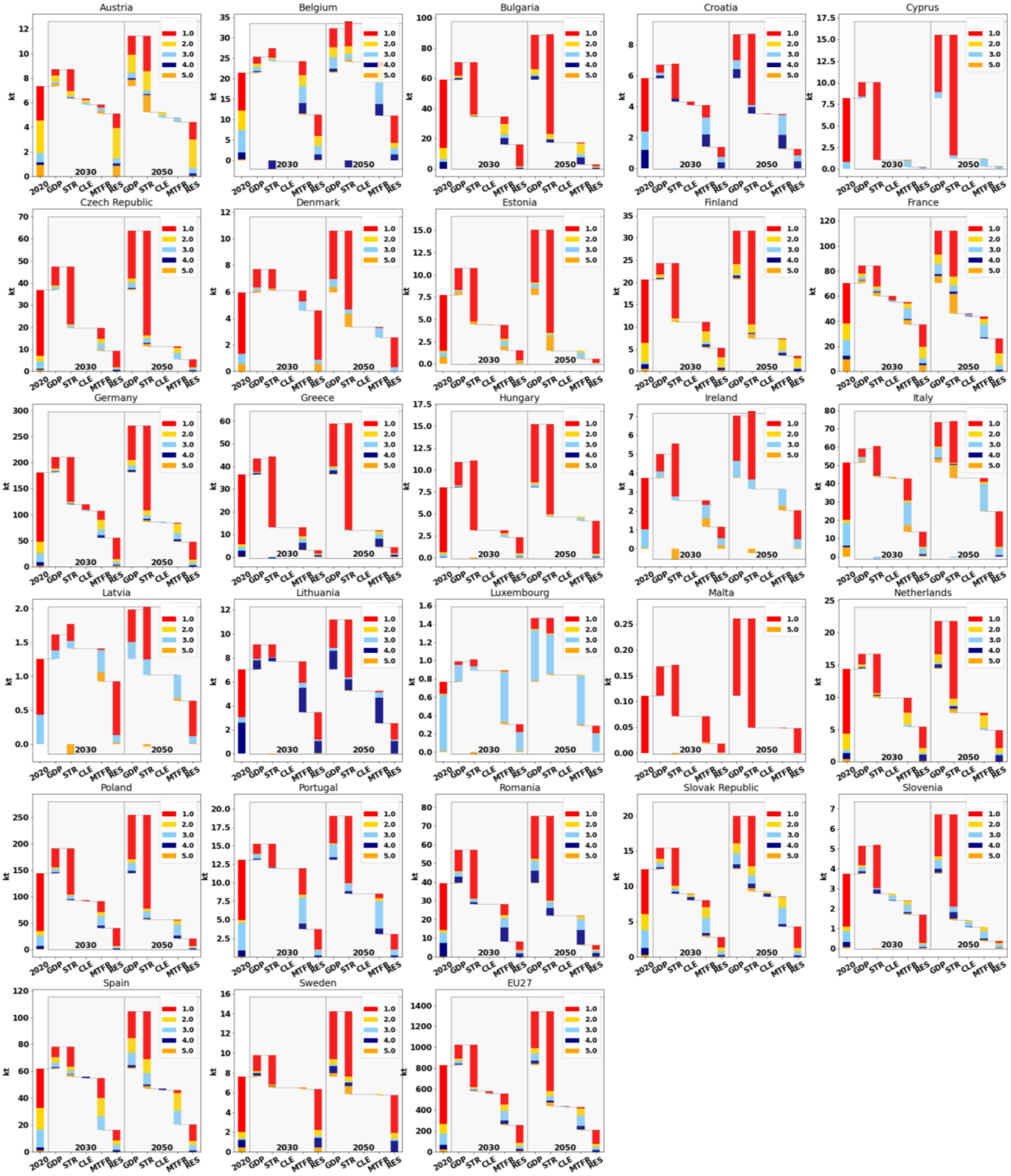


Figure 10-2 Contribution of key mitigation factors to the reductions of NO_x by the IED sectors in the Baseline and MTFR scenarios. (Note: IED codes in Table 1-1)

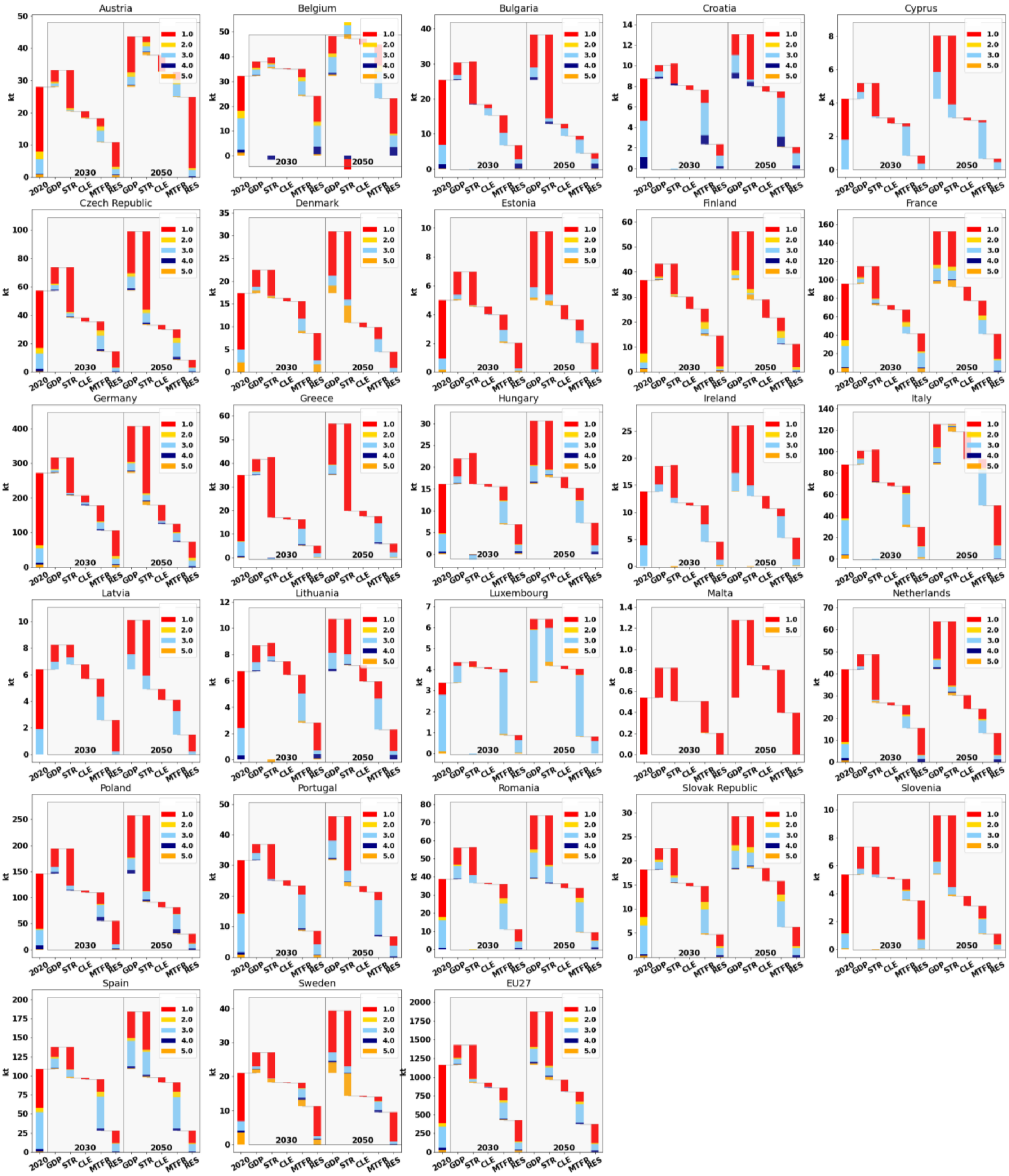
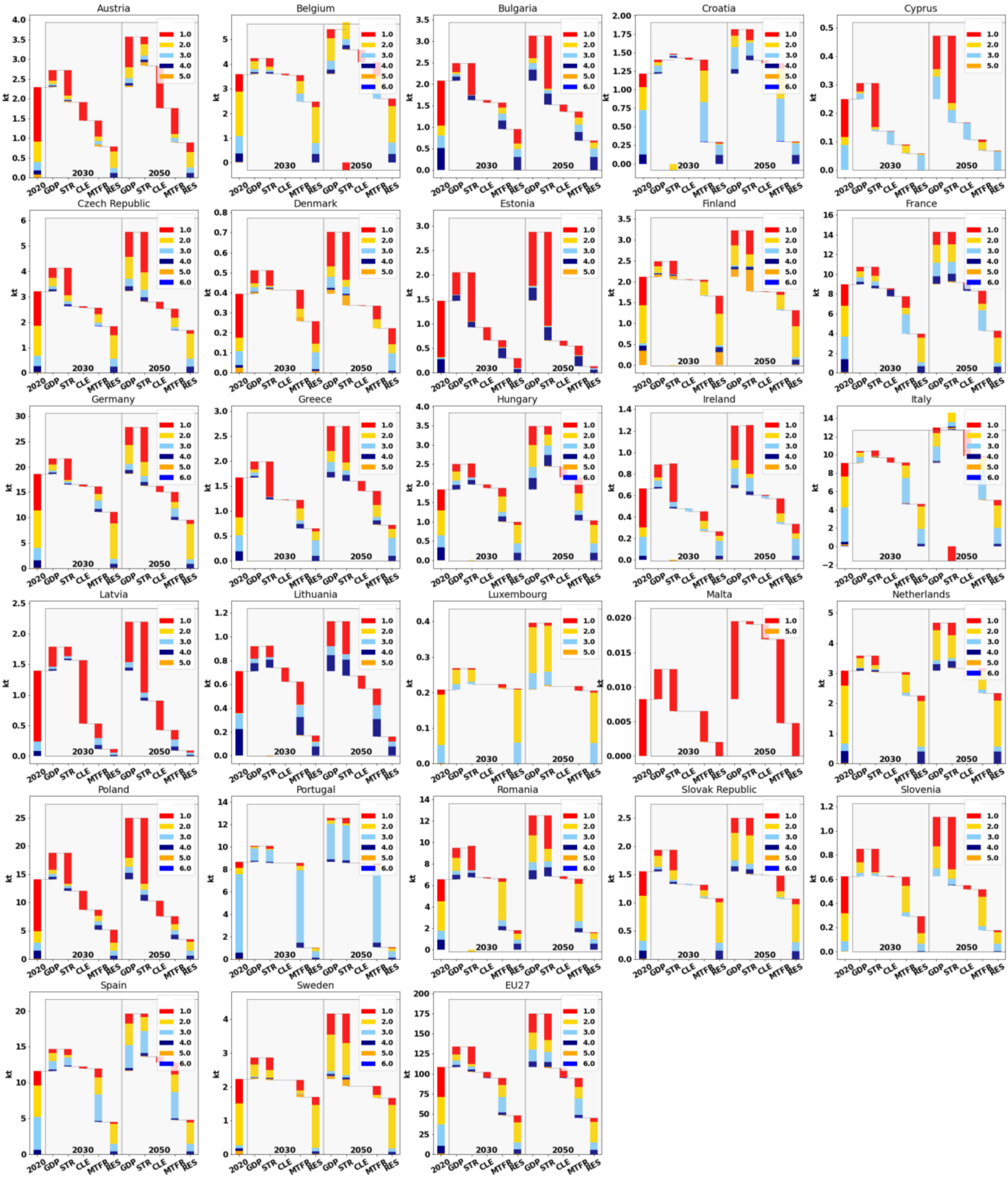


Figure 10-3 Contribution of key mitigation factors to the reductions of $PM_{2.5}$ by the IED sectors in the Baseline and MTFR scenarios. (Note: IED codes in Table 1-1)



11. ANNEX VI - Key emitting IED activities by MS

Figure 11-1 Ranking of top IED emitters of SO_2 in 2050 in the Baseline. (Note: IED codes in Table 1-1)

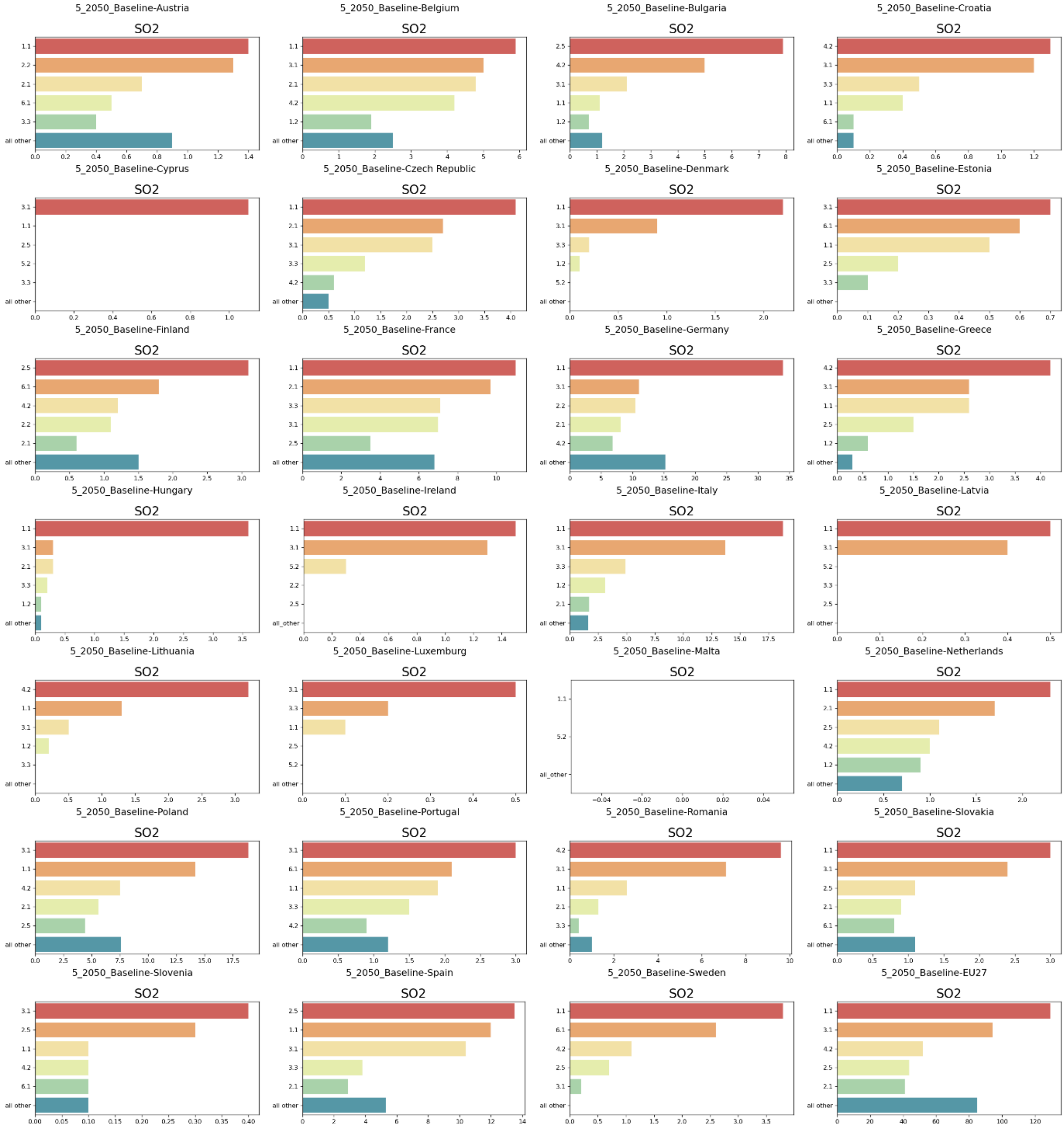


Figure 11-2 Ranking 3of top IED emitters of NO_x in 2050 in the Baseline. (Note: IED codes in Table 1-1)

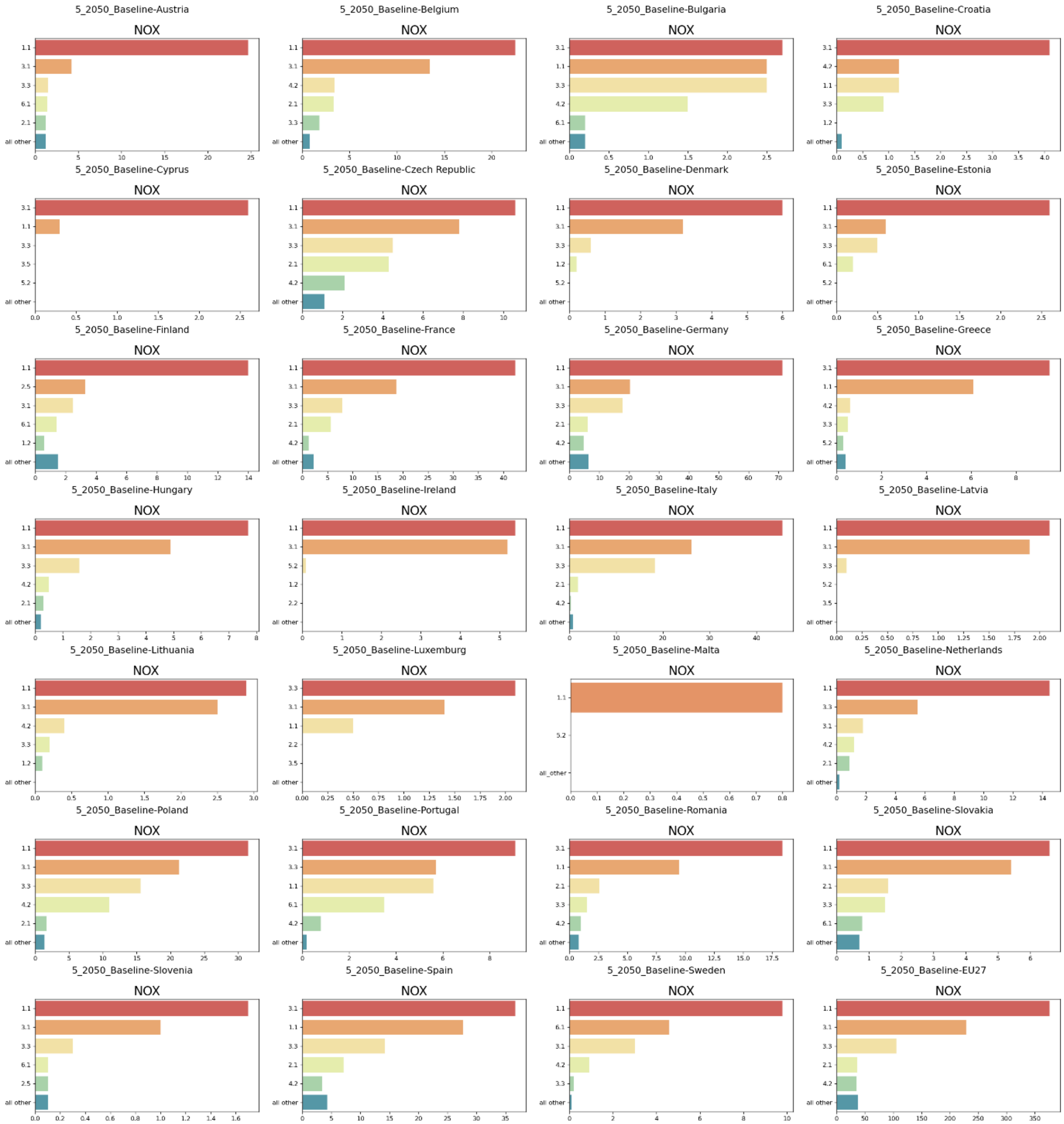


Figure 11-4 Ranking of top IED emitters of $PM_{2.5}$ in 2050 in the Baseline. (Note: IED codes in Table 1-1)

Figure 11-5 Ranking of top IED emitters of NMVOCs in 2050 in the Baseline. (Note: IED codes in Table 1-1)

12. ANNEX VII – Mitigation potential for the IED activities in MTFR

Figure 12-1 Ranking of IED activities by the mitigation potential of SO_2 in MTFR in 2050. (Note: IED codes in Table 1-1)

Figure 12-2 Ranking of IED activities by the mitigation potential of NO_x in MTFR in 2050. (Note: IED codes in Table 1-1)

Figure 12-3 Ranking of IED activities by the mitigation potential of $PM_{2.5}$ in MTFR in 2050. (Note: IED codes in Table 1-1)

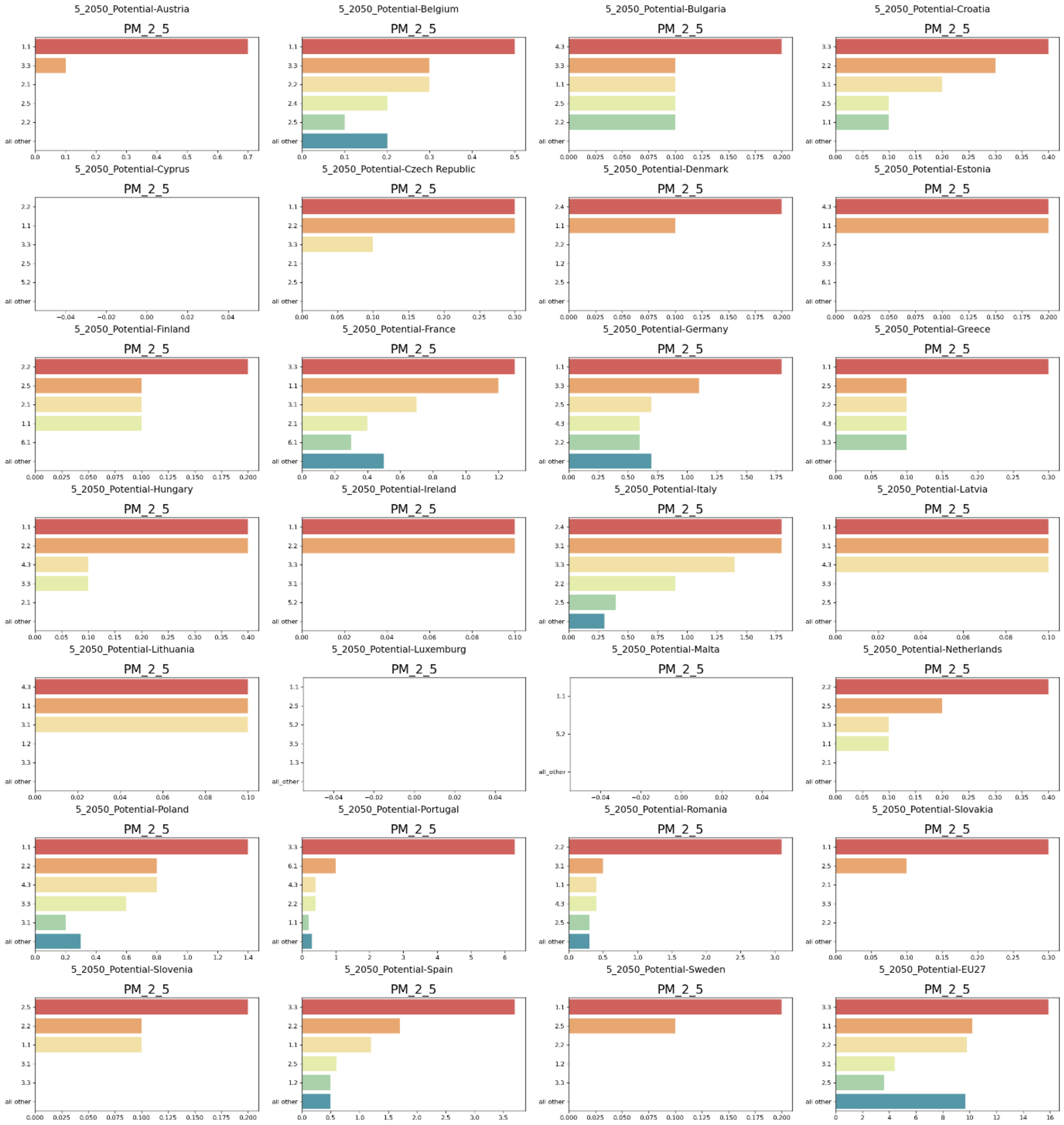
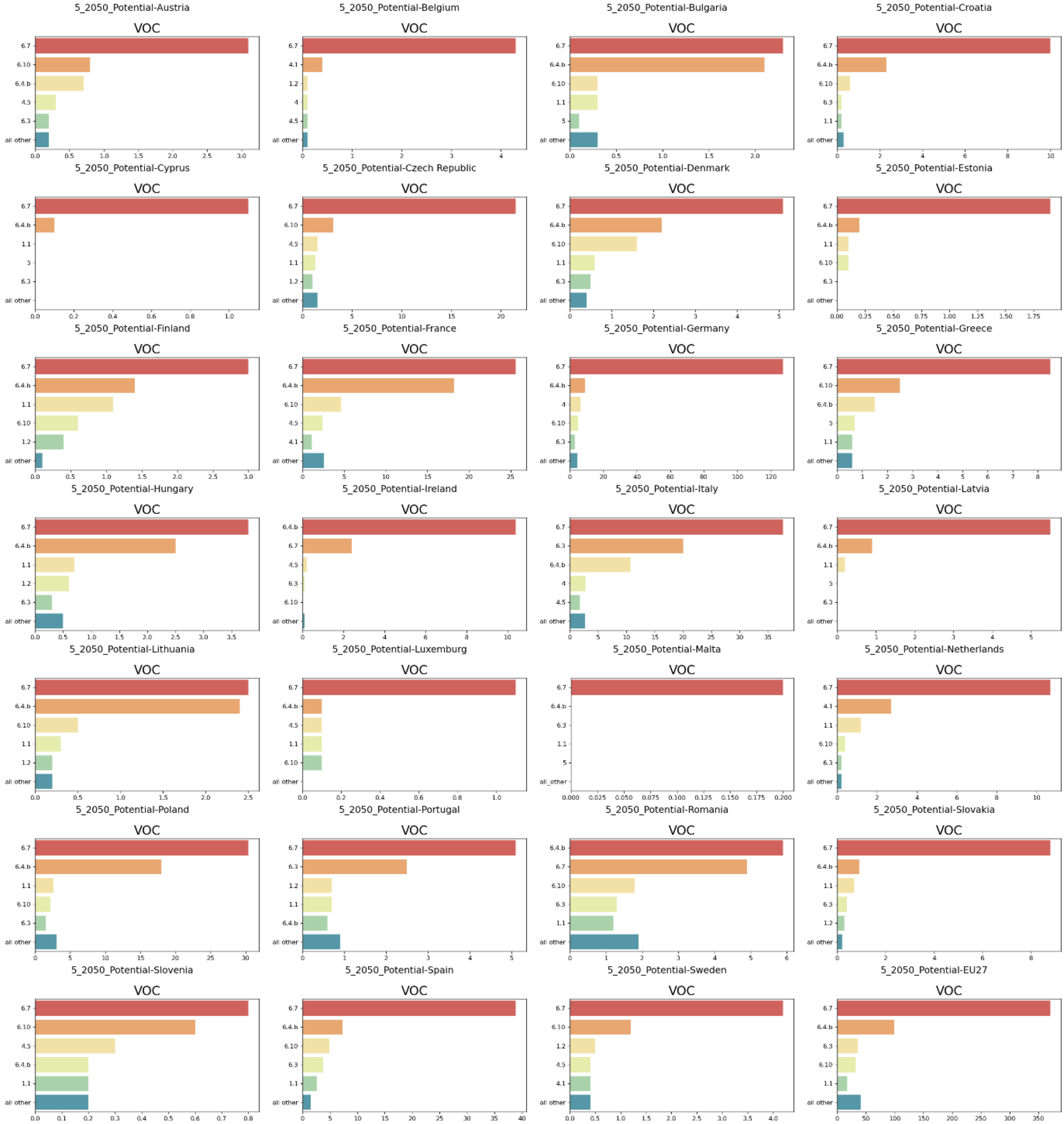


Figure 12-4 Ranking of IED activities by the mitigation potential of NMVOCs in MTFR in 2050. (Note: IED codes in Table 1-1)



13. ANNEX VIII – Control cost by the IED sectors and MS

Figure 13-1 Control cost for SO_2/NO_x/$PM_{2.5}$ by IED sectors in the Baseline and MTFR scenarios. (Note: IED codes in Table 1-1)

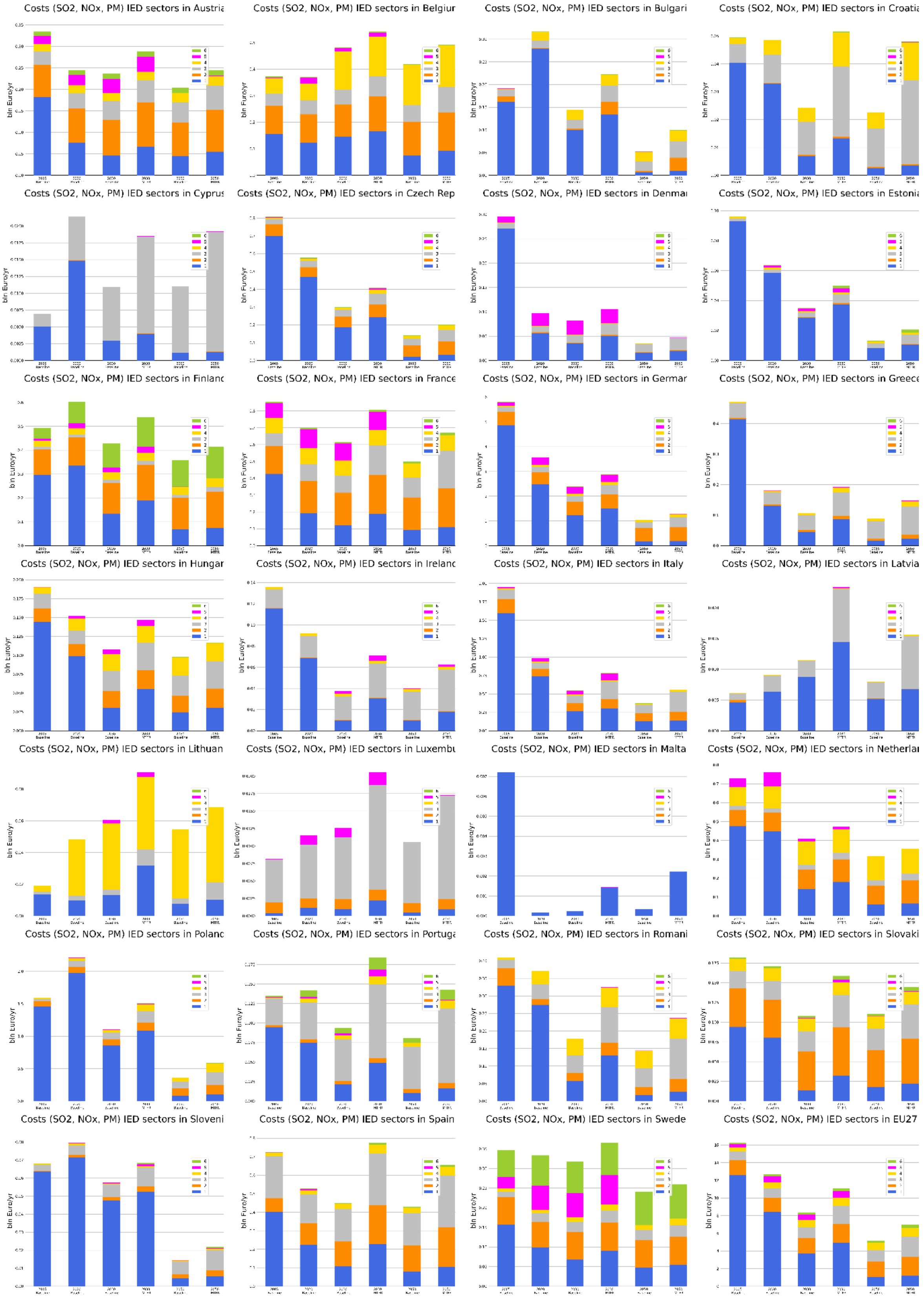


Figure 13-2 Total control cost for NMVOCs by the IED sectors in the Baseline and MTFR scenarios. (Note: IED codes in Table 1-1)

Costs VOC IED sectors in Austria

Costs VOC IED sectors in Belgium

Costs VOC IED sectors in Bulgaria

Costs VOC IED sectors in Croatia

Costs VOC IED sectors in Cyprus

Costs VOC IED sectors in Czech Republic

Costs VOC IED sectors in Denmark

Costs VOC IED sectors in Estonia

Costs VOC IED sectors in Finland

Costs VOC IED sectors in France

Costs VOC IED sectors in Germany

Costs VOC IED sectors in Greece

Costs VOC IED sectors in Hungary

Costs VOC IED sectors in Ireland

Costs VOC IED sectors in Italy

Costs VOC IED sectors in Latvia

Costs VOC IED sectors in Lithuania

Costs VOC IED sectors in Luxemburg

Costs VOC IED sectors in Malta

Costs VOC IED sectors in Netherlands

Costs VOC IED sectors in Poland

Costs VOC IED sectors in Portugal

Costs VOC IED sectors in Romania

Costs VOC IED sectors in Slovakia

Costs VOC IED sectors in Slovenia

Costs VOC IED sectors in Spain

Costs VOC IED sectors in Sweden

Costs VOC IED sectors in EU27

14. ANNEX IX – Methodology for decomposition of CO_2 reductions

The objective of the decomposition analysis of decarbonisation trends modelled in the PRIMES scenarios is to quantify the relative contribution of different pre-defined factors to the change of one explained variable[59]. The method applied here for the analysis of the carbon reductions differs to the one used for examining drivers of air pollutant emissions (Section 2.2.2), therefore it is described in more details below.

A widespread tool to analyse the results of climate policy scenarios, specifically in terms of the determinants of the reductions in CO_2 emissions, is the Kaya identity[60]. It decomposes the total CO_2 emissions into main underlying factors as:

$$CO2 = GDP \times \frac{FE}{GDP} \times \frac{CO_2}{FE}$$

where *GDP* is the Gross Domestic Product, the fraction $\frac{FE}{GDP}$ represents the final energy intensity (EI) of GDP, and $\frac{CO_2}{FE}$ is the is the carbon intensity (CI) of final energy. For this exercise, we have adapted the Kaya identity to our needs as follows:

$$CO2 = ACT \times \frac{FEC}{ACT} \times \frac{FEC_{fossil}}{FEC} \times \frac{CO_2}{FEC_{fossil}}$$

where *ACT* is the sectoral value added (in MEuro'15) of the industrial sector, *FEC* is the final energy consumption of industry, $\frac{FEC}{ACT}$ represents the energy intensity of *ACT*, $\frac{FEC_{fossil}}{FEC}$ depicts fuel shifts towards electrification, renewables and hydrogen, and $\frac{CO_2}{FEC_{fossil}}$ is the CI of fossil-fuelled technologies. The four components of the above decomposition formula are interpreted as follows:

1. Economic activity: A reduction of the economic activity of industry (measured as a reduction in *ACT* – sectoral value added) directly leads to a decrease in final energy consumption that in turn leads to lower carbon emissions.
2. Energy intensity of *ACT* (EI): A reduction in energy intensity (the ratio of final energy demand to *ACT*) can be attributed to energy efficiency improvements (heat recovery, more efficient technologies etc.) promoted via policies or standards, structural changes of the economy away from energy intensive industrial sectors (e.g., ferrous, and non-ferrous metals, chemicals, cement etc.)[61].
3. Fuel shifts towards electrification, renewables, and hydrogen: this component $\frac{FEC_{fossil}}{FEC}$ represents the fuel switch happening in the industrial sector. An increase of the component shows a cleaner fuel mix and the substitution of fossil fuels.
4. Carbon intensity of fossil fuelled technologies: A reduction in the carbon intensity of fossil fuelled energy consumption (rate of CO_2 emissions to fossil fuelled final energy consumption) corresponds to changes in the energy mix, specifically the substitution within the fossil fuel mix (natural gas replaces coal and oil).

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[59] Marcucci, A., & Fragkos, P. (2015). Drivers of regional decarbonization through 2100: A multi-model decomposition analysis. Energy Economics, 51, 111-124.

[60] Kaya, Y. (1990). Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios, Paper presented to the IPCC energy and industry subgroup. Response Strategies Working Group, Paris.

[61] Energy efficiency improvements can be caused by structural changes in economic production, e.g., de-industrialization process as GDP increases.