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Non-CO₂ greenhouse gas emissions in the EU27 from 2005 to 2070 with mitigation potentials and costs

- GAINS model methodology

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List of Abbreviations

API	American Petroleum Institute
CAPRI	Common Agricultural Policy Regionalized Impact (agro-economic model by University of Bonn)
CDD	Cooling degree days
CRF	Common Reporting Format (of official reportings of national greenhouse gas inventories to UNFCCC)
CWPB	Center-worked prebake (specific technology in aluminium production)
DG-ECFIN	Directorate General for Economic and Financial Affairs
DPI	Dry powder inhaler
EEA	European Environment Agency
EFMA	European Fertilizer Manufacturers Association
EHPA	European Heat Pump Association
EIA	Energy Information Administration
ESIA	European Semiconductor Industry Association
ETP	Energy Technology Perspective
ETS	Emissions Trading System
EU	European Union
EU-27	27 member countries of the European Union
FAO	United Nation's Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization's statistical database
FBC	Fluidized bed combustion
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies (integrated assessment model by IIASA)
GHG	Greenhouse Gas
GIS	Gas Insulated Switchgear
GSHP	ground source heat pumps
GWP	Global Warming Potential
HFO	Hydrofluoroolefins
IIASA	International Institute for Applied Systems Analysis
IEA	International Energy Agency
IFA	International Fertilizer Association
IPCC	Intergovernmental Panel on Climate Change
LABORSTA	Labour Statistics database from International Labor Organization
MAC	Mobile air-conditioners
MDI	Metered dose inhaler
NTUA	National Technical University of Athens
OECD	Organization for Economic Co-operation and Development
PCAs	Pollution Control Agreements
PFPB	Point-feeder prebake (specific technology in aluminium production)

PRIMES	Modelling system for energy supply and demand in EU-28 (by NTUA)
SWPB	Side-worked prebake (specific technology in aluminium production)
TEAP	Technology and Economic Assessment Panel of UNEP
TIMER	Targets IMage Energy Regional (simulation model by Netherlands Environmental Assessment Agency)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VAM	Ventilation air methane
VSS	Vertical stud Söderberg (specific technology in aluminium production)
XPS	Extruded polystyrene

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1 Introduction

This report presents the methodology for constructing European Union (EU) non-CO₂ emission scenarios in the Greenhouse gas, air pollution interactions and synergies (GAINS) model developed by the International Institute for Applied Systems Analysis (IIASA). The described methodology refers in particular to the EUCLIMIT6¹ scenarios for non-CO₂ greenhouse gases (GHGs), their future mitigation potentials and associated costs projected for the EU-27 countries in five-year intervals to 2070. The EUCLIMIT6 project is financed by the European Commission and conducted by a European-wide research consortium representing five interlinked process-based assessment models. The purpose of the project is to produce long-term projections for all GHG emissions in the EU-27 consistent with the European Commission's latest available macroeconomic and population projections. This report provides detailed information on the GAINS model methodology for the projections of the non-CO₂ GHGs, i.e., methane (CH₄), nitrous oxide (N₂O) and three groups of fluorinated gases (F-gases) viz. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆).

Throughout the text in this report there are references made to a “baseline” scenario. Please note that in this context a “baseline” non-CO₂ scenario refers to any scenario that describes emissions under a continuation of the current legislation implemented to control non-CO₂ emissions. Hence, a non-CO₂ “baseline” takes the energy sector input data from the PRIMES model as given, also when the PRIMES energy input data describes a full decarbonization of the energy sector. The non-CO₂ “baseline” scenario describes the starting point for assessing the technical mitigation potentials in non-CO₂ “mitigation” scenarios.

The report is structured as follows. Section 2 presents the general GAINS methodology for estimating non-CO₂ greenhouse gas emissions for EU-27. Sections 3, 4 and 5 describe in detail the methodology applied for estimation of emissions by source for CH₄, N₂O and F-gases, respectively. Finally, Section 6 provides a discussion about uncertainty and a comparison between emissions reported by member states to the UNFCCC (as of submissions April 2022 and August 2023, respectively) for years 2005, 2015, 2010 and 2020 and the emissions estimated by the GAINS model for the same years.

¹The EUCLIMIT6 project is financed by the European Commission under Service Contract N° Subcontract to Service Contract 090203/2021/856538/CLIMA.C.1/REN.

2 GAINS emission estimation methodology

2.1 Estimation of emissions

In the general GAINS methodology (Amann et al. 2011), emissions from source s in region i and year t are calculated as the activity data A_{its} times an emission factor ef_{ism} . If emissions are controlled through implementation of technology m , the fraction of the activity controlled is specified by $Appl_{itsm}$, i.e.,

$$E_{its} = \sum_m [A_{its} * ef_{ism} * Appl_{itsm}], \quad (1)$$

$$\text{where } ef_{ism} = ef_{is}^{NOC} * (1 - remeff_{sm}) \text{ and } \sum_m Appl_{its} = 1, \quad (2)$$

and where

- A_{its} is the activity (e.g., number of animals, amounts of waste),
- ef_{ism} is the emission factor for the fraction of the activity subject to control by technology m ,
- $Appl_{itsm}$ is the application rate of technology m to activity s ,
- ef_{is}^{NOC} is the no control emission factor for activity s , and
- $remeff_{sm}$ is the removal efficiency of technology m when applied to activity s .

Hence, for each emission source sector, country and year specific sets of application rates for all the possible technologies (including no control among the possible technologies) are defined such that application rates always sum to unity.

2.2 Activity data

In GAINS, activity drivers for emission projections enter calculations externally using projections from different internationally recognized sources. For EU projects, the GAINS model uses energy scenarios produced by the PRIMES model (E3Modelling, Athens) and agricultural scenarios from the CAPRI model (EuroCare, Bonn). These activity scenarios are produced in consistency with the macroeconomic and population scenarios of the European Commission's 2022 Ageing report (EC, 2022). These are also the basis for deriving activity data in GAINS, which are not part of the input data provided by the PRIMES or CAPRI models (i.e., activity data for the waste, wastewater, industrial processes, and F-gas source sectors).

2.3 Emission factors

The choice of emission factors for estimation of non-CO₂ greenhouse gas emissions in GAINS follows the methodology recommended in IPCC reports and guidelines (IPCC, 2006 and the 2019 revision) as closely as available data allows. This includes conversion to CO₂ equivalents using Global Warming Potentials (GWP) without climate-carbon feedbacks from the Fifth Assessment Report (AR5) of 28 times that of CO₂ for methane, 265 times that of CO₂ for nitrous oxide, and various species specific GWPs for the various F-gases. With the ambition to produce as consistent estimates across countries as possible, an extensive survey and compilation of available country-specific information on parameters with significant effects on emissions was undertaken. For several emission sources, there is enough country-specific information available to derive emission factors that are closer to IPCC Tier 2 factors than Tier 1 default

factors. Emission factors that are derived from underlying country-specific information improve the consistency in estimates across countries and provide an opportunity to better understand inconsistencies and uncertainty in emission estimates reported by countries to the UNFCCC and other inventories.

2.4 Baseline assumptions on emission control

Within the EUCLIMIT6 project, the GAINS baseline emission scenarios reflect current and future impacts on emissions from legislation adopted as of June 2023, and including also a number of policy proposals put forward by the European Commission as part of the “Fit for 55” package (EC, 2021). The latter include the Council proposal on Methane emissions reduction in the energy sector 2021/0423 (COD), the 2023 Commission proposal for a Review of the regulation of the fluorinated greenhouse gases 2022/0099 (COD), the Commission proposal for a revised Urban Wastewater Treatment Directive 2022/0345 (COD), and the European Parliament’s revised proposal from July 2023 of the Commission proposal 2022/0104(COD) for a Revision of the Industrial Emissions Directive affecting non-CO₂ GHGs from large agro-industrial farms.

2.5 Non-CO₂ GHG mitigation and cost estimation in GAINS

2.5.1 Technical mitigation potentials

The mitigation potential assessed in the marginal abatement cost curves of the GAINS model refers to feasible reductions in emissions through adoption of mitigation technologies defined as installations or applications of physical equipment or material, or modifications in physical parameters affecting emissions. It should be noted that the technical mitigation potential may differ from the politically feasible mitigation potential as the latter also takes into account costs and political barriers for implementation. In the GAINS baseline scenarios for non-CO₂ greenhouse gases, no effects on costs and removal efficiencies from technological development are accounted for. The reason is that incentives to adopt (and therefore further develop) technology that will reduce non-CO₂ greenhouse gases are to a large extent driven by the introduction of policies directed specifically at non-CO₂ mitigation. An exception would be technologies that simultaneously reduce methane emissions and recover or save gas that can be utilized for energy purposes. Demand for the latter technologies may arise spontaneously if the future price of gas is expected to be high enough to make gas recovery profitable in the long run. Hence, in contrast to most CO₂ mitigation opportunities, where demand for adoption and development of more energy-efficient technologies is primarily driven by a wish to save on energy costs, there is generally less reason to invest in development of improved mitigation technologies for non-CO₂ greenhouse gases (since most of them have only additional costs and do not generate revenues – with exceptions such as anaerobic digestion) unless directed policies are put in place and maintained for a foreseeable future. The development of non-CO₂ abatement technology therefore rely heavily on the stringency of the policies implemented and their effectiveness in stimulating continuous technological development. E.g., policies that merely require adoption of pre-defined best-available-technology are less likely to stimulate continuous technological development than policies that financially penalize every additional unit of emissions released (see e.g., Popp 2003; Pizer and Popp 2008; OECD 2011). The

existence of incentives for continuous technological development of non-CO₂ abatement technology is therefore considerably more uncertain than for CO₂ mitigation technology.

A common way to include the effect of technological change in mitigation technology in assessment models is to make assumptions about the learning effect on costs from cumulative technology adoption (see e.g., Jamasb and Köhler 2007). In such experience curves, the learning effect is usually measured in terms of a percentage reduction in unit costs C for each doubling of the cumulative capacity installed Cap , i.e.,

$$C = \alpha \times Cap^{-\varepsilon} \quad (3)$$

$$LR = 1 - 2^{-\varepsilon} \quad (4)$$

where α is a constant, ε is the learning elasticity and LR is the learning rate.

Jamasb and Köhler (2007) survey the literature on experience curves to sample empirical estimates of learning rates. They conclude that the variability is very large both between technologies and sectors and for different time periods. A majority of published learning rate estimates refer to development in electricity generation technologies. McDonald and Schratzenholzer (2001) survey these technologies and find empirical measurements of learning rates ranging from 1.4 to 35 percent reduction in unit costs for every doubling in the cumulative technology capacity. They conclude that a 17% learning rate would be appropriate for long-term energy models. However, Jamasb and Köhler (2007) point out that the evidence on declining learning rates over time suggests that a 20 percent learning rate might be on the high side when taken as a general assumption. This is particularly true when modeling further development of already existing technologies. For non-CO₂ mitigation technology we adopt effects on costs from a 15 percent learning rate, which in Equation 4 implies a learning elasticity of 23.4% and a doubling of the adopted capacity every 15 years. It is further assumed that the effect of technological development on costs lasts for 30 years after policy incentives have been introduced.

Depending on whether the estimates available from literature on costs of specific technologies are representative of the situation today or reflect costs expected in the future, the starting year for the learning effect on costs differs between technologies. Table 1 presents the adjustment factors applied to investment and operation and maintenance costs for two categories of technologies. The first category refers to existing technologies that can be implemented already from the year 2025 and for which current costs are fairly well known. For this category, an effect of technological development on costs is expected from 2025 onwards. The second category refers to technologies that are described in literature as still under development (i.e., reduction of CH₄ emissions from enteric fermentation through breeding or changes in animal feed) or to technologies for which cost estimates from literature are stated as expected future costs (i.e., options to control N₂O emissions from agricultural soils). For these options an effect on costs from technological development is accounted for from 2035 onwards.

Table 1: Adjustment factors for investment costs, operation and maintenance (O&M) costs, and emission factors used in GAINS to account for effects of technological development of non-CO₂ mitigation technology from 2025 to 2070.

Year	Category 1 technologies		Category 2 technologies	
	Technologies with current costs and removal efficiencies provided in literature. Include all technologies except those specified as Category 2		Technologies with future expected costs and removal efficiencies provided in literature. Includes CH ₄ measures addressing enteric fermentation emissions (i.e., breeding and animal feed options) and N ₂ O measures addressing emissions from agricultural soils (i.e., VRT, nitrification inhibitors and precision farming)	
	Investment and O&M costs	Emission factors	Investment and O&M costs	Emission factors
2025	1	1	1	1
2030	0.88	0.95	1	1
2035	0.82	0.9044	1	1
2040	0.765	0.8601	0.88	0.95
2045	0.72	0.8179	0.82	0.9044
2050	0.68	0.7778	0.765	0.8601
2055	0.651	0.7397	0.72	0.8179
2060	0.651	0.7397	0.68	0.7778
2065	0.651	0.7397	0.651	0.7397
2070	0.651	0.7397	0.651	0.7397

Apart from lowering costs, technological development in abatement technology can also come in the form of improved removal efficiency. The effect on removal efficiency is closely linked to whether or not policies target emissions directly, e.g., through emission charges. Command-and-control regulations which require installations of best available technology are poor stimulators of improvement in removal efficiency, while market-based instruments that are directly linked to emission reductions are more likely to stimulate improvements in the removal efficiency (Popp, 2003). Empirical analyses of how environmental regulations affect technological development through effects on application rates for abatement technology patents usually show “peak” patterns, i.e., a sharp increase in technological development activities just after the introduction of a regulation, then a high level of development for a few years, and finally a leveling off reflecting that much of the readily available opportunities for technological development have been exhausted (OECD, 2011). Similar “peak” patterns have also been found for improvements in removal efficiencies following introductions of incentive-based environmental regulations (Popp, 2003; Höglund-Isaksson and Sterner, 2010). As no information is available in the literature for control of non-CO₂ emissions per se, we survey the literature for known effects on patent application rates and removal efficiencies of technologies in response to waste management regulations and air pollution control. Similar to non-CO₂ control, development of waste management and air pollution technologies relies to a high degree on implementation of directed policies to drive incentives for technological development.

OECD (2011, p.30) shows how the number of patent applications for solid waste management technologies (recycling, composting and incineration) closely responds to the timing of regulation introductions in different countries. Denmark was the first country to adopt an environmental protection law in 1973 and an important objective was to control the amount of waste deposited to landfills when land area was becoming scarce (Copenhagen Cleantech Cluster 2012; Civilstyrelsen 2012). Danish patent applications in this sector started to rise sharply in the beginning of the 1980s, peaked in the early 1990s and have since declined (OECD 2011). Similar increases in patent applications for waste management technology occurred in the US in the late 1980s and in Japan in the early 1990s following the amendment of the US

Resource, Conservation and Recovery Act in 1984 and the Japanese Recycling Law in 1991, respectively (OECD 2011, p.131).

From the early 1990s, the US and Sweden introduced market-based instruments complementing or replacing command-and control regimes in air pollution control. As shown by Popp (2003), the command-and control regulations of SO₂ emissions from coal-fired utility plants in the US introduced under the Clean Air Acts of 1970 and 1977, are reflected in a considerable increase in US patent applications for scrubbers during this period. Notable is that this technological development was primarily focused on developing technology at lower costs and without significant improvements in removal efficiencies. Only after the 1990 Clean Air Act, when a cap- and trade scheme for SO₂ emissions was introduced, did the removal efficiency of the available technologies improve significantly. Popp (2003) interprets this as a result of a switch in policy target from targeting adoption of certain technology to targeting emission reductions directly. Table 2 summarizes the empirical findings of the short and long-term effects of air pollution regulations in the US (Popp, 2003), Sweden (Höglund-Isaksson and Sterner, 2010) and Japan (Matsuno et al., 2010). While Popp (2003) measures technological development directly when he measures the annual improvement in removal efficiency of a certain technology (scrubbers), the other studies use indirect measures, where the effect of technological development on emissions is summed up with the effect on emissions of adopting existing technology. The latter produces higher annual changes in emission rates, in particular in the short run as it then also reflects the plants' initial adoption of technology in responses to the regulations. In the long run, it can be expected that a larger fraction of the annual change is due exclusively to the effects of technological development.

On the basis of the long-term effects found in the literature survey presented in Table 2, we assume a long-term improvement in the effectiveness of non-CO₂ mitigation technology to remove emissions of one percent per year. The resulting adjustment factors applied on emission factors are presented in Table 1 for Category 1 and 2 technologies, respectively. Like for costs, the effect on removal efficiencies from technological development are assumed to last for 30 years after implementation of policy incentives. No effect from technological development is assumed for F-gas mitigation options that reflect substitution of F-gases with low global warming alternatives like propane, isobutane, CO₂, etc. as the global warming potentials of these are physical constants.

Table 2: Some empirical evidence of the effects of air pollution regulations on targeted emissions in short and long runs.

Source	Regulation	Year of first implementation	Number and type of plants in analyzed sample	Emission parameter description	Total effect		Short-term effect		Long-term effect	
					Entire period	Average annual change in parameter	Period with rapid decline in parameter	Average annual change in parameter	Period with slower decline in parameter	Average annual change in parameter
Popp (2003)	US 1970, 1977, 1987 CAA (command-and control)	1970	193 coal-fired plants with scrubber	SO ₂ emission rate of new scrubbers	1974-1990	about -0.4%	1974-1978	about -1.5%	1978-1990	about 0
	US 1990 CAA (cap-and trade)	1990			1990-1997	about -1.6%	not available		not available	
Höglund-Isaksson and Sterner (2010)	Swedish NOx charge -plants not (yet) adopting abatement technology	1992	180 to 280 power plants (> 50 MWh) targeted in 1992 to 2007	NO _x emissions per energy output of targeted plants	1992-2007	-3.5%	1992-1997	-5.8%	1997-2007	-2.4%
	Swedish NOx charge -plants having adopted abatement technology	1992			1992-2007	-5.7%	1992-97	-11.2%	1997-2007	-2.9%
Matsuno et al. (2010)	Japanese SO ₂ compensation law	1974	>3000 sites targeted by pollution load regulation	SO ₂ emissions of targeted plants	1973-2003	-7.1%	1973-1987	-11.5%	1987-2003	-3.0%

2.5.2 Mitigation costs

Unit costs for mitigation of non-CO₂ GHGs per unit of activity are in GAINS calculated as the sum of investment costs, labour costs, non-labour operation and maintenance costs, cost-savings due to recovery or saving of electricity, heat or gas, and non-energy cost savings. The unit cost of technology m in country i and year t is defined as:

$$C_{itm} = I_{im} \left[\frac{(1+r)^{T_m \times r}}{(1+r)^{T_m - 1}} \right] + M_{im} + (L_{im} \times W_{it} \times w_{is}) - S_{im} - (E_{im} \times p_{it}^{electr}) - (H_{im} \times p_{it}^{heat}) - (G_{im} \times p_{it}^{gas}) \quad (5)$$

where I_{im} is the upfront investment cost for technology m in country i ,

$\left[\frac{(1+r)^{T_m \times r}}{(1+r)^{T_m - 1}} \right]$ is the annualization factor for the investment cost with interest rate r and technology lifetime of T_m years,

M_{im} is the annual operation and maintenance cost for technology m ,

L_{im} is the fraction of annual work hours for operating technology m ,

W_{it} is the annual average wage in country i in year t ,

w_{is} is a country-specific wage adjustment factor for type of sector s (agriculture or manufacturing industry),

S_{im} is the sum of non-energy annual cost-savings,

E_{im} is the amount of energy recovered and utilized as electricity,

p_{it}^{electr}	is the industry electricity price in country i in year t ,
H_{im}	is the amount of energy recovered and utilized as heat,
p_{it}^{heat}	is the industry heat price in country i in year t ,
G_{im}	is the amount of gas recovered, and
p_{it}^{gas}	is the industry gas price in country i in year t .

In the EUCLIMIT6 scenarios, the unit costs are expressed in constant 2015 Euros per unit of activity and a market interest rate of 10 percent is adopted in order to be consistent with the relevant (market) interest rate used in PRIMES (E3modelling, 2023) mitigation costs for CO₂.

Country and sector specific annual average wages were updated to EUROSTAT (2023) for historical years and growth in future wages is proportional to the expected future development in sector value added as provided by PRIMES (E3modelling, 2023) and in consistency with the European Commission's 2022 Ageing Report (EC, 2022).

In the GAINS estimation of CH₄ mitigation costs, energy recovery from biogas production or reduced leakage of natural gas during production, transmission and distribution is valued at the electricity, heat or gas consumer price in industry as estimated and projected by PRIMES (E3modelling, 2023).

Gas recovery refers to recovered gas of an upgraded quality of 97 percent CH₄. For some mitigation options, e.g., when biogas is recovered from large-scale anaerobic digestion (note not applicable to small farm anaerobic digesters), upgrading from 60 to 97 percent CH₄ is necessary for supplying the gas to the grid (Persson, 2003). Costs for upgrading gas have in these cases been included in investment costs.

Similar to how the country and year specific emission level E_{its} is estimated for each sector in equation (1), the total mitigation cost in sector s in country i and year t is defined for sets of application combinations of the possible technologies applicable in the sector. For a given country, year and sector, a technology setting is defined such that the sum of all application rates $Appl_{itms}$ of possible technologies m (including the no control option) is always unity. The total cost of each technology set is defined as:

$$TC_{its} = \sum_m [A_{its} * C_{itm} * Appl_{itms}] , \quad (6)$$

where A_{its} is the activity level, C_{itm} is the cost per unit of activity and $\sum_m Appl_{itms} = 1$.

The average cost per unit of reduced emissions is first calculated for each technology available to a sector by dividing the unit cost with the difference between the technology emission factor and the no control emission factor, such that:

$$AC_{itm} = \frac{C_{itm}}{ef_{it}^{Nocontrol} - ef_{itm}} . \quad (7)$$

Within a sector, the technologies available are first sorted by their respective average cost. The technology with the lowest average cost is ranked the first-best technology and assumed adopted to its full extent in a given sector. The second-best technology is the technology with the second lowest average cost and is assumed available for adoption provided it can achieve an emission factor that is lower than the first-best technology. The marginal cost of the second-best technology when implemented in the cost curve is defined as:

$$MC_{it2} = \frac{c_{it2} - c_{it1}}{ef_{it1} - ef_{it2}} \quad (8)$$

In a similar manner, each additional technology available in a sector is added on top of the next best available technology. Note that a technology with both a higher average cost and a higher emission factor than another technology available to a sector will not be adopted at all as it is less effective in reducing emissions and come at a higher cost than other available technologies. In this way, a marginal mitigation cost curve with strictly convex properties is built up sector-wise by country and year.

3 CH₄ emission sources

3.1 Overview of CH₄ emission sources and control implemented in the baseline scenario

CH₄ emission sources in the GAINS model include anthropogenic CH₄ emissions from livestock, rice cultivation, biodegradable solid waste, wastewater, coal mining, oil and gas production, gas transmission pipelines, gas consumer distribution networks, and combustion emissions from fuel used for energy consumption and from open burning of agricultural waste residuals (Höglund-Isaksson et al., 2020). Other types of open burning of biomass for non-energy purposes, e.g., human-induced forest fires, have been excluded from the analysis due to lack of systematic information. Table 3 provides an overview of the structure of CH₄ sources in GAINS and their respective control options.

In addition to the structure presented in Table 3, it should be mentioned that the livestock categories dairy cows, non-dairy cattle, pigs, poultry and sheep have been further split into the following farm-size classes; less than 15 livestock units (LSU), 15 to 50 LSU, 50 to 100 LSU, 100 to 500 LSU, and above 500 LSU. This allows for considering the impact of scale on mitigation potentials and costs.

Table 4 presents a list of current legislation affecting CH₄ emissions in the EU member states, including also a number of policy proposals put forward by the European Commission as part of the “Fit for 55” package (EC, 2021).

Table 3: Overview of GAINS structure of CH₄ emission sources and mitigation options.

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Coal mining	MINE_BC_PRE	Brown coal mining: pre-mining emissions	BC_DEGAS	Pre-mining degasification
	MINE_BC_VAM	Brown coal mining: emissions during mining	none	no option identified
	MINE_BC_POST	Brown coal mining: post-mining emissions	none	no option identified
	MINE_HC_PRE	Hard coal mining: pre-mining emissions	HC_DEGAS	Pre-mining degasification
	MINE_HC_VAM	Hard coal mining: emissions during mining	VAMOX VAMOX_VENT	Oxidation of ventilation air methane VAMOX combined with improved ventilation system
	MINE_HC_POST	Hard coal mining: post-mining emissions	none	no option identified
	COAL_ABAND	Abandoned coal mines	FLOODING	Good practice -flooding of mines
Oil production	PROD_AGAS -CRU	Oil production: venting associated gas	REC_USE	Extended recovery and utilization of associated gas
			REC_USE2	Monitoring of flaring and venting of associated gas not recovered
	PROD_LEAK -CRU	Oil production: unintended leakage	GP	Leakage control using LDAR technology
Oil refinery	PR_REF	Oil transportation, storage and refining	FLA_REF	Leakage control using LDAR technology
Gas production	PROD_AGAS -GAS	Gas production: venting associated gas	REC_USE	Extended recovery and utilization of associated gas
	PROD_LEAK -GAS	Gas production: unintended leakage	GP	Leakage control using LDAR technology
Long-distance gas transportation	TRANS -GAS	Gas transmission pipelines	CONT_TRANS	Leakage control through LDAR programs
			COMPRESS	Pipeline upgrade to minimum leakage rate, benchmark is Denmark with 0.003% leakage
Consumer gas distribution networks	DOM/TRA_** - GAS/BIOG -GAS/BIOG -CAST_IRON	Domestic and transport sector: gas fuel (natural gas and upgraded biogas) -cast iron distribution networks	CONT_NET	Leak detection and repair (LDAR) programs
			PE_PVC	Replacement grey cast iron with PE_PVC networks
			PE_PVC_CONT	LDAR program on PE/PVC networks
	DOM/TRA_** - GAS/BIOG -STEEL	Domestic and transport sector: gas fuel (natural gas and upgraded biogas) -steel distribution networks	CONT_NET	Leak detection and repair (LDAR) programs
			PE_PVC	Replacement grey cast iron with PE_PVC networks
			PE_PVC_CONT	LDAR program on PE/PVC networks
	DOM/TRA_** - GAS/BIOG -OTHER	Domestic and transport sector: gas fuel (natural gas and upgraded biogas) -other non-PE/PVC distribution networks	CONT_NET	Leak detection and repair (LDAR) programs
			PE_PVC	Replacement grey cast iron with PE_PVC networks
	DOM/TRA_** - GAS/BIOG -PE_PVC	Domestic and transport sector: gas fuel (natural gas and upgraded biogas) -PE/PVC distribution networks	PE_PVC_CONT	LDAR program on PE/PVC networks
			PE_PVC_CONT	LDAR program on PE/PVC networks
IN_**/PP_**/NONEN - GAS -STEEL	Industrial boilers and power plants: gas fuel (natural gas) -steel distribution networks	CONT_NET	Leak detection and repair (LDAR) programs	
		PE_PVC	Replacement grey cast iron with PE_PVC networks	
		PE_PVC_CONT	LDAR program on PE/PVC networks	
IN_**/PP_**/NONEN - GAS -OTHER	Industrial boilers and power plants: gas fuel (natural gas) -other non-PE/PVC distribution networks	CONT_NET	Leak detection and repair (LDAR) programs	
		PE_PVC	Replacement grey cast iron with PE_PVC networks	
IN_**/PP_**/NONEN - GAS -PE_PVC	Industrial boilers and power plants: gas fuel (natural gas) -PE/PVC distribution networks	PE_PVC_CONT	LDAR program on PE/PVC networks	
LNG terminals	LNG_TERM	LNG import terminals	BAT	LDAR technology for LNG terminals
Bunker fuels	BUNK - MD/HF/GAS/LPG/H2	Fugitive and combustion emissions from bunker fuel use	BAT	Leakage control using VOC control measures
Combustion in stationary sources	DOM -various fuels	Domestic sector: various fuels	none	no option identified
	IN_BO -various fuels	Industrial boilers: various fuels	none	no option identified
	IN_OC -various fuels	Other industry combustion: various fuels	none	no option identified
	PP_EX_OTH -various fuels	Power plants existing: various fuels	none	no option identified
	PP_NEW -various fuels	Power plants new: various fuels	none	no option identified
	CON_COMB -various fuels	Other combustion sources: various fuels	none	no option identified
Combustion in mobile sources	TRA_RD_HDB/HDT/LD4C/LD4T -various fuels	Road transport/bus/trucks/cars/vans: various fuels	none	no option identified
	TRA_OT_AGR/CNS/INW/LB/RAI -various fuels	Non-road transport: various modes and fuels	none	no option identified

Continued Table 3: Overview of GAINS structure of CH₄ emission sources and mitigation options.

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Livestock	AGR_BEEF -OL_F	Non-dairy cattle with liquid manure management: enteric fermentation emissions	FEED	Feed additives and/or changed feed management practices
			BREED	Breeding through selection on farms with > 50 LSU: enhance productivity, fertility and longevity to minimize kg CH ₄ /kg milk
	AGR_BEEF -OL	Non-dairy cattle with liquid manure management: manure management emissions	FARM_AD	Farm-scale anaerobic digestion on farms with minimum size 100 LSU
	AGR_BEEF -OS	Non-dairy cattle with solid manure management: enteric fermentation and manure management emissions	FEED	Feed additives and/or changed feed management practices
			BREED	Breeding through selection on farms with > 50 LSU: enhance productivity, fertility and longevity to minimize kg CH ₄ /kg milk
	AGR_COWS -DL_F	Dairy cows with liquid manure management: enteric fermentation emissions	FEED	Feed additives and/or changed feed management practices
			BREED	Breeding through selection on farms with > 50 LSU: enhance productivity, fertility and longevity to minimize kg CH ₄ /kg milk
	AGR_COWS -DL	Dairy cows with liquid manure management: manure management emissions	FARM_AD	Farm-scale anaerobic digestion on farms with minimum size 100 LSU
	AGR_COWS -DS	Dairy cows with solid manure management: enteric fermentation and manure management emissions	FEED	Feed additives and/or changed feed management practices
			BREED	Breeding through selection on farms with > 50 LSU: enhance productivity, fertility and longevity to minimize kg CH ₄ /kg milk
	AGR_PIG -PL	Pigs with liquid manure management	FARM_AD	Farm-scale anaerobic digestion on farms with minimum size 100 LSU
	AGR_PIG -PS	Pigs with solid manure	none	no option identified
	AGR_POULT -LH	Laying hens	none	no option identified
	AGR_POULT -OP	Other poultry	none	no option identified
AGR_OTANI -BS	Buffaloes	none	no option identified	
AGR_OTANI -HO	Horses	none	no option identified	
AGR_OTANI -SH	Sheep and goats	BREED	Breeding through selection on farms with > 50 LSU: enhance productivity, fertility and longevity to minimize kg CH ₄ /kg milk	
Rice cultivation	RICE_FLOOD	Rice cultivation	COMB_RICE1, COMB_RICE2	Water management (intermittent aeration), alternative hybrids and soil amendments
Agricultural waste burning	WASTE_AGR	Open burning of agricultural waste	BAN	Enforcement of ban to openly burn agricultural waste

Continued Table 3: Overview of GAINS structure of CH₄ emission sources and mitigation options

Emission source	GAINS sector	Sector description	GAINS technology	Technology description
Solid waste	MSW_FOOD	Municipal solid waste: food and garden	TREAT_AD	Source separation & anaerobic digestion with biogas recovery
			TREAT_HSC	Household composting
			TREAT_LSC	Source separation & large-scale composting
			TREAT_INC	Incineration of mixed waste with energy recovery
			SWD_FLA	Landfill with recovery and flaring of landfill gas
			SWD_USE	Landfill with recovery and utilization of landfill gas
	MSW_PAP/ MSW_TEX/ MSW_WOOD	Municipal solid waste: paper/ textile	TREAT_REC	Source separation & recycling
			TREAT_INC	Incineration of mixed waste with energy recovery
			SWD_FLA	Landfill with recovery and flaring of landfill gas
	INW_FOOD	Industrial solid waste: food, beverages	SWD_USE	Landfill with recovery and utilization of landfill gas
			FOOD_AD	Anaerobic digestion with biogas recovery
			FOOD_COM	Composting
			FOOD_INC	Incineration
	INW_PAP	Industrial solid waste: pulp and paper	SWD_FLA	Landfill with recovery and flaring of landfill gas
			SWD_USE	Landfill with recovery and utilization of landfill gas
			PAP_INC	Recovery of black liquor for energy utilization
	INW_TEX	Industrial solid waste: Textile, footwear, leather	SWD_FLA	Landfill with recovery and flaring of landfill gas
			SWD_USE	Landfill with recovery and utilization of landfill gas
			TEX_INC	Incineration with energy recovery
	INW_WOOD	Industrial solid waste: wood and wood products	SWD_FLA	Landfill with recovery and flaring of landfill gas
SWD_USE			Landfill with recovery and utilization of landfill gas	
WOOD_REC			Recycling for chip board production	
WOOD_INC			Incineration with energy recovery	
Wastewater	WW_DOM_CC_TRM	Domestic wastewater: centralized collection	DOM_CC_AER	Aerobic treatment
			DOM_CC_23	Anaerobic treatment
			DOM_CC_23U	Anaerobic treatment (secondary/tertiary) with biogas recovery
	WW_DOM_DC_NOC	Domestic wastewater: decentralized collection, no treatment	none	no option identified
	WW_DOM_DC_TRM	Domestic wastewater: decentralized collection, with treatment	none	no option identified
	IND_FOOD_TRM	Industrial wastewater: food, beverages	IND_FOOD_AERO	Aerobic treatment
			IND_FOOD_ANAE_NON	Anaerobic treatment without biogas recovery
			IND_FOOD_ANAE_USE	2-stage: Anaerobic with biogas recovery followed by aerobic treatment
	IND_PAP_TRM	Industrial wastewater: pulp and paper	IND_PAP_AERO	Aerobic treatment
			IND_PAP_ANAE_NON	Anaerobic treatment without biogas recovery
			IND_PAP_ANAE_USE	2-stage: Anaerobic with biogas recovery followed by aerobic treatment
	IND_OTH_TRM	Industrial wastewater: other organic	IND_OTH_AERO	Aerobic treatment
			IND_OTH_ANAE_NON	Anaerobic treatment without biogas recovery
			IND_OTH_ANAE_USE	2-stage: Anaerobic with biogas recovery followed by aerobic treatment

Table 4: Current legislation and foreseeable policy proposals affecting CH₄ emissions in EU member states in the GAINS Baseline.

Sector	Policy	Regional coverage	Policy description and implementation in GAINS
Agriculture	Feed-in tariffs or other subsidies to stimulate co-digestion of manure on farms	Italy, Netherlands, Latvia, Sweden, Cyprus, Austria, Croatia, Germany	Reflected via assumptions on uptake of farm-scale biogas technology consistent with information from EurObserv'ER (2020) on installed capacity. Future uptake follows trend in biogas production from anaerobic digestion as projected in the PRIMES model Reference scenario.
	EU Common Agricultural Policy (CAP) and EU Nitrate Directive (EEC/676/1991) with revisions	EU-wide	Reflected in GAINS through input of CAPRI model data on trends in livestock numbers, milk yield and fertilizer use.
	European Parliament's revised proposal from July 2023 of the Commission proposal 2022/0104(COD) for a Revision of the Industrial Emissions Directive	EU-wide	Affect non-CO ₂ GHG emissions from large agro-industrial farms with more than 500 LSU.
	Ban on burning of crop residues	EU-wide	Assumed not fully enforced. GAINS uses information derived from satellite images (e.g., MODIS) as approximate estimates of the mass of crop burned on fields.
Waste & wastewater	EU Landfill Directive (EC/31/1999) with amendment (EC/850/2018) and EU Waste and Packaging Directives (EC/851/2018, EC/852/2018)	EU-wide	Biodegradable waste diverted away from landfills (relative 1990 by -25% in 2006, -50% in 2009 and -65% in 2016). All landfill sites equipped with gas recovery by 2009. By 2035, countries must not landfill more than 10% of MSW generated. Member states that landfill more than 60% of MSW in 2013 are given a 5 years grace period but must not landfill more than 25% in 2035. GAINS Reference scenario assumes future targets will be met.
	EU Waste Management Framework Directive (EC/98/2008)	EU-wide	The following hierarchy is to be respected in waste treatment: recycling and composting preferred to incineration/energy recovery, which in turn is preferred to landfill disposal. Considered in GAINS when simulating pathway for compliance with the Landfill Directive target.
	Decree on waste landfill	Slovenia	Decree on landfill of waste beyond EU Landfill Directive. Includes partial ban on landfill of biodegradable waste.
	Legislation to replace current composting with anaerobic digestion of food waste	Germany	In GAINS, the current composting of organic waste is phased-out linearly and replaced with anaerobic digestion between 2020 and 2050.
	Ban on landfill of biodegradable waste.	Austria, Belgium, Denmark, Germany, Netherlands, Sweden	Complete ban on landfill of untreated biodegradable waste. Reflected in GAINS.
	EU urban wastewater treatment directive (EEC/271/1991)	EU-wide	GAINS reflects an "appropriate treatment" of wastewater from urban households (all agglomerations > 2000 people) and food industry must be in place latest by end of 2005. This means discharge must ensure receiving waters meet relevant quality objectives.
	Commission proposal for a revised wastewater treatment directive (2022/0345(COD))	EU-wide	GAINS reflects the new requirements related to "appropriate treatment" of wastewater from urban agglomerations of >= 1000 p.e. This means discharge must ensure receiving waters meet the quality objectives. It integrates the future expected energy neutrality in wastewater treatment plants treating a load of 10000 p.e. and above by 50% in 2030, 75% by 2035 and by 100% by 2040. GAINS baseline assumptions represent the energy target by phasing in adoption of anaerobic aerobic treatment with gas recovery and use.
Energy	Council proposal on methane emissions in the energy sector (2021/0423(COD))	EU-wide	GAINS reflects proposed control of CH ₄ leakage from gas distribution networks, above ground gas storage, gas transmission pipelines, and LNG terminals, proposed control of gas leakage and prohibition of venting of associated gas during oil and gas production, proposed inclusion in the ETS permit system of CH ₄ and N ₂ O emissions from bunker fuels useage in international shipping, and proposed control of venting of CH ₄ from ventilation shafts in thermal coal mines.
	Fuel/EU Maritime regulation adopted by the EU Council in July 2023. Regulation on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC	EU-wide	CH ₄ and N ₂ O emissions from use of bunker fuels included in GAINS as an ETS (Emissions Trading System) sector.

3.2 Energy sector

3.2.1 Coal mining

Formation of coal produces CH₄, which is released to the atmosphere during mining. IPCC (2006, Vol.2, p.4.9) identifies three sources of CH₄ emissions from coal mining: liberation of CH₄ during breakage of coal in the coal mine, post-mining emissions during handling, processing and transportation of mined coal, and emissions from abandoned coal mines. Following the split of the activity data into brown and hard coal, emissions are calculated separately for the two coal types. All brown coal is assumed to be surface mined, while hard coal is assumed being partly surface mined and partly mined underground. Emissions from peat production are understood to be negligible and have been set to zero.

Emissions from brown and hard coal production are calculated as follows:

$$E_{BC;it} = A_{BC;it} \times [ef_{m;i}^{surface} + ef_{postm;i}^{surface}] \quad (9)$$

$$E_{HC;it} = A_{HC;it} \times [\gamma_{HC;i}^{undergr} \times (ef_{m;i}^{undergr} + ef_{postm;i}^{undergr})] + A_{HC;it} \times [(1 - \gamma_{HC;i}^{undergr}) \times (ef_{m;i}^{surface} + ef_{postm;i}^{surface})] \quad (10)$$

where

$$ef_{m;i}^{surface} = ef_{m;i;NOC}^{surface} \times (1 - r_{dgas}) \times CLEappl_{dgas;i}, \quad (11)$$

$$ef_{m;i}^{undergr} = ef_{m;i;NOC}^{undergr} \times [\alpha_{VAM;i} \times (1 - r_{VAM}) \times CLEappl_{VAM;i}] + ef_{m;i;NOC}^{undergr} \times [(1 - \alpha_{VAM;i}) \times (1 - r_{dgas}) \times CLEappl_{dgas;i}] \quad (12)$$

and where

$A_{BC;it}$ and $A_{HC;it}$	are amounts of brown and hard coal produced in country i in year t ,
$ef_{m;i;NOC}^{surface}$	is a country-specific no control emission factor for surface mining emissions,
$ef_{postm;i}^{surface}$	is the average world IPCC default emission factor for post-mining emissions from surface mines,
$ef_{m;i;NOC}^{undergr}$	is a country-specific no control emission factor for underground mining emissions,
$ef_{postm;i}^{undergr}$	is the average world IPCC default emission factor for post-mining emissions from underground mines,
$\gamma_{HC;i}^{undergr}$	is a country-specific fraction of hard coal being mined underground as opposed to surface mining,
$\alpha_{VAM;i}$	is a country-specific fraction of underground mining emissions being released through the ventilation air as opposed to pre-mine degasification emissions,

r_{dgas} and r_{VAM} are the removal efficiencies of technologies removing degasification and ventilation air methane, respectively,

$CLEappl_{VAM;i}$ is the application of technology removing ventilation air methane, and

$CLEappl_{dgas;i}$ is the application of technology removing degasification methane.

Country-specific information about emissions released from surface and underground mines in year 2020 were taken from UNFCCC-CRF (2022) together with information about the fraction of hard coal mined in surface mines. Information on the current application of pre-mining degasification was extracted from the same source. The fraction of underground mine gas exiting as ventilation air methane as opposed to being released during pre-mining degasification is taken from USEPA (2003). No country-specific information about post-mining emissions was found and, hence, IPCC (2006) default emission factors for surface and underground mining, respectively, were applied to all countries for post-mining emissions. Finally, the implied emission factor for all coal mining sources was scaled to match GAINS emissions with UNFCCC-CRF reported emissions for year 2020. The resulting derived emission factors for coal-mining in EU-27 countries are presented in Table 5. For clarity, the derived emission factors presented in Table 5 are reproduced in Table 6 in terms of ton CO₂eq per TJ coal produced using country-specific calorific values of coal from IEA-WEO (2009).

Emissions from both surface and underground mines can be reduced if CH₄ is recovered through pre-mining drainage up to ten years before the mining starts (USEPA, 2008a). Currently in the US, at least 90 percent of degasification emissions from underground coal mines are recovered and utilized (USEPA, 2010a). In GAINS, this is assumed technically possible in other countries as well. There is, however, only one project known to be recovering and utilizing CH₄ from pre-mine drainage at a surface mine and details about the removal efficiency of this option are uncertain (Sino-US New Energy Sci-Tech Forum, 2009). In GAINS, it is considered technically possible to recover 90 percent of the drainage gas also from surface mines. Costs for degasification are taken from Thakur (2006) and reflect costs for in-mine drilling, underground pipeline costs, and hydraulic fractioning of vertical wells and other gob wells.

Ventilation air methane (VAM) from underground coalmines can be recovered and oxidized through installation of VAM oxidizers (Mattus and Källstrand, 2010). Although the application on coalmines is still in an early phase, the technology is well known from control of odor and VOC emissions worldwide. The technology oxidizes at least 95 percent of VAM when applied to a ventilation shaft. It uses the energy released during the oxidation to keep the process running, which keeps fuel costs limited to the initial start-up phase. For a thermal oxidation process to run without interruptions the CH₄ concentration in the ventilation air needs to be at least 0.3 percent. For some recent installations in China a catalytic oxidation process is in use, which operate with CH₄ concentration rates in the ventilation air as low as 0.2% (Somers and Burklin, 2012). Securing this concentration level without increasing explosion risks (i.e. CH₄ concentrations in the air should never be in the explosive range between 5 and 15 percent), may in some mines require investments in more efficient ventilation systems. A general assumption is made in GAINsv4 that it is technically possible to keep CH₄ concentration levels at a steady rate of at least 0.3 percent, and therefore to install self-sustained VAM oxidizers (Mattus and Källstrand, 2010), on 50 percent of the ventilation air emitted from underground coal mines in

all countries. Combining a catalytic oxidation VAM technology with an improved ventilation system is assumed to extend the feasible application of VAM oxidizers to 70 percent of VAM emitted from underground mines in all countries. An improved ventilation system is taken to double the ventilation capacity of the mine compared with a conventional system, thereby doubling the amount of electricity used for ventilation. Costs for VAM oxidation technology and installation are taken from USEPA (2003, p.30) and GMI (2008) and refer to installations in the US and China. Costs for increased electricity use for ventilation in mines are based on information from Unruh (2002) and Papar et al. (1999). No mitigation potential is assumed for post-mining emissions.

In the Baseline, implications of the Council proposal on methane emissions reduction in the energy sector (2021/0423 (COD)) have been considered. The proposed regulation prohibits CH₄ venting from ventilation shafts above certain emission rate thresholds for all mines producing thermal coal. Exempt from the regulation is coking coal mines, which in Europe are found in Poland. With thermal coal mining expected to be close to completely phased out in all EU countries within the next 10 years, we assume the only further CH₄ mitigation potential is from installation of VAM technology on remaining coking coal mines in Poland.

Table 5: Coal mining emission factors in 2020 for EU-27+UK in the GAINS model.

Country	Coal production 2020		Derived no control CH ₄ emission factors for year 2020								Implied emission factor 2020	
	Brown coal	Hard coal	Brown coal mining				Hard coal mining				All coal types and sources	
			total	pre-mining	mining	post-mining	total	pre-mining	mining	post-mining	No control	Including current control
	Mt coal	Mt coal	kt CH ₄ /Mt coal produced				kt CH ₄ /Mt coal produced				kt CH ₄ /Mt coal produced	
Belgium	0.060	0.009	0.871	0.322	0.482	0.067	18.207	7.098	10.506	0.603	3.172	2.402
Bulgaria	21.339	0.250	1.326	0.490	0.734	0.102	24.550	9.656	14.291	0.603	1.595	1.219
Czech Rep.	27.386	3.625	1.717	0.393	1.243	0.082	8.545	3.295	4.876	0.374	2.515	2.054
Estonia	0	0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
France	0	0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Germany	106.769	0	0.013	0.004	0.006	0.004	n.a	n.a	n.a	n.a	0.013	0.011
Greece	12.511	0	1.203	0.445	0.666	0.093	n.a	n.a	n.a	n.a	1.203	0.923
Hungary	2.657	0	0.027	0.008	0.012	0.008	n.a	n.a	n.a	n.a	0.027	0.022
Italy	0	0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Latvia	0	0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Lithuania	0	0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Poland	43.374	53.570	1.183	0.437	0.655	0.091	9.935	3.790	5.610	0.535	6.019	4.577
Romania	15.107	0.018	1.057	0.391	0.585	0.081	18.049	7.035	10.411	0.603	1.077	0.825
Slovakia	0.785	0	8.001	0.392	7.528	0.082	n.a	n.a	n.a	n.a	8.001	7.754
Slovenia	3.196	0	3.307	0.399	2.840	0.067	n.a	n.a	n.a	n.a	3.323	3.071
Spain	0	0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
United Kingdom	0	1.567	n.a	n.a	n.a	n.a	10.110	3.801	5.626	0.682	10.110	4.210

Sources: Emission factors calibrated to emissions reported to the UNFCCC (2022). UNFCCC-CRF 2010 for reported emissions from surface and underground coal mines, for the fraction of hard coal surface mined, and for current control through degasification.; USEPA 2003 for assumptions on the fraction of underground mine gas exiting as ventilation air methane as opposed to released during pre-mining degasification; IPCC (2006) for default post-mining emission factors specified for surface and underground mining, respectively. Note that default IPCC emission factors have been scaled to better match national emission factors reported to the UNFCCC.

Table 6: Coal mining emission factors in 2020 for EU-27+UK expressed in tCO₂eq/TJ coal produced. Energy conversion factor: 41.868 GJ/toe. Global Warming Potential (GWP) for CH₄ is 28 times that of CO₂ per ton over 100 years (IPCC Sixth Assessment Report).

Country	Calorific values used in GAINS (source: IEA)		Derived no control CH ₄ emission factors for year 2020							
	Brown coal (lignite) toe/t coal	Hard coal (bitumen coal) toe/t coal	Brown coal mining				Hard coal mining			
			total	pre-mining	mining	post-mining	total	pre-mining	mining	post-mining
t CO ₂ eq/TJ coal mined										
Belgium	0.515	0.666	0.725	0.268	0.401	0.056	11.718	4.568	6.761	0.388
Bulgaria	0.165	0.600	3.445	1.273	1.906	0.265	17.538	6.898	10.209	0.431
Czech Rep.	0.301	0.435	2.446	0.560	1.769	0.116	8.420	3.246	4.805	0.369
Estonia	0.200	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
France	0.409	0.631	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Germany	0.212	0.583	0.027	0.008	0.011	0.008	n.a.	n.a.	n.a.	n.a.
Greece	0.130	n.a.	3.966	1.466	2.195	0.305	n.a.	n.a.	n.a.	n.a.
Hungary	0.335	0.348	0.035	0.010	0.015	0.010	n.a.	n.a.	n.a.	n.a.
Italy	0.250	0.641	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Latvia	0.350	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Lithuania	0.350	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Poland	0.203	0.525	2.498	0.923	1.382	0.192	8.112	3.095	4.580	0.437
Romania	0.181	0.607	2.503	0.925	1.385	0.193	12.745	4.967	7.352	0.426
Slovakia	0.301	n.a.	11.394	0.558	10.720	0.116	n.a.	n.a.	n.a.	n.a.
Slovenia	0.312	0.620	4.543	0.549	3.902	0.092	n.a.	n.a.	n.a.	n.a.
Spain	0.174	0.539	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
United Kingdom	0.200	0.604	n.a.	n.a.	n.a.	n.a.	7.175	2.698	3.993	0.484

3.2.2 Abandoned coal mines

Countries reporting CH₄ emissions to the UNFCCC in the Annex-1 category are expected to enter emissions from abandoned coalmines in the Common Reporting Formats (CRFs). The reported emissions make up the activity data for this source sector in GAINS. Projections for the future have been developed under the assumption that emissions from abandoned coal mines phase-down linearly by 80% between 2015 and 2070. This assumption mimics the release of CH₄ from abandoned coal mines in the UK (DEFRA, 2011).

The release of CH₄ emissions from abandoned coal mines typically depends on the status of the abandoned mine, i.e., whether it is left open for venting in order to prevent build-up of explosive CH₄ pockets underground, flooded to prevent CH₄ emissions from escaping, or sealed through cement plugging (USEPA, 2004). For the modelling in GAINS, it is assumed that without regulation the no control case is venting. The control option considered is flooding, which is assumed to prevent 90% of emissions compared to the venting case. Sealing is not considered a CH₄ control option in GAINS, because to effectively prevent gas leakage, at least 95% of shafts must be sealed (USEPA, 2004), which likely makes it relatively expensive. In contrast, the cost of flooding abandoned coal mines is likely low or even profitable, as abandoned mines can potentially fill a role in a future transformation to renewable energy. Abandoned coal mines can be used as pumped storage hydroelectric plants (Pujades et al., 2016; Jessop et al., 1995) or flooded and converted to giant floating solar farms as in Huainan, China (China Daily, 2017). The net cost to society of flooding abandoned coal mines is therefore taken to be zero in GAINS.

3.2.3 Oil and gas production and processing

Extraction of crude oil and natural gas gives rise to CH₄ emissions, partly as a result of intended flaring or venting of associated gas for security reasons and partly due to unintended leakage of fugitive emissions, which occur along the whole production process from well head to upgrading and storage (IPCC, 2006, Vol.2, Section 4.2). Associated gas is a gas compound mainly consisting of CH₄, which is released as oil or natural gas is brought to the surface. For security reasons, the associated gas needs to be released and is therefore flared off or simply vented. Alternatively, the associated gas can be recovered and utilized for energy purposes provided there is an infrastructure present to transport the recovered gas to consumers.

The methodology for estimating methane emissions from oil and gas production has been described in Höglund-Isaksson (2017). Emissions from venting and flaring of associated gas are calculated separately for fugitive emissions and unintended leakage. Total emissions from oil and gas production are the sum of venting, flaring and leakage emissions:

$$E_{its} = E_{its}^{venting} + E_{its}^{flaring} + E_{its}^{leakage} \quad (13)$$

Venting emissions from production of oil and gas, respectively, are calculated as:

$$E_{it;oil}^{venting} = A_{it}^{oil} * 20 * (1 - r_i) * (c_i a_i^{conv} v_i^{conv} + (1 - c_i) a_i^{heavy} v_i^{heavy}) \quad (14)$$

$$E_{it;gas}^{venting} = A_{it}^{gas} * 20 * a_i^{gas} (1 - r_i) v_i^{gas} \quad (15)$$

where $A_{it}^{oil;gas}$ is energy content of crude oil or dry gas produced in country i in year t ,
 20 20 kt CH₄/PJ conversion of energy content to amount of CH₄,
 c_i fraction of conventional oil (as opposed to heavy oil) produced,
 $a_i^{conv}, a_i^{heavy}, a_i^{gas}$ are associated gas as fractions of the total energy content of conventional, heavy oil, or gas produced in year t ,
 r_i is the fraction of associated gas recovered for utilization or reinjection in year t , and
 $v_i^{conv}, v_i^{heavy}, v_i^{gas}$ are fractions of unrecovered associated gas that is vented (as opposed to flared).

Combustion emissions from flaring are derived assuming on average two percent incomplete combustion of CH₄ from open flares (Johnson and Kostiuk, 2002). The volume of gas flared is the fraction of unrecovered associated gas that is not vented, i.e. methane emissions from flaring are estimated as:

$$E_{it;oil}^{flaring} = 0.02 * A_{it}^{oil} * 20 * (1 - r_i) * (c_i a_i^{conv} (1 - v_i^{conv}) + (1 - c_i) a_i^{heavy} (1 - v_i^{heavy})) \quad (16)$$

$$E_{it;gas}^{flaring} = 0.02 * A_{it}^{gas} * 20 * a_i^{gas} (1 - r_i) (1 - v_i^{gas}) \quad (17)$$

Country-specific information for the year 2005 on amounts of associated gas and the fraction of associated gas reinjected or recovered are taken from EIA (2015) International Energy Statistics and used as starting point for emission estimates. From EIA (2015) Country Analysis Briefs, types of hydrocarbon produced are identified, i.e. conventional crude oil, heavy crude

oil (API gravity <22.3°), oil sands and natural gas, as well as the fraction of offshore production. For gas production only two measurement results have been found for the fraction of associated gas to the energy content of gas produced. These are 0.03 percent for Canada (Johnson and Coderre, 2011), which is adopted as representative also for the EU countries.

Measurement data on unrecovered associated gas vented as opposed to flared from oil and gas wells are rare and no such measurements from European oil and/or gas wells have been found in published sources. We note however that the technology to use satellite observations to continuously monitor methane emissions is under rapid development with the TROPOMI satellite being able to detect major emission events, primarily from oil and gas operations (SRON, 2021). There are several initiatives to improve the methane detection precision of satellites, anticipating the ability to detect methane emissions at the facility level in a few years time from now (e.g., MethaneSAT at www.methanesat.org, Kayrros at www.kayrros.com, and Blue Sky Satellite Communications www.bluesky-sat.com). For now, we resort to a bottom-up process-based approach described in Höglund-Isaksson (2017a). It makes use of direct measurement results published by Johnson and Coderre (2011) for over 6000 oil and gas wells active in the province of Alberta in 2008 and specified for different types of hydrocarbons produced (i.e., conventional or heavy oil and conventional natural gas). The results of the Canadian measurements are summarized in Table 7 and the last row shows the fraction of unrecovered associated gas that is vented instead of flared. These factors are assumed representative also for EU circumstances. Note that the assumptions on the total associated gas generated, recovered and reinjected are country-specific and taken from EIA (2015). By calibrating the country-specific recovery rate, the estimated volumes of associated gas vented and flared were matched to the total volumes of associated gas flared as estimated from satellite images of gas flares (NOAA, 2011). The resulting derived emission factors for venting of associated gas are presented in Table 8.

Table 7: Recovery, venting and flaring from oil and gas wells in the province of Alberta 2002-2008. Adapted from Johnson and Coderre (2011).

		Conventional oil	Heavy oil	Natural gas
Associated gas	% of production	35.5%	5.1%	0.03%
Recovered/ reinjectd	% of associated gas	97.1%	85.8%	0%
Flared		2.1%	1.7%	60%
Vented		0.8%	12.4%	40%
Sum		100%	100%	100%
Vented	% of flared/vented	29.1%	87.7%	40%

Maximum technically feasible reduction of CH₄ emissions from associated gas management related to oil and gas production is defined such that for all countries it is assumed possible to recover and utilize 99 percent of the associated gas generated. This high level of associated gas recovery is already achieved in Norway (Husdal et al., 2016a,b; EIA, 2015) and it is therefore assumed possible to achieve the same recovery rate in other countries as well. As shown in Table 8, many EU countries already recover 95 percent or more of the associated petroleum gas generated. In the Baseline, implications of the Council proposal on methane emissions reduction in the energy sector (2021/0423 (COD)) have been considered, assuming for oil and gas production that 98% of the associated gas generated will be recovered from 2025 onward

in all EU countries. Hence, the additional mitigation potential through extended recovery rates for associated gas is accordingly limited to moving from 98 to 99 percent recovery. Costs are taken from OME (2001) and described in detail in the Supplements of Höglund-Isaksson et al. (2012; 2020).

In addition to extending associated gas recovery rates to 99 percent, it is assumed technically possible to reduce venting through maximized flaring of the one percent of associated gas that is not recovered. In a Leak Detection and Repair (LDAR) program (USEPA, 2016; McCabe and Fleischmann, 2014), infrared cameras can be used to frequently scan equipment for methane leakages, which are promptly repaired. If installed to scan flares of associated gas, LDAR would allow for identification and remedy of ‘super-emitting’ events, reduced routine venting as well as reduced number and duration of temporary flare shut-downs caused by unfavorable weather and wind conditions (Husdal et al., 2016b, p.31). Details on costs and removal efficiency of LDAR technology are described below in conjunction with control of unintended fugitive leakage from oil and gas systems. To our knowledge, LDAR programs have until now been introduced in Europe to control unintended fugitive leakages from gas processing plants and transmission and distribution networks (Saunier et al., 2017), however, not to control venting of associated gas. The applicability and cost of the technology for this purpose is therefore highly uncertain. As a conservative assumption we assume that it is possible to reduce venting of unrecovered associated gas by 30 percent if LDAR is implemented across all oil and gas production facilities. The marginal cost is very high (exceeding 500 €/t CO₂eq) as LDAR is assumed applied on top of a 99 percent recovery rate of associated gas and therefore only addressing emissions from the one percent associated gas that is not recovered.

Table 8: Assumptions for deriving emission factors for CH₄ venting, flaring and unintended leakage from oil and gas production in EU production countries.

Country	Fraction offshore production (EIA, 2010)	Oil production: venting and unintended leakage 2020			Gas production: venting and unintended leakage		Inefficient combustion of gas flares
		Recovery/ reinjection of associated petroleum gas (calibrated to satellite images of gas flares)	Implied emission factor: venting of associated gas	Implied emission factor: unintended leakage (IPCC, 2006, Vol.2, Table 4.2.4)	Implied emission factor: venting of associated gas	Implied emission factor: unintended leakage (IPCC, 2006, Vol.2, Table 4.2.4)	Implied emission factor: flaring of associated gas (98% combustion efficiency, 86 vol% CH ₄)
	%	kt CH ₄ /PJ oil produced	kt CH ₄ /PJ oil produced	kt CH ₄ /PJ gas produced	kt CH ₄ /PJ gas produced	kt CH ₄ /PJ gas flared	
Austria	0%	96.0%	0.052	0.060	0.00194	0.10802	0.2892
Belgium	n.a.	n.a.	n.a.	n.a.	0.00194	0.06	0.2892
Bulgaria	n.a.	n.a.	n.a.	n.a.	0.00194	0.06	0.2892
Croatia	0%	97.0%	0.039	0.060	0.00194	0.06	0.2892
Cyprus	n.a.	n.a.	n.a.	n.a.	0.00194	0.06	0.2892
Czech Republic	0%	89.1%	0.142	0.060	0.00194	0.06	0.2892
Denmark	100%	98.0%	0.026	0.000015	0.00194	0.009615	0.2892
France	80%	94.1%	0.078	0.012	0.00194	0.00396	0.2892
Germany	0%	99.0%	0.013	0.060	0.00194	0.06	0.2892
Greece	0%	99.0%	0.013	0.060	0.00194	0.25206	0.2892
Hungary	0%	97.0%	0.039	0.060	0.00194	0.07921	0.2892
Ireland	0%	n.a.	n.a.	n.a.	0.00194	0.06	0.2892
Italy	0%	98.0%	0.026	0.060	0.00194	0.0345	0.2892
Lithuania	0%	94.1%	0.078	0.060	0.00194	0.06	0.2892
Netherlands	100%	95.0%	0.065	0.000015	0.00194	0.007695	0.2892
Poland	0%	9.9%	1.176 ^a	0.060	0.00194	0.07152	0.2892
Romania	0%	69.3%	0.401	0.060	0.00194	0.06	0.2892
Slovakia	0%	69.3%	0.401	0.060	0.00194	0.25206	0.2892
Slovenia	0%	n.a.	n.a.	n.a.	0.00194	0.25206	0.2892
Spain	0%	69.3%	0.401	0.060	0.00194	0.25206	0.2892
United Kingdom	100%	97.0%	0.039	0.000015	0.00194	0.011535	0.2892

^a Note that the low recovery rate for Poland and the resulting high implied emission factor are consistent with national reporting of associated gas vented from oil production (UNFCCC, 2022).

Fugitive CH₄ emissions from unintended leakage during oil and gas production are estimated separately from fugitive emissions from venting and flaring of associated gas. Unintended leakage is usually irregular and therefore highly uncertain. In GAINS, fugitive leakage emissions from oil and gas production are calculated as follows:

$$E_{it;oil}^{leakage} = A_{it}^{oil} * \left(\gamma_i e_{offshore}^{oil} + p_i e_{oilsand} + (1 - \gamma_i - p_i) \left((1 - c_i) e_{onshore}^{heavy} + c_i e_{onshore}^{conventional} \right) \right) \quad (18)$$

$$E_{it;gas}^{leakage} = A_{it}^{gas} * \left(\gamma_i e_{offshore}^{gas} + (1 - \gamma_i) e_{onshore}^{gas} \right) \quad (19)$$

where A_{it}	is the energy content of marketable oil (or gas) produced in country i in year t ,
γ_i	is the fraction of oil (or gas) produced offshore,
p_i	is the fraction of oil produced from oilsands,
$e_{oilsand}^{oil}$	is the IPCC default emission factor for oil production from oilsands,
c_i	is the fraction of conventional oil produced,
$e_{offshore}^{oil;gas}$	is the IPCC default emission factor for fugitive emissions from oil/gas produced offshore,
$e_{onshore}^{conv}$	is the IPCC default emission factor for fugitive emissions from conventional oil produced onshore
$e_{onshore}^{heavy}$	is the IPCC default emission factor for fugitive emissions from heavy oil produced onshore
$e_{onshore}^{conv}$	is the IPCC default emission factor for fugitive emissions from conventional oil produced onshore
$e_{offshore}^{gas}$	is the IPCC default emission factor for fugitive emissions from natural gas produced offshore
$e_{onshore}^{gas}$	is the IPCC default emission factor for fugitive emissions from natural gas produced onshore

GAINS uses IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) default emission factors as specified separately for developed countries and developing/transitional countries. All EU countries have here been treated as developed countries, adopting the median of the emission factor range given by IPCC as default. Adopted fugitive emission factors and IPCC ranges for default emission factors are presented in Table 9.

There are several cost-effective and low cost options available to reduce unintended leakage during extraction and processing of oil and natural gas (USEPA, 2014a, 2016; ICF International, 2016). But addressing leakages requires that these are first detected. Recent development of LDAR technologies, in particular the use of infrared cameras, has lowered the

costs of leak detection significantly (ICF International, 2016; USEPA, 2016; McCabe and Fleischmann, 2014). In a survey of LDAR programs in Europe installed to reduce unintended leakages from gas production, transportation and storage facilities, Saunier et al., (2017) find that when used regularly and systematically, LDAR effectively detects leakages of which 61 percent are successfully repaired and reducing emissions by at least 90 percent, while 31 percent are less successfully repaired and reducing emissions by less than 50 percent and sometimes even increasing emissions. In an industry survey of US oil and gas facilities, ICF International (2016) finds that if all facilities are subject to annual LDAR emission surveys, an overall emission reduction of 40 percent is feasible. Drawing on these two studies, we assume it possible to reduce emissions from unintended leakages by 45 percent when LDAR technology is implemented across all facilities.

The cost of LDAR programs is likely to be highly site-specific and to vary with the gas price as reduced gas leakages means higher profits from gas sales. After detection of leakages, there is a long list of possible repairs that are available at a wide range of costs (see e.g., Table 3-1 in ICF International, 2016). As we do not have access to industry data on the incidence of different types of leakages in European oil and gas systems, it is not possible to make an assessment of the expected number and types of repairs that will be needed and the associated costs. Such assessments exist for US gas and oil systems, usually based on detailed data reported by industry to the USEPA and complemented by industry surveys (USEPA, 2014a; ICF International, 2016). To estimate costs for gas leakages repairs in the EU countries, we have sought to align the assumptions with the ranges for the US marginal abatement costs estimated for different industry segments (i.e., production, processing, transmission and distribution). It should however be stressed that the estimated abatement costs for these emission sources are highly uncertain and may be subject to revisions in the future if data that is more representative for European conditions become available.

Recently, a few EU countries have shown an interest in exploring the possibilities for large-scale extraction of shale gas. According to EIA (2011) some EU countries hold considerable reserves of technically recoverable shale gas. A survey by AEAT (2012) of the current knowledge of CH₄ emissions from shale gas extraction shows that uncertainty in emissions is very high. The PRIMES (E3modelling, 2023) energy scenario does not include shale gas extraction in future projections. Therefore all CH₄ emissions from future gas production in the EU are estimated using emission factors for conventional gas extraction.

Table 9: Default emission factors for unintended fugitive emissions from oil and gas production used in GAINS and in comparison with IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5).

		Developed countries		Developing/transitional countries	
		GAINS	IPCC (2006) range	GAINS	IPCC (2006) range
		kt CH ₄ /PJ	kt CH ₄ /PJ	kt CH ₄ /PJ	kt CH ₄ /PJ
Oil production	Conventional oil on-shore	0.06	0.00004-0.094	0.12	0.00004-1.5
	Heavy oil on-shore	0.1863	0-0.3726	0.3726	0.1863-3.066
	Conventional and heavy oil off-shore	0.000015	0-0.00003	0.000015	0.000013-0.00013
	Oilsands	0.0542	0.0135-0.095	0.0542	0.018-0.135
Gas production	Natural gas on-shore	0.06	0-0.12	0.12	0.1-2.15
	Natural gas off-shore	0.00974	0-0.0195	0.00974	0.0058-0.034

3.2.4 Crude oil transportation and refining

CH₄ emissions from oil refinery and transport are fugitive emissions related to evaporation losses from storage, filling and unloading activities as well as fugitive leaks (IPCC, 2006, Vol.2, p. 4.34). The IPCC (2006, Vol.2, pp.4.52-4.61) guidelines provide emission factors for oil transportation based on the amount of oil transported, while emission factors for refining and storage are based on the amount of oil input to refineries as taken from PRIMES (E3modelling, 2023). Since it is not possible to find systematic data on the amount of oil transported by tanker, trucks or rails by region, GAINS assumes that the amount transported corresponds to the amount of oil refined. Thus, to calculate emissions from this source the activity data used is amount of oil refined combined with IPCC default emission factors for the sum of oil refined and transported:

$$E_{it} = \sum_m [A_{it} * (ef^{refined} + ef^{transported}) * (1 - remeff_m) * Appl_{itm}], \quad (20)$$

where A_{it} is amount of oil refined in country i in year t ,
 $ef^{refined}$ is the IPCC default emission factor for oil refined,
 $ef^{transported}$ is the IPCC default emission factor for oil transported,
 $remeff_m$ is the removal efficiency of technology m , and
 $Appl_{itm}$ is the application rate of technology m to emissions in country i in year t .

IPCC default emission factors for this sector are presented in Table 10 together with GAINS assumptions for no control and controlled emission factors.

The maximum technically feasible reduction is defined by the sum of the lower range IPCC default emission factor for oil refined and a fifty percent reduction in leakage emissions from oil transportation. This corresponds to the relative reduction in leakage emissions considered technically feasible for oil and gas production. Costs for these measures are taken from AEAT (1998).

Table 10: Default emission factors for CH₄ emissions from oil refinery and transport. Source: Derived from IPCC (2006, Vol.2, pp.4.52-4.61)

Emission source	GAINS		IPCC (2006)	unit
	No control	Control		
Fugitive emissions at oil refinery	0.0455	0.0029	0.0029 to 0.0455	kt CH ₄ /Mt oil refined
Fugitive emissions from transport by pipeline	0.0049	0.00245	0.0049	kt CH ₄ /Mt oil transported by pipeline
Fugitive emissions from transport by tanker, truck and rail cars	0.0225	0.0166	0.0225	kt CH ₄ /Mt oil transported by tanker/truck
All sources	0.0729	0.0166	0.0303 to 0.0729	kt CH ₄ /Mt oil refined

3.2.5 Long-distance natural gas transportation

Leakage of CH₄ emissions from long-distance gas pipelines arises for several reasons, e.g., untight compressor seals and valves or because pipelines are flushed with gas during start-ups (Ecofys, 1998; 2009). For Tier 1 estimations the IPCC guidelines (2006, Vol. 2, p.4.48-4.62) recommend the use of default emission factors per million m³ of marketable gas. We find it problematic to use the IPCC default factors here as emissions from gas transmission are likely to be influenced by both the volume of gas transported, the distance the gas is transported as well as pipeline pressure and maintenance. Leakage rates are therefore likely to be specific to the circumstances prevalent in each country and pipeline system. For this reason, GAINS uses country-specific volumes of gas transported and leakage rates as reported to UNFCCC-CRF (2022) whenever such information is available. Table 12 provides an overview of the data compiled in GAINS for deriving amounts of gas transported and leakage rates for year 2020 in the EU-27 countries. The low leakage rate of 0.003% reported for Sweden and Slovakia (UNFCCC-CRF, 2022) is adopted as the controlled emission factor, representing the lowest technically feasible leakage rate reported. The percent assumed control in year 2020 is a reflection of the leakage rate reported by countries. Maximum technically feasible reduction is assumed feasible if all countries move to the low rate of 0.003% by improving control through implementation of LDAR programs and/or replacing high-leakage pipelines. It is further assumed that 50% of current emissions come from major leaks and 50% from minor leaks. From Kemp and Ravikumar (2021), Carbon Limits (2017a; 2017b) and McCabe and Fleischman (2014), we can construct Table 11 showing the efficiency of LDAR surveys for different frequency intervals.

Table 11: GAINS model assumptions on removal efficiency of CH₄ emissions when employing LDAR surveys to gas infrastructure at different frequency interval.

GAINS model assumptions on emission removal efficiency of LDAR programs	
LDAR survey frequency	Sources: Kemp and Ravikumar (2021), Carbon Limits (2017a; 2017b) and McCabe and Fleischman (2014)
Every 1 months	-85%
Every 3 months	-70%
Every 6 months	-50%
Every 12 months	-30%
Every 24 months	-20%
Every 36 months	-10%

For baseline projections into future years, implications of the Council proposal on methane emission reductions in the energy sector (2021/0423 (COD)) have been considered. According to the Council proposal, all above ground transmission pipelines with leaks >500 ppm must be subject to LDAR surveys with a frequency of every 36 months. With reference to the Table 11 above, this is in the GAINS baseline assumed to remove 20% of emissions from major leaks and 10% of emissions from minor leaks from gas transmission pipelines from 2025 onward. Costs for reducing methane emissions from gas transmission pipelines are taken from USEPA (2006).

Table 12: Documentation of how methane emission factors for long-distance gas transmission pipelines were derived in GAINS for year 2020.

Country	Amount of gas transported through on-shore pipelines 2020		CH4 emissions reported for year 2020 to UNFCCC-CRF (2022)			GAINS model estimates for year 2020			
			Transmission & Storage	Implied emission factor	Leakage rate when 50 MJ/kg CH4	Transmission & Storage	No control emission factor	Controlled emission factor	Assumed current control
							when leakage rate is 0.3%	(leakage 0.003%)	corresponding to reported implied ef % of max technically feasible control
PJ	Source activity data	kt CH4	kt CH4/PJ	% leak	kt CH4	ktCH4/PJ	ktCH4/PJ		
Austria	1337	TAG (2007; 2015; 2020)	3.85	0.0029	0.014%	3.85	0.06	0.0006	96.2%
Belgium	619	UNFCCC-CRF (2022)	4.23	0.0068	0.034%	4.23	0.06	0.0006	89.5%
Bulgaria	316	UNFCCC-CRF (2022)	6.93	0.0219	0.110%	6.92	0.06	0.0006	64.1%
Croatia	107	UNFCCC-CRF (2022)	1.43	0.0134	0.067%	1.43	0.06	0.0006	78.5%
Cyprus	0	UNFCCC-CRF (2022)	n.a.	n.a	n.a.	0.00	0.06	0.0006	n.a
Czech Republic	1500	UNFCCC-CRF (2022)	6.61	0.0044	0.022%	6.61	0.06	0.0006	93.6%
Denmark	110	UNFCCC-CRF (2022)	0.20	0.0018	0.009%	0.20	0.06	0.0006	98.0%
Estonia	15	UNFCCC-CRF (2022)	0.09	0.0057	0.029%	0.09	0.06	0.0006	91.4%
Finland	72	UNFCCC-CRF (2022)	0.19	0.0026	0.013%	0.19	0.06	0.0006	96.6%
France	1470	UNFCCC-CRF (2022)	10.9	0.0074	0.037%	10.9	0.06	0.0006	88.6%
Germany	6215	UNFCCC-CRF (2022)	72.37	0.0116	0.058%	72.37	0.06	0.0006	73.2%
Greece	153	UNFCCC-CRF (2022)	1.27	0.0083	0.042%	1.27	0.06	0.0006	87.0%
Hungary	374	UNFCCC-CRF (2022)	15.48	0.0414	0.207%	15.48	0.06	0.0006	31.2%
Ireland	211	UNFCCC-CRF (2022)	0.36	0.0017	0.008%	0.36	0.06	0.0006	98.2%
Italy	2721	UNFCCC-CRF (2022)	38.66	0.0142	0.071%	38.66	0.06	0.0006	77.1%
Latvia	42	UNFCCC-CRF (2022)	0.0083	0.0002	0.001%	0.025	0.06	0.0006	100.0%
Lithuania	369	UNFCCC-CRF (2022) Derived from reported leakage	2.23	0.0060	0.030%	2.23	0.06	0.0006	90.8%
Luxembourg	26	UNFCCC-CRF (2022)	0.34	0.0130	0.065%	0.34	0.06	0.0006	79.2%
Malta	0	UNFCCC-CRF (2022)	n.a.	n.a.	n.a.	0.00	0.06	0.0006	n.a
Netherlands	3006	UNFCCC-CRF (2022)	4.00	0.0013	0.007%	4.00	0.06	0.0006	98.8%
Poland	655	UNFCCC-CRF (2022)	9.21	0.0141	0.070%	9.21	0.06	0.0006	77.3%
Portugal	1.134	UNFCCC-CRF (2022)	0.056	0.0489	0.245%	0.056	0.06	0.0006	19%
Romania	2439	UNFCCC-CRF (2022)	3.02	0.0012	0.006%	3.02	0.06	0.0006	98.9%
Slovakia	1792	UNFCCC-CRF (2022)	1.06	0.0006	0.003%	1.08	0.06	0.0006	100.0%
Slovenia	31	UNFCCC-CRF (2022)	0.34	0.0109	0.055%	0.33	0.06	0.0006	82.6%
Spain	1027	UNFCCC-CRF (2022)	2.76	0.0027	0.013%	2.76	0.06	0.0006	96.5%
Sweden	151	UNFCCC-CRF (2022) Derived from reported leakage	0.079	0.0005	0.003%	0.091	0.06	0.0006	100.0%
United Kingdom	1645	UNFCCC-CRF (2022)	2.94	0.0018	0.009%	2.94	0.06	0.0006	98.0%

3.2.6 Consumer gas distribution networks

CH₄ emissions from gas use come from leakage in consumer distribution networks and during end-use by consumers. The activity data is amount of gas consumed by sector as provided by the PRIMES (E3modelling, 2023) model for the EU-27 countries and United Kingdom. The uncertainty ranges for the IPCC (2006, Vol.2, Tables 4.2.4 and 4.2.5) Tier 1 default emission factors is very wide, up to ± 500 percent. An important factor contributing to the large variability in leakage rates is the material composition of the gas distribution networks, with cast iron networks being the most leaky, followed by steel, and PE-PVC networks. In GAINS, we derive own Tier 2 emission factors, making use of extensive country-specific information on the material composition of the length of gas distribution infrastructure from Marcogaz (2018) for the year 2015. The data was extended to include the year 2020 by collecting information on total kilometer gas distribution networks from UNFCCC (2022) and various national sources (Rajal and Santic, 2022; Dansk Gasteknisk Center A/S, 2022; GRDF, 2022; PGNiG, 2022; IEA, 2022a; Energynomics, 2022; Acosta, 2022; Energimarknadsinspektionen, 2021; SwitchPlan, 2022; EPH Group, 2022), and assuming all recently added network capacity is of PE/PVC material. The result is presented in the first column of Table 15.

Information on the relative leakiness of different network materials is taken from Marcogaz (2018), who provides average emission factor estimated for EU27+UK as presented in Table 13.

Table 13: GAINS assumptions on the relative leakiness and no control emission rates of different gas distribution network materials.

Pipeline material	Average annual emission rate from Marcogaz (2018) kg CH ₄ per km	GAINS model assumptions	
		Leakiness relative cast iron distribution networks % of average leakage from cast iron networks	No control annual emission rates after calibration to total CH ₄ emissions from gas distribution networks in the EU27+UK in year 2020 reported to the UNFCCC (2022), i.e., Marcogaz emission rates scaled by a factor 3. kg CH ₄ per km
Cast iron	1079	100%	3237
Steel	150	13.9%	450
Polyethylene	30	3.2%	90
PVC	40		120
Other	660	61.2%	1980

To assess emissions and future mitigation potentials we need to attribute reported emissions to residential and non-residential users (i.e. power plants and industry), respectively. Dennett and Vallender (2011) provide measurement results for the UK on how the leakage from residential mains compares to leakage from mains supplying larger users (power plants and industry). The UK measurements show that total gas losses from gas distribution grids in the UK are 0.57 percent of throughput, with 80 percent from low pressure mains systems supplying small consumers. This translates into losses from residential and non-residential sectors of 1 and 0.23

percent of gas consumption, respectively. The same proportional split (i.e., 23%) between losses in residential and non-residential sectors is assumed in GAINS for all EU countries.

The relative leakiness of different network materials as well as the lower leakiness from non-residential users relative residential users are in the GAINS model maintained fixed throughout the estimation of CH₄ emissions from gas distribution networks. In addition, all use of cast iron networks are attributed to the residential (domestic) sector with the assumption that cast iron networks are not used for gas distribution to large-scale users in industry or power sectors.

The estimated emissions have been calibrated to emissions from gas distribution networks reported by countries to the UNFCCC (2022) for the year 2020. To maintain consistency in model assumptions across countries, the calibration to reported emissions was done in three steps. In a first step, emissions were estimated using the average annual emission rates reported by Marcogaz (see Table 13). This resulted for year 2020 in total emissions from EU27+UK corresponding to less than half of what these countries have reported to the UNFCCC (2022) for the same year. To perform the calibration, it was therefore necessary to scale up the no control emission factors by a factor of three, which then resulted in at least as high emissions as the reported. Finally, to arrive closer to the reported emissions, while still maintaining consistency in the modelling across countries, country-specific assumptions were derived about the levels of control currently implemented in the baseline.

The no control emission factors for gas distribution networks are country-specific and derived by material i and residential/non-residential sector R as follows:

$$e_i^R = (1/d) \times M_i \times (L^R/A^R) \times s$$

where M_i is the material-specific emission rate reported by Marcogaz (see Table 13),

A^R is the amount of gas in PJ consumed in the residential or non-residential sector, respectively,

s is the scaling factor (=3) necessary to at least match the total emissions reported by EU27+UK to the UNFCCC (2022) for the year 2020,

d is a factor adjusting for the higher leakage propensity in residential networks relative non-residential networks ($d=0.23$ for residential and $d=1$ for non-residential),

and L^R is the country-specific total network length, which for the residential sector is defined as:

$$L^{Res} = L_{CastIron} + \frac{A^{Res}}{(A^{Res} + A^{nonRes})} \times [L_{Steel} + L_{PE_PVC} + L_{Other}]$$

and for the non-residential sector as:

$$L^{nonRes} = \frac{A^{Res}}{(A^{Res} + A^{nonRes})} \times [L_{Steel} + L_{PE_PVC} + L_{Other}]$$

where L_i are the total network lengths of the respective materials.

The derived no control emission factors are presented in Table 15. Note that the no control emission factors are country-specific, which is to be expected as the quantities of gas transported through the networks can be very different despite similar lengths of the networks.

For projections of future emission, these are driven by the development in gas consumption by sector as provided by the PRIMES model (E3modelling, 2023). Implied emission factors (current leakage rates) remain constant unless there are new efforts made to introduce additional control.

CH₄ emissions from consumer distribution networks can be controlled by the use of LDAR technology (see Section 3.2.3 for details) or by replacing cast iron, steel, or other material with PE or PVC materials, which are considerably less leaky. The least leaky option identified in GAINS is to install PE/PVC networks with LDAR control (see Table 14).

Table 14: GAINS assumptions on maximum technically feasible emission control for gas distribution networks.

		GAINS assumptions on maximum technically feasible emission control with alternative abatement options			
		% emissions remaining relative no control cast iron networks in the residential sector			
Sector	Pipeline material	No control	Control with LDAR	Upgrade to PE/PVC	PE/PVC with LDAR
Residential sector	Cast iron	100%	15%	3.24%	0.032%
	Steel	13.9%	2.09%	3.24%	0.032%
	Other	61.2%	9.18%	3.24%	0.032%
	PE/PVC	3.24%	0.032%	n.a.	n.a.
Non-residential sector (industry & power)	Cast iron	23%	3.45%	0.75%	0.0075%
	Steel	3.2%	0.48%	0.75%	0.0075%
	Other	14.1%	2.11%	0.75%	0.0075%
	PE/PVC	0.75%	0.007%	n.a.	n.a.

Sources: Kemp and Ravikumar (2021), Carbon Limits (2017a; 2017b) and McCabe and Fleischman (2014)

The construction cost of replacing old gas distribution networks with new networks of PE/PVC quality standard is assumed to 450k Euro/km, which is in the range of 300k-600k Euro/km suggested by CEER (2019) for networks in the diameter range of 12-24 inches. The lifetime of gas distribution networks is assumed to be 50 years and it is further assumed that on average the networks are replaced 15 years before their end of life, thereby only attributing 30% of the full construction cost to CH₄ emission control. The investment cost per km is converted to a country-specific cost per PJ gas distributed by dividing with the country- and sector (domestic or industry/power) -specific PJ gas distributed per km network.

Costs for installation of LDAR technology on gas distribution networks are based on the assumptions that an LDAR device costing 100k Euro (Carbon Limits, 2021) is installed every 20 km and that a one week survey campaign is performed monthly and then covering 200 km (i.e., 10 devices needed) of networks. The cost of one survey campaign is assumed to 1000 Euros (Kemp and Ravikumar, 2021), making the annual operating cost 12k Euro. Investment and operation costs per km are converted to country-specific costs per PJ gas distributed by dividing with the country- and sector (domestic or industry/power) -specific PJ gas distributed per km network.

Table 15: GAINS model assumptions for estimation of CH₄ emissions from gas distribution networks by network material for year 2020.

country	Length gas distribution networks 2020 km	Network material, % of total length (adapted from Marcogaz, 2018). Average used as default when information missing.				CH ₄ emissions when assuming Marcogaz material-specific emission factors kt CH ₄	CH ₄ emissions from gas distribution in 2020 reported to UNFCCC (2022) kt CH ₄	No control emission factors in the GAINS model								Calibration of control to match UNFCCC (2022)		CH ₄ emissions from gas distribution in 2020 in GAINS kt CH ₄
		Cast iron %	Steel %	PE/PVC %	Other %			Residential sector				Industry & power plants (23% of domestic sector emission factors)				Derived level of control of cast iron, steel and other networks	Derived level of control of PE/PVC networks	
								Cast iron kt CH ₄ /PJ	Steel kt CH ₄ /PJ	PE/PVC kt CH ₄ /PJ	Other kt CH ₄ /PJ	Steel kt CH ₄ /PJ	PE/PVC kt CH ₄ /PJ	Other kt CH ₄ /PJ	% of max technical control	% of max technical control		
Austria	30569	0.005%	25.9%	70.8%	3.3%	2.7	1.5	1.357	0.189	0.044	0.830	0.043	0.010	0.191	100%	100%	1.6	
Belgium	71609	0.6%	23.7%	73.4%	2.3%	6.2	14.4	1.579	0.218	0.051	0.960	0.050	0.012	0.221	100%	17%	14.1	
Bulgaria	5292	2.0%	32.0%	64.7%	1.3%	0.5	3.3	0.843	0.115	0.027	0.506	0.026	0.006	0.116	5%	0%	3.3	
Croatia	19448	2.4%	37.0%	59.1%	1.5%	2.2	0.9	2.736	0.371	0.087	1.634	0.085	0.020	0.376	100%	100%	2.1	
Cyprus ¹	0	0%	0%	100%	0%	0	0	n.a.	n.a.	0.014	n.a.	0.014	0.003	n.a.	100%	0%	0.007	
Czech Rep.	73181	0%	42.0%	58.0%	0%	6.3	16.3	n.a.	0.413	0.096	n.a.	0.095	0.022	n.a.	95%	0%	15.9	
Denmark	18218	0%	14.3%	83.2%	2.5%	1.3	0.1	n.a.	0.416	0.097	1.830	0.096	0.022	0.421	100%	100%	0.7	
Estonia	2150	2.5%	39.2%	56.7%	1.6%	0.3	0.6	1.149	0.156	0.036	0.685	0.036	0.008	0.158	92%	0%	0.6	
Finland	1911	1.0%	4.3%	94.6%	0%	0.1	0.3	0.280	0.039	0.009	n.a.	0.009	0.002	n.a.	70%	0%	0.3	
France	200713	1.6%	26.5%	71.2%	0.6%	18.1	19.6	1.998	0.273	0.064	1.202	0.063	0.015	0.276	100%	96%	19.3	
Germany	503543	2.3%	41.3%	56.5%	0%	54.7	117.9	2.046	0.278	0.065	n.a.	0.064	0.015	n.a.	100%	14%	117.5	
Greece	6087	2.2%	21.0%	76.6%	0.1%	0.5	1.7	0.421	0.057	0.013	0.252	0.013	0.003	0.058	73%	0%	1.7	
Hungary	80770	2.5%	39.1%	56.8%	1.6%	9.6	36.6	3.083	0.418	0.098	1.839	0.096	0.022	0.423	79%	0%	36.4	
Ireland	11339	0%	1.0%	99.0%	0%	0.5	2.3	n.a.	0.120	0.028	n.a.	0.028	0.006	n.a.	100%	0%	2.1	
Italy	257844	1.1%	70.5%	27.9%	0.5%	34.0	172.5	1.499	0.206	0.048	0.906	0.047	0.011	0.208	42%	0%	172.1	
Latvia	5501	2.5%	39.1%	56.8%	1.6%	0.7	3.3	1.981	0.269	0.063	1.182	0.062	0.014	0.272	39%	0%	3.3	
Lithuania	8300	2.5%	39.1%	56.7%	1.6%	1.0	0	1.404	0.190	0.044	0.837	0.044	0.010	0.193	100%	100%	0.8	
Luxembourg	1962	2.5%	39.1%	56.7%	1.6%	0.2	0.8	1.126	0.153	0.036	0.672	0.035	0.008	0.154	91%	0%	0.8	
Malta ¹	0	0%	0%	100%	0%	0.0	0.0	n.a.	n.a.	0.014	n.a.	0.014	0.003	n.a.	100%	0%	0.09	
Netherlands	125280	3.0%	15.0%	80.1%	2.0%	11.7	5.4	1.364	0.184	0.043	0.810	0.042	0.010	0.186	100%	100%	12.5	
Poland	195200	0%	54.3%	45.7%	0%	19.5	20.1	n.a.	0.524	0.122	n.a.	0.121	0.028	n.a.	100%	78%	18.3	
Portugal	19100	0.1%	11.0%	88.9%	0%	1.0	1.9	1.405	0.195	0.046	n.a.	0.045	0.010	n.a.	100%	31%	1.9	
Romania	43563	0%	43.6%	56.4%	0%	3.8	26.6	n.a.	0.222	0.052	n.a.	0.051	0.012	n.a.	0%	0%	25.7	
Slovakia	34004	0%	55.2%	44.8%	0%	3.4	5.5	n.a.	0.348	0.081	n.a.	0.080	0.019	n.a.	100%	23%	5.3	
Slovenia	4342	2.5%	39.2%	56.7%	1.6%	0.5	1.0	2.259	0.306	0.071	1.347	0.070	0.016	0.310	97%	0%	1.0	
Spain	87700	1.4%	10.6%	88.0%	0%	5.8	3.9	1.176	0.161	0.038	n.a.	0.037	0.009	n.a.	100%	100%	3.9	
Sweden	3546	1.4%	30.0%	67.3%	1.2%	0.3	1.3	0.817	0.112	0.026	0.493	0.026	0.006	0.113	52%	0%	1.3	
UK	241700	13.7%	5.7%	64.6%	15.9%	69.5	127.1	1.264	0.152	0.035	0.667	0.035	0.008	0.153	100%	40%	125.4	
EU27+UK	2052872	2.9%	36.1%	58.7%	2.4%	254.6	585.0	1.748	0.240	0.055	1.213	0.054	0.013	0.214			587.9	
EU27	1811172	1.5%	40.1%	57.9%	0.6%	185.1	457.9	1.842	0.266	0.060	1.141	0.056	0.013	0.251			462.5	

¹ Cyprus and Malta have no gas distribution networks reported for year 2020, however, still some small gas consumption in the domestic and transport sectors. All distribution of this gas is assumed to use PE/PVC networks with very low losses.

3.2.7 LNG import terminals

An increasing fraction of natural gas used in Europe is imported as liquified natural gas (LNG). At the exporting end, the natural gas is liquified by cooling it to -162°C , which reduces its volume by a factor of 600 (Carbon Limits, 2021), making it suitable for transportation by ship. At the receiving, importing end, the LNG is typically regasified and entered into the regional and local gas transmission and distribution systems. In contrast to transportation of gas via pipelines, there are certain segments of the gas supply chain that are specific to LNG, namely liquification, loading, shipping, unloading and regasification. This section focuses on methane emissions from the sources that are specific to LNG. Emissions from the other supply-chain segments (before liquification and after regasification) are accounted for under the respective sources described in previous Sections. As all LNG terminals in the EU and UK are import terminals and emission inventories are production-based, the emissions accounted for in the GAINS emission inventory are limited to emissions during offloading, regasification and storage at the LNG import terminals in Europe. It should however be pointed out that the highest methane emissions in the LNG value-chain are likely to take place during the liquification (for export) and the LNG carrier transport (Carbon Limits, 2021). Hence, the GAINS emission inventory does not reflect emissions from the entire value-chain of using LNG in Europe.

According to Carbon Limits, the main sources of methane from LNG export/import terminals are fugitive leaks from equipment and from loading arms, venting of methane from LNG storage tanks and equipment for pressure control or emergency purposes, venting of methane during cooling process of equipment at the terminal, incomplete combustion of gas fuel from power generating equipment, and incomplete combustion of boil-off-gas during operations and blowdown gas from flare systems during maintenance and emergency shutdown.

There are a few estimates of methane emissions from LNG terminals available. USEPA (2022) reports that it is possible to limit emissions to 25 g CH_4 per metric ton LNG liquified on well-managed plants. Marcogaz (2018) conducted in 2015 a survey of methane emissions from LNG terminals in Europe. The survey collected information for 18 out of 20 terminals operational in the EU in the year 2015, with detailed data on methane emissions for 9 of these. They estimate in total 4.7 kt CH_4 released from LNG terminals in the EU in 2015. Carbon Limits (2021) has converted this estimate to an emission factor of 165 g CH_4 per metric ton LNG processed.

3.2.8 Bunker fuels

In 2023 the Council of the European Union adopted the FuelEU Maritime regulation (EC, 2023) aimed at reducing the GHG emissions from the shipping industry through switch of fuels and by including the GHG emissions from bunker fuels use in international shipping in the EU-ETS emissions trading system. This includes fugitive CH_4 emissions from bunkering of fuels, as well as emissions from incomplete combustion of fuels. Of particular concern for methane emissions is a replacement of liquid bunker fuels (e.g., heavy fuel oil) with liquified natural gas (LNG). Often used ways of LNG bunkering of marine vessels are: from truck to ship (for smaller volumes), from ship to ship, from terminal to ship, and by swapping portable tanks (Corbett et al., 2015). In addition to CH_4 leakages during bunkering, there is the possibility of a CH_4 slip from the engines. The size of the slip varies significantly with the type of engine and fuel with throughput leakage rates ranging between 2% and 5% for LPDF 2- or 4-stroke engines and close to zero for HPDF 2-stroke engines (Balcombe et al., 2021; Pavlenko et al., 2020; Corbett et al., 2015). In lack of country-specific information on the types of engines used in international shipping in the EU, we adopt a default assumption of 4 g CH_4/kWh (about 1.11 kt CH_4/PJ),

which corresponds to about 2.5% loss of throughput LNG (Balcombe et al., 2021). For liquid fuels, the CH₄ emission factor is typically significantly lower. For heavy fuel oil and diesel, we adopt the IPCC (2006, Vol 2, Ch 4, Table 8 https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_4_Waterborne_Navigation.pdf) default emission factor of 0.007 kt CH₄/PJ.

The abatement options identified for CH₄ emissions from the use of gaseous fuels in shipping are assumed to be the same as installations to control emissions of VOCs. The removal efficiency of such installations is assumed to 88% and the cost is corresponding to the cost for medium/large installations as referenced in Rentz et al. (1998) Table 6.5.2.

3.2.9 Combustion in stationary sources

During combustion processes CH₄ emissions are released due to incomplete oxidation of fossil and biogenic fuels. Activity data for combustion emissions from power plants is the energy content of the fuel used, which is taken from the PRIMES (E3modelling, 2023) model. Emission factors are differentiated for different sectors and type of fuel combusted. For industry and power plants, CH₄ emission factors were taken from IPCC (2006). For residential boilers, CH₄ emission factors are differentiated for different types of boilers and taken from Delmas (1994), Johansson et al. (2004), Kjällstrand and Olsson (2004) and Olsson and Kjällstrand (2006).

No specific mitigation options have been identified for CH₄ emissions from combustion sources.

3.2.10 Combustion in mobile sources

Incomplete combustion in mobile sources gives rise to CH₄ emissions. Activity data is amount of fuel used as adopted from the PRIMES (E3modelling, 2023) model for each vehicle type as specified in Table 3. GAINS uses default emission factors from the European transport emission database COPERT (EMISIA, 2013 <http://www.emisia.com/copert/General.html>). Emission factors are specified by vehicle category, type of fuel used and the emission control standard of the vehicles (EURO I to EURO VI).

3.3 Agriculture sector

3.3.1 Livestock

CH₄ emissions from livestock emerge from enteric fermentation during the digestive process in the stomachs of ruminants. When the organic content in livestock manure decomposes, emissions of CH₄ and N₂O are released. CH₄ release occurs when manure is handled under anaerobic conditions, while the formation of N₂O requires aerobic conditions with access to oxygen.

Emissions from livestock are estimated as the sum of the emission types n (enteric fermentation and/or manure management) for a certain animal type s in country i and year t :

$$E_{its} = \sum_{bmns} [A_{itbs} * ef_{ibns}^{NOC} * (1 - remef_{mns} * h_{itsm}) * Appl_{itstm}], \quad (21)$$

where A_{itbs} is the number of animals of type s in country i and year t , with type of manure management b (solid or liquid),

ef_{is}^{NOC} is the no control emission factor for emission type n , animal type s in country i and subject to manure management b ,

rem_{mns}	is the removal efficiency of technology m when applied to emissions of type n and animal type s ,
h_{ism}	is a factor correcting for application limitations of technology m , e.g., indoor housing rates for feed options or large farm rate for farm-scale anaerobic digestion,
$Appl_{itsbm}$	is the application rate of technology m to animal type s with type of manure management b , in country i and year t .

GAINS estimates CH₄ emissions separately for the animal types dairy cows, non-dairy cattle, pigs, poultry, sheep and goats, buffaloes, and horses. For dairy cows, non-dairy cattle and pigs, animal numbers are further split by whether animals are subject to liquid or solid manure management. The split in the number of animals by liquid or solid manure management is stored in the GAINS model and was recently reviewed by member state experts during IIASA consultations in preparation of the GAINS database for the Clean Air Outlook 1 (in 2018) and 2 (in 2020), see EC (2020). The source for historical animal numbers for historical years is EUROSTAT (2022), except for horses and buffaloes where FAOSTAT (2022) is the source. Projections are based on future trends in animal numbers as estimated in the CAPRI model Reference and LIFE scenarios (EuroCare, 2023).

To better reflect future mitigation potentials and costs, the animal categories dairy cows, non-dairy cattle, pigs, poultry, sheep and goats are further split by five farm size classes, i.e., less than 15 livestock units (LSU), 15 to 50 LSU, 50 to 100 LSU, 100 to 500 LSU, and above 500 LSU. The source for data on historical farm-size distributions is EUROSTAT (2015). Projections for the future development of farm-size classes have been made applying a multi-nominal logistic function weighing in the development observed in historical years from 1990 onwards. The development of farm-size classes has implications for the development of the fractions of animals on liquid and solid manure management and on the future applicability of control technology options. Typically, over time more animals tend to move into the larger farm-size classes with liquid manure management and away from smaller farm-size classes with solid manure management.

Country-specific emission factors corresponding to the implied emission factors reported to UNFCCC (2022) for year 2020 were adopted for enteric fermentation and manure management emissions, respectively.

For dairy cows, both enteric fermentation emissions and manure management emissions per animal are affected by the milk productivity of the cow. This effect is particularly accentuated for highly productive milk cows. To capture this, the no control emission factor for dairy cows is specified as the sum of a fixed emission factor per animal for cows producing up to 3000 kg per head per year and an additional term describing the emission factor per milk yield for milk production exceeding the productivity level 3000 kg per animal per year, i.e.,

$$ef_{it,cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * (x_{it} - 3000) \quad (22)$$

where ef_i^{animal} is the default emission factor for cows in country i producing 3000 kg milk per year,

ef_i^{milk} is the emission factor per kt milk produced above the threshold level 3000 kg milk per animal per year, and

x_{it} is the average milk yield per animal in country i and year t .

A linear relationship between the CH₄ emissions per cow and the milk yield per cow was fitted from default emission factors per cow provided by IPCC (2006, Ch.10) for different world regions representing a range of average milk yield levels. Starting from country-specific implied emission factors reported to UNFCCC for year 2005, the derived linear relationship determine the future emission pathway from the development in milk yield and animal numbers. Hence, as milk yield per cow increases CH₄ emissions per cow increase while emissions per kg milk produced decline when fewer animals are needed to produce the same amount of milk. Whether the overall effect on methane emissions is positive or negative will depend on the importance of the effect of increased methane emissions per animal relative the effect of declining animal numbers. The derived CH₄ emissions per kg milk produced at different average milk yield levels are well in line with the ranges estimated empirically for Germany between 1990 and 2010 (Piatkowski and Jentsch, 2013).

Breeding through selection offers several different ways to reduce enteric methane emissions from livestock. First, an increase in productivity per animal could mean that a smaller animal stock produces the same amount of produce with potentially lower methane emissions per unit of produce. Milk cow productivity has improved significantly in the EU over the past few decades. This is primarily the result of breeding leading to an increased use of high-producing cow types, e.g., Holsteins, in the stocks. If the increase in milk yield per cow means keeping smaller animal stocks to produce the same amount of milk, then methane emissions per unit of milk produced are likely to fall. In many EU countries, methane emissions per unit of milk produced may, however, not have fallen as a consequence of increased milk yield, because the tremendous increase in milk yield has in many countries been accompanied by an increased fraction of unproductive animals in the stocks due to poorer health and fertility of the high-productive cow breeds (see e.g., Lovett et al., 2006; Berglund, 2008; Bell et al., 2011). Highly productive cows are effective in converting feed energy into milk, but may as a consequence lack enough energy reserves to maintain health and reproduction (Berglund, 2008). Many EU countries have seen falling reproductive performance of the milk cows as milk yield increased (Nyman et al., 2014; Nilforooshan et al., 2010; Nilforooshan et al., 2013; Evans et al., 2006), however, the breeding schemes in the Scandinavian EU countries have shown that it is possible through breeding for both productivity and reproduction traits, to achieve top level milk yield *and* maintain fertility and animal health levels (Berglund, 2008). Hence, to achieve lasting methane reductions per unit of milk produced, it is likely that breeding programs must aim at the dual objective of increasing milk yield while maintaining animal health and fertility. This appears to be the case not only for animals fed on concentrates, but also for forage-fed and grazing animals (Bell et al., 2011; O'Brien et al., 2010). Maintaining animal health and fertility levels is likely to better sustain profitability of the milk farmers in the long-run, as it is costly to keep and feed large fractions of unproductive animals in the stock (Evans et al., 2006). According to Bell et al. (2012) and the conclusions of the EU 7th Framework Programme “Animal change” project (Animal change, 2014), genetic improvement through breeding is likely to be a cost-effective measure as it achieves methane emission reductions that are cumulative and permanent. O'Brien et al. (2014a) estimate reduction potentials in 2020 from adoption of accelerated breeding schemes for Irish dairy cows at 555 kt CO₂eq per year when using a lifecycle assessment method and by 596 kt CO₂eq per year

when using the IPCC national inventory approach.² The mitigation cost is estimated at -519 and -483 €/tCO₂eq with respective methodology. There are no estimates available in the literature of what a dual objective breeding scheme could achieve in terms of methane reductions at an EU level. Several authors however mention that such a development would require large databases on the genetic variation to favourably capture the complex interactions of different positive genetic traits (De Haas et al., 2011; Berry and Crowley, 2013). In addition, time is needed for a careful selection process to run its course, often mentioned to at least 10 years (Knapp et al., 2014; De Haas et al., 2011).

Second, breeding can be used to enhance the feed efficiency in animals, which is likely to reduce methane emissions as methane production is essentially a loss of energy. Profitability in meat production systems is closely linked to the feeding costs, which makes it particularly interesting for financial and environmental reasons to use breeding to enhance feed efficiency in animals and simultaneously reduce methane emissions. Berry and Crowley (2013) show in a meta-analysis of 39 scientific publications that genetic variation in feed efficiency in cattle has a pooled heritability for residual feed intake (RFI) and feed conversion efficiency of 0.33 and 0.23, respectively (for cows, the corresponding heritability is much lower at 0.06 and 0.04, respectively). Hence, there appears to be scope for further improvements in feed efficiency through breeding in beef cattle, provided that large quantities of routinely collected feed intake information on individual animals become available (Berry and Crowley, 2013). The link between feed efficiency in cattle and methane emissions is expected. Nkrumah et al. (2006) linked the variation in RFI directly to variation in methane emissions. They found for 27 Canadian hybrid beef steers that methane production was 25% lower for low-RFI individuals than for high-RFI individuals. Hegarty et al. (2007) found among 66 Angus steers that methane emissions were lower for the most feed efficient animals (i.e., with the lowest RFI). The effect on methane emissions from selection for feed efficiency is likely to be the greatest for grazing ruminants, which includes dairy cows, non-dairy beef cattle and sheep (Animal Change, 2014). According to estimates by DEFRA (2012), 10 years of breeding on beef cattle in the UK using current approaches is expected to result in a cumulative increase in farmers' profits of 31 million pounds when measured over a twenty years period and reduce GHG emissions by 3%. Adding more selection indices to the traits currently targeted, is expected to increase profits further and extend the emission reduction potential to 10% below current emission levels.

Third, there is the possibility to use breeding to directly select for individual animals with low formation of methane in the rumen, thereby reducing enteric methane emissions per animal. De Haas et al. (2011) state that, on the basis of the existing genetic variation in Dutch dairy cows, it is theoretically possible to reduce enteric methane production per animal by selecting for more methane efficient individuals. This potential would correspond to enteric methane reductions in the order of 11 to 26% over 10 years. Although theoretically possible, realistic methane reduction rates will depend on several factors, e.g. the accuracy and intensity of selection, the number of records available, and the generation interval (De Haas et al., 2011). De Haas et al. call for an international effort to establish a reference database on genetic variation in dairy cows to be used for genomic selection.

Fourth, breeding has the potential to reduce methane emissions if it is combined with different types of feed as different breeds appear to respond with different levels of enteric methane formation to different types of feed (Bell et al., 2012; Bell et al., 2010; Knapp et al., 2014; O'Brien et al., 2010). In addition

² Note that it is not clear from the source from what baseline these emission reductions are estimated. However, if we use GAINS baseline estimates, then the accelerated breeding option would reduce dairy cow emissions in the order of 16 to 18%.

to matching feed with the breed, Knapp et al. also mention the importance of optimizing management practices, which could otherwise limit the ability of the animals to reach their full genetic potential.

Finally, in addition to breeding through selection of traits, there are a number of reproductive technologies available that have the potential to reduce methane emissions (Hristov et al., 2013b). These include gender-selected semen, embryo transfer, and hormonal synchronization, which all have the potential to enhance the reproductive efficiency, thereby reducing the number of animals kept in the stock at a systems level. With fewer animals in the system, greenhouse gases are likely to decline per unit of output produced. Hristov et al. (2013b) estimate the methane mitigating effect of assisted reproductive technologies to between 3.5 to 5.5 percent.

We have here described a number of different ways through which breeding through selection and the use of reproductive technologies can achieve persistent reductions in system methane emissions from milk and meat production. The uncertainty of the long-term effects on systems methane emissions is high and difficult to assess with more certainty. At the same time, when taken together it is most likely that these options can offer future opportunities to reduce enteric methane emissions if policies are put in place, which provide incentives for the adoption of reproductive technologies and for large-scale breeding schemes that specifically target reductions in methane emissions.

To estimate the abatement potential from breeding schemes aimed at enhancing productivity and animal health and fertility in dairy cows, we set a benchmark at 14.3 kt CH₄/kt milk produced, which corresponds to the average 2020 emission factor for Swedish dairy cows consistent with the reporting to UNFCCC (2022). The assumption is that with this type of broader breeding schemes set up from 2020 onwards, all dairy cows on farms with more than 50 LSU ought to, from 2040 onwards, be able to reach the same emission level per unit of milk produced as Swedish cows had in 2020. Considering that successful breeding schemes take time, the effect on emissions are assumed to be gradually phased in between 2030 and 2040. The country-specific abatement potentials from breeding of dairy cows are illustrated in Figure 1 as the difference between the baseline emission factor (orange line) and the target emission factor (grey line).

An abatement potential from different types of breeding of 10% is in GAINS assumed possible for non-dairy cattle and sheep from 2030 onwards. Estimates by DEFRA (2012) show that farmers' profits are likely to increase due to enhanced productivity, which would suggest a negative cost for breeding. However, there are likely to be costs involved for establishing a reference database on genetic information and associated research. Although uncertain, a general assumption in GAINS is that breeding as a measure to mitigate methane emissions is cost-effective (i.e., available at zero costs).

Changing animal diets or adding substances known to reduce methane formation in the rumen are possible methane mitigation options. Reviews from the FAO by Hristov et al. (2013a) and Gerber et al. (2013a) provide comprehensive information about the current state of knowledge with a global scope. Both reports provide limited information for Europe specifically. Gerber et al., provide information about the expected effect on mixed dairy systems in Western Europe of using lipids as feed additives and find it small (expected reduction in enteric fermentation emissions is 1.2% to 3.6%). The effects of different types of non-lipid additives or feed management options were, however, not evaluated for Western Europe by Gerber et al. (2013a).

Feed management options include mechanical ways to treat the feed to facilitate digestion, ways to combine different types of feed to minimize enteric methane formation, as well as precision feeding,

which means very closely monitoring the timing and the feed mix supplied to the animals in order to optimize feeding against both economic and environmental parameters. As an effective feed management is important for the profitability of many European farmers, the scope for further reductions in methane emissions through improved efficiency in feed management is likely to be limited. There may, however, be some scope for mitigation from wider use of precision feeding (Dalgaard et al., 2011).

Knapp et al. (2014) review enteric fermentation methane mitigation measures for intensive dairy systems. They conclude that feeding and nutrition have modest reduction potential (2.5 to 15%) to mitigate enteric methane in intensive dairy operations in developed countries and that “To date, rumen modifiers other than nitrate have not shown sustained reductions in CH₄/ECM”. Dalgaard et al. (2011) analyze possible measures to reduce GHG emissions in Danish agriculture to 2050. They estimate that a 50-70% reduction in Danish agricultural greenhouse gas emissions is achievable in 2050 relative the 1990 emission level. The contribution from different feed options to methane emission reductions is, however, limited to between 15 and 20% and would involve precision feeding. Results compiled by Hristov et al., (2013a) on the effectiveness of individual feed mitigation measures show a mixed bag with limited potential for intensive European livestock systems from feed management and lipid additives (due to already high efficiency with respect to these parameters in the systems) but with potential effects from some non-lipids additives e.g., nitrate, propionate precursors and phytochemical substances.

Significant efforts have recently been put into development and marketing of different methane-suppressing feed additives to be provided as supplements to ruminant livestock. A comprehensive literature review by the Global Research Alliance on Agricultural Greenhouse Gases (Hegarty et al., 2021) identified ten groups of additives distinguished by the type of active ingredient. Only two of these groups were found to routinely deliver at least a 20% reduction in methane emission formation without negative effects on animal productivity. These are 3-Nitrooxypropanol (3-NOP), which works by blocking an enzyme (methyl-coenzyme M reductase) needed in the formation of methane in the rumen, and products based on the seaweed *Asparagopsis*, which contains bromoform as the principal methane-suppressing agent. In addition, authors find that increased intake of nitrates (NO₃) has the potential to reduce methane emissions by about 10%, however due to its toxicity it must be phased-in slowly and at closely monitored dosage so as not to poison the animals. All other groups of additives were found not to be expected to deliver at least 10% mitigation in a relatively safe manner and are therefore not considered here. The authors point out that there is insufficient evidence regarding the claim by some commercial developers that the additive will enhance animal productivity. Furthermore, the high mitigation potentials of 60% or higher sometimes presented from *in-vitro* experiments, where the additive is continuously fed into every mouthful, are according to the report authors not likely to be reproduced when the supplement is fed once daily or even less frequently. In conclusion, we assume in GAINS that the use of feed additives can contribute to a 20% reduction in enteric fermentation methane emissions when applied to dairy cows, beef cattle and sheep that are at least partly kept indoor and fed concentrates. We do not consider the option feasible for grazing beef cattle or sheep. Information on the average number of days per year that animals spend indoor has been collected by animal category in the GAINS database during consultations with experts from EU member states, most recently during IIASA-member state consultations in preparation of the GAINS database for the Clean Air Outlook 1 (in 2018) and 2 (in 2020), see EC (2020).

Costs will depend on the feed additive in question (e.g., nitrate-based additives are likely to be very cheap while additives based on 3-NOP or seaweed are likely to be more expensive) and on the possibility and costs of effectively distributing the additive in the right dosage in order to avoid negative effects on

animal health or productivity. DSM (2014) mention that for the launch in 2018 of a new feed additive, they evaluated different options for dosage and distribution in order to offer a financially feasible mitigation option to farmers. With further technological development, we expect the launch of new additives on the market to be accompanied by a development in dosage technologies. In the absence of information on expected future costs of this option, we consider a financially and politically viable annual cost level to be about 7 Euros per animal head. This cost level corresponds to an average cost range of about 5 to 30 Euro/t CO₂eq when implemented for dairy cows and with higher average cost levels for non-dairy cattle and sheep.

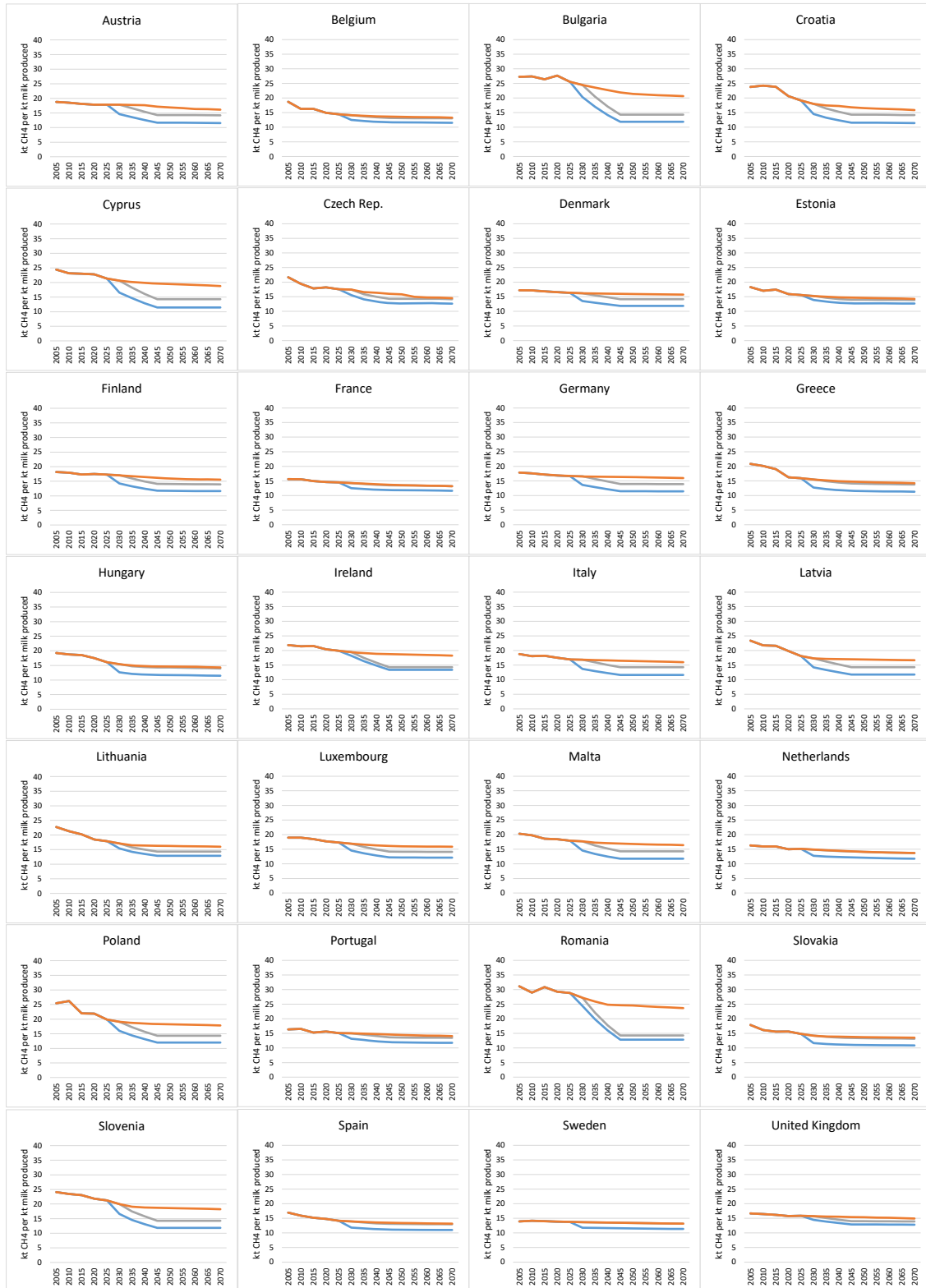


Figure 1: Enteric fermentation emission intensity in kt CH₄ per kt milk produced as assumed in GAINS. Baseline scenario (orange lines) are taken from CAPRI (2023). Technical mitigation potentials are modelled in GAINS; With breeding (grey lines), and With joint effects of breeding and feed additives (blue lines). Options only assumed applicable on livestock farms with more than 50 LSU.

Treatment of animal manure in anaerobic digesters (ADs) that generate biogas can be an efficient way to reduce methane emissions from manure handling at a low cost (Hristov et al., 2013b). The process has the advantage of not only reducing emissions, but also to generate energy that can be used on the farm or sold to external local users, and at the same time produces an odor-free organic fertilizer, which can substitute the use of mineral fertilizers (Sommer et al., 2013).

The minimum electricity generation capacity of co-generation plants currently available on the market is 15 kW_{electric} and requires at least 100 LSU (Pellerin et al., 2013). Hence, farm AD is likely to be economically infeasible for farms smaller than 100 LSU. In the GAINS model, farm-scale anaerobic digestion (AD) is assumed to be applicable to manure from dairy cows, non-dairy cattle and pigs kept in systems with liquid manure management on farms with at least 100 livestock units (LSU). It is also assumed that manure is only available for anaerobic digestion during the periods that animals are kept indoor. Information on the average number of days per year that animals spend indoor has been collected by animal category in the GAINS database during consultations with member state experts, most recently during IIASA-member state consultations in preparation of the GAINS database for the Clean Air Outlook 1 (in 2018) and 2 (in 2020), see EC (2020). No potential for farm-scale anaerobic digestion is assumed for animals kept on farms smaller than 100 LSU, nor for animals in solid manure management systems, and nor for periods when animals are grazing outdoor.

An additional possible source of manure as input to anaerobic digesters is poultry excretion. This source of substrate has been excluded from this analysis because of its insignificance as a methane emissions source.

The amount of manure available for anaerobic digestion is derived from the average volatile solid excretion rate per animal per day reported by countries to the UNFCCC-CRF (2019) for the year 2015. Given that volatile solids (VS) make up 80% of total solids (TS) in the manure and that the manure (or rather the slurry as it derives from liquid manure management systems) has a water content of 85% (Sommer et al., 2013), the amount of manure generated per head per year (m) in country i is calculated as:

$$m_i = 0.001 \frac{(365 \times VS_i / 0.8)}{(1 - 0.85)}, \quad (23)$$

where VS_i is the country-specific average daily excretion rate for the analyzed animal type.

The cost of farm AD is sensitive to scale. We therefore estimate the methane reduction potential and costs separately for “large farms” defined as farms with 100 to 500 LSU and “extra large farms” with more than 500 LSU. The total amount of manure available for farm-scale anaerobic digestion in country i in a future year t is the sum of manure excreted by animals on large farms and extra large farms during times when animals are kept indoor, i.e.,

$$M_{it} = \sum_s A_{it}^{liquid} \times VS_i \times \gamma_{its} \quad M_{it} = \sum_s A_{it}^{liquid} \times m_i \times \gamma_{its} \times h_i, \quad (24)$$

where A_{it}^{liquid} is the number of animals on liquid manure management, γ_{its} is the fraction of animals found on farms of size s in country i and year t , and h_i is the fraction of a year that animals are housed indoor.

The cost of farm-scale AD is derived as the sum of the annualized investment cost and the operating costs (including costs for labour and additional organic substrate), minus the revenues and cost-savings of utilizing the generated electricity and fertilizers. Hence, the unit cost per head of installing a farm AD

plant for treatment of cattle and pig manure is in GAINS defined for country i in year t and for farm scale s in the following way:

$$C_{its} = I_{its} \times \frac{r(1+r)^T}{(1+r)^T - 1} + R_{its}p_R + L_{its}w_{it} - 0.6p_{it}^{ind}E_{its} - F_{its}p_f \quad (25)$$

where I_{its} is the fixed initial investment cost,
 T is the expected lifetime of the equipment,
 r is the interest rate,
 R_{its} is the amount of organic substrate added to the co-digestion,
 p_R is the unit price of organic substrate,
 L_{its} is the fraction of annual work hours spent on operation of AD plant,
 w_{it} is the average annual wage for the agricultural sector,
 p_{it}^{ind} is the average electricity price for the industry sector,
 E_{its} is the amount of energy generated from the AD process,
 F_{its} is the amount of pure fertilizer nutrients (N-P₂O₅-K₂O) generated from the AD process,
and
 p_f is the unit price of fertilizer nutrients.

The efficiency of energy production of an anaerobic digester loaded with animal manure only is rather poor, because much of the organic matter in manure degrades slowly and with a relatively low content of micronutrients needed by the anaerobic bacteria to form methane. The performance can be considerably enhanced if manure is co-digested with other organic material rich in micronutrients (Sommer et al., 2013). In farm AD plants, which primarily digest manure, it is therefore typical to add at least 20% other organic substrate to enhance the energy-generating performance of the process (ETH, 2008). In GAINS it is assumed that the feedstock contains 20% organic substrate and 80% manure and that both these substrates have a water content of 85%, respectively.

There is a wide range of organic waste materials available, which are suitable as additional substrate to manure in a farm AD plant (EC, 2001). These include straw and other crop residuals like maize stems, food residuals from restaurants and municipalities, food industry waste (e.g., residuals from slaughterers or waste from beverage or fat production), and sewage sludge from wastewater treatment. If there is a risk that the organic substrate contains pathogens, it will need to be pasteurized through the use of a thermophilic process or the digestate resulting from the digestion process cannot later be spread as fertilizer on fields (Sommer et al., 2013). In consistency with the European animal by-products regulation (EC 1069/2009), the digestate needs to be subject to minimum pasteurization equivalent to one hour at 70°C. In equivalence of this, some biogas plants perform pasteurization at a lower temperature, e.g., 53°C, but with the longer retention time of 10 hours (IEA Bioenergy Task 37, 2014b) to better preserve some of the bacterial content of the feedstock.

Because of the wide variety of sources for organic substrate and fluctuations in its availability over time and space, it is hard to make general assumptions about the unit price of organic substrate. It may vary

from zero cost for organic waste, which suppliers would otherwise have had to pay to get rid of in an appropriate way, to 150 Euros per ton if feed crops (e.g., maize) are used. In the GAINS mitigation scenarios produced here, we assume the price of organic substrate is 100 Euros/ton.

The amount of energy generated per ton of feedstock from a biogas digester can fluctuate widely depending on e.g., the composition of the feedstock and different operating conditions. From a survey of published case-studies of farm-scale AD plants, we find three European plants currently in operation for which information on both the amount of feedstock loaded and the amount of energy generated, are clearly stated. These are the McDonnell farms in Limerick, Ireland (SEAI, 2014) co-digesting 7600 ton cattle manure per year with 2800 ton food waste and 360 ton glycerine, the Stowell farms in Wiltshire, UK (EnviTec, 2012), co-digesting 4000 ton cow manure with 8000 ton maize silage, and Alviksgården, Luleå, Sweden (Svenska Gasföreningen, 2014) co-digesting 16000 ton pig slurry with 1800 ton slaughter waste. All three farms use or sell the digestate as organic fertilizer. Figure 2 plots the reported net energy generated against the amount of wet substrate loaded for the three plants as well as for a “typical” farm used in model simulations to assess the potential for farm AD in Switzerland (ETH, 2008). For the latter plants, a feedstock of 80% manure and 20% co-substrate is assumed. The energy comes in the form of electricity or heat and typically about 50% is converted to electricity and 50% is utilized as heat.

The three plants currently in operation and illustrated in Figure 2 report net energy generation of 381, 637 and 539 kWh/ton substrate, respectively, while the Swiss study assumes 245 kWh/ ton substrate. In GAINS it is assumed that it is possible to generate on average 380 kWh/ton substrate loaded.

Based on the split between electricity and heat generated as reported by the surveyed farm AD plants, it is assumed in GAINS that half of the 380 kWh/ton substrate generated is converted to electricity, which is sold to local industry at the country-specific industry sector price of electricity and heat taken from PRIMES (E3modelling, 2023). 40 percent is used on farms as heat, and 10 percent is heat used up by the pasteurization process or lost without any economic value.

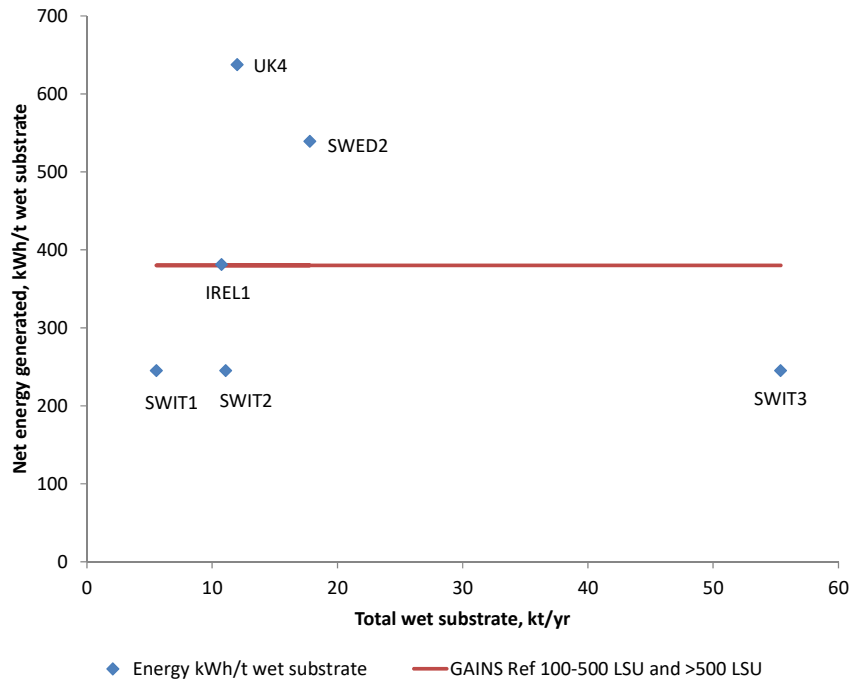


Figure 2: Net energy generation per ton wet substrate loaded for three farm AD installations currently in operation (IREL1, SWED2 and UK4) and for three model simulations (SWIT1, SWIT2, SWIT3) of “typical” Swiss farm AD installations.

Apart from the carbon content of the manure, which has partly been converted into biogas, the nutrients present in the manure feedstock will remain in the digestate after the anaerobic digestion is completed. During digestion, the organic nutrients present in the manure are transformed to inorganic compounds, e.g., organic nitrogen is converted to ammonia. The inorganic compounds can be more readily taken up by the plants than the organic nutrients present in undigested manure (Sommer et al., 2013). The digestate is therefore well suited as organic fertilizer. Table 16 presents typical nutrient contents of animal manure as well as for a few organic waste sources considered suitable as additive organic substrate in co-digestion with manure. The nutrients considered to be essential as fertilizers are nitrogen (N), phosphorous (P_2O_5), and potassium (K_2O). As shown in Table 16, the range for the nutrient contents is wide. As a conservative assumption, we assume that cattle and pig slurry contains 0.6 percent of nutrients N- P_2O_5 - K_2O in the proportions 50-17-33 and that added organic waste contains 2.7 percent of nutrients N- P_2O_5 - K_2O in the proportions 55-30-15. The assumptions give us a basis for estimating the amount of nutrients present in the digestate and therefore available for use as organic fertilizer. The value of pure nutrients in the proportions above is set to 1000 Euros per ton N- P_2O_5 - K_2O , which would correspond to a price of 500 Euros/ton for an organic fertilizer containing 50 percent pure nutrients.

Table 16: Typical nutrient content in animal waste and some organic waste sources in Europe. % of substrate mass weight.

Substrate source:		unit	Min	Max	Mean
Fresh cattle manure	DS content	% of manure	20	50	n.a.
	N	% of manure	0.55	1.21	n.a.
	P2O5	% of manure	0.1	0.8	n.a.
	K2O	% of manure	0.25	1.2	n.a.
Cattle slurry	Dry solids (DS)	% of slurry	1	18	n.a.
	N	% of slurry	0.26	2.02	n.a.
	P2O5	% of slurry	0.1	1.2	n.a.
	K2O	% of slurry	0.2	1.5	n.a.
Fresh pig manure	Dry solids (DS)	% of manure	n.a.	n.a.	25
	N	% of manure	0.57	0.95	n.a.
	P2O5	% of manure	0.1	0.76	n.a.
	K2O	% of manure	n.a.	n.a.	0.4
Pig slurry	Dry solids (DS)	% of slurry	1	18	n.a.
	N	% of slurry	0.41	1.96	n.a.
	P2O5	% of slurry	0.1	1.2	n.a.
	K2O	% of slurry	0.2	0.9	n.a.
Food & drink industry sludge	Dry solids (DS)	% of sludge	1.3	91	12
	N	% of DS	0.73	16	4
	P2O5	% of DS	0.1	16	2.4
	K2O	% of DS	0.1	16	1.4
Slaughter waste - guts content	Dry solids (DS)	% of waste	2.4	21	n.a.
	N	% of DS	0.2	27.2	n.a.
	P2O5	% of DS	0	3.4	n.a.
	K2O	% of DS	0	1	n.a.
Slaughter waste sludge	Dry solids (DS)	% of sludge	8	25	16
	N	% of DS	2	80	22.1
	P2O5	% of DS	1.7	36	11
	K2O	% of DS	0.8	4.4	1.3
GAINS assumption: cattle & pig slurry	Dry solids (DS)	% of slurry	-	-	15
	N	% of slurry	-	-	0.3
	P2O5	% of slurry	-	-	0.1
	K2O	% of slurry	-	-	0.2
GAINS assumption: Organic waste substrate	Dry solids (DS)	% of waste	-	-	15
	N	% of waste	-	-	1.5
	P2O5	% of waste	-	-	0.8
	K2O	% of waste	-	-	0.4

Source: EC, 2001. Chapter 4: PROPERTIES OF WASTES RELEVANT TO AGRICULTURAL BENEFIT AND ENVIRONMENTAL IMPACT, European Commission-Directorate-General for Environment, Brussels.

http://ec.europa.eu/environment/waste/studies/compost/landspreading_4-6.pdf

Figure 3 shows the fixed initial investment cost per ton of wet substrate loaded per year against the wet substrate loading capacity for six anaerobic digestion plants currently in operation and for which information was available on both investment cost and substrate load. In addition to the Swedish and Irish plants presented in Figure 2, these include the Mountstephen farm in Devon UK co-digesting 2373 ton cow slurry and chicken litter with 1095 ton maize and the Langage farm in Devon UK co-digesting 3000 ton cow slurry with 13000 ton food industry waste. Also illustrated in Figure 3 are the assumptions used for model simulations of the potential for farm AD in Switzerland (ETH, 2008). To illustrate the importance of scale for the investment cost of anaerobic digestion plants, Figure 3 also present the investment cost per ton substrate loaded for two large Danish plants co-digesting manure from several farms with organic waste from other sources. For the farm AD plants illustrated, investment costs vary between 75 and 225 Euro/t wet substrate loaded annually over a load range of 3.5 to 55 kt wet substrate per year, while the corresponding costs for the two Danish co-digestion plants are 21 and 37 Euro/t wet substrate for annual loads of 281 and 164 kt wet substrate, respectively. In GAINS the adopted investment cost for AD plants on farms of the size 100-500 LSU is 200 Euro/t wet substrate loaded, while for farms of the size larger than 500 LSU it is 100 Euros/t wet substrate loaded. Because the amount of wet substrate per animal is derived from country-specific volatile excretion rates, the derived investment cost per head is country-specific (see Figure 4). The investment cost is the product of the investment cost per ton wet substrate for farm size s and the country-specific amount of wet substrate loaded per animal head, i.e.,

$$I_{its} = i_s \times m_i \times 1.25. \quad (26)$$

Note that the total amount of wet substrate loaded per head is 1.25 times the manure generated per head as the total substrate contains 80 percent manure and 20 percent other organic substrate.

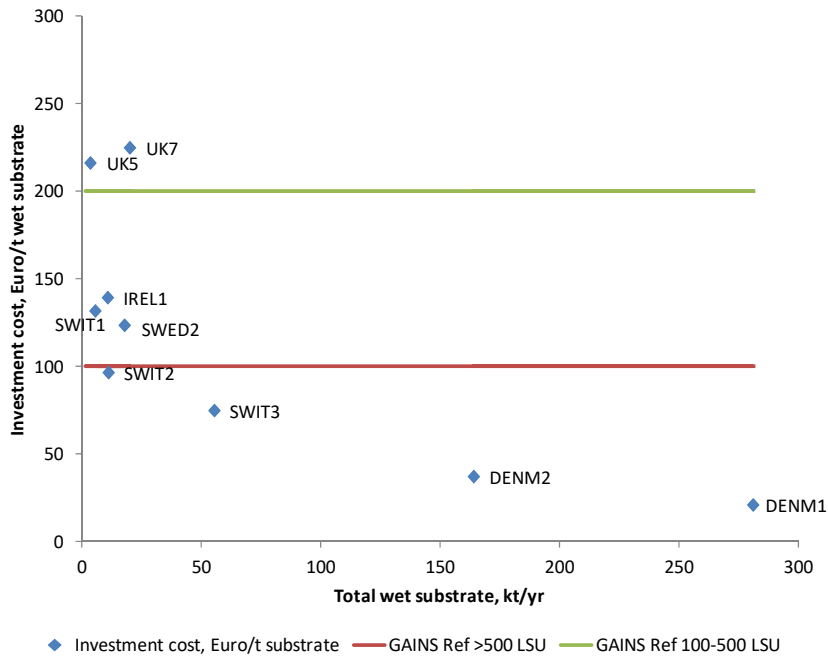


Figure 3: Fixed initial investment cost per ton of wet substrate loaded annually for four currently operating farm AD plants (IREL1, SWED2, UK5, UK7), three model simulation plants (SWIT1, SWIT2, SWIT3) and two large co-digestion plants (DENM1, DENM2) co-digesting manure and industrial organic waste.

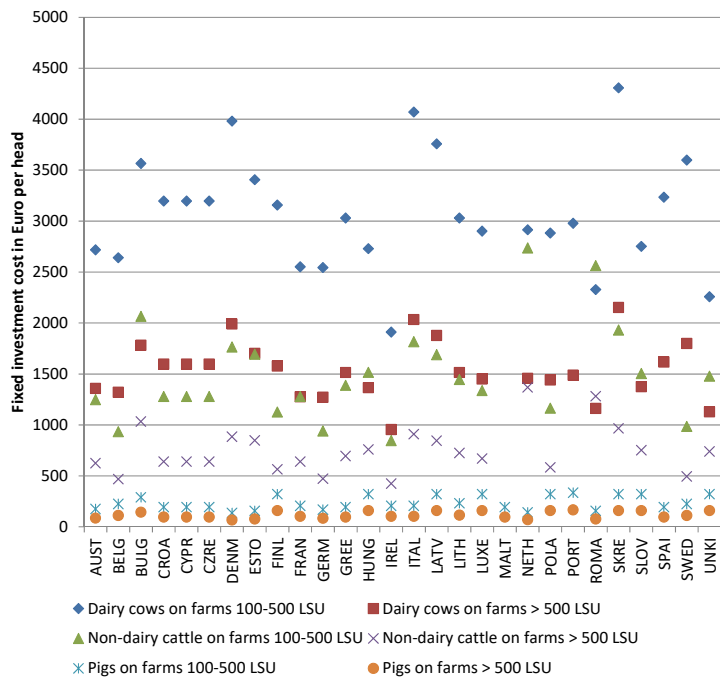


Figure 4: Derived fixed investment cost per animal head.

There are few quantifications of labour costs for the operation of farm AD plants available. There are examples of farmers mentioning high maintenance requirements in particular during the start-up of an AD plant (e.g., Farming Futures, 2010a; Svenska gasföreningen, 2014). When operation and maintenance (O&M) costs are mentioned, these usually reflect the sum of labour costs and the cost of additional organic feedstock, which makes it hard to quantify labour costs separately. Walla (2004) describes two farm AD plants of sizes 100 and 170 kW digesting manure from 140 and 170 LSU dairy cows, respectively. The plants co-digest manure (amount unknown) with 800 and 2300 ton energy crop, respectively, and estimate O&M costs to 34000 and 88000 Euros per year, respectively. USEPA (2014b, 2014c) report O&M costs for two farm AD plants, which only digest manure without adding co-substrate to the process. O&M costs are therefore likely to mainly reflect labour costs. One of the plants has the power of 180 kW and digests manure from 8000 pigs and report annual O&M costs corresponding to 19250 Euros or 2.4 Euros per pig. The other farm is a dairy farm with an AD plant of 215 kW and digesting only manure from 900 dairy cows. The latter reports O&M costs corresponding to 38500 Euros per year, i.e., 43 Euros per dairy cow or 3 Euros/ton manure for cows generating 14 tons/head/year. 3 Euros/ton manure convert to about 0.2 work hours per ton manure if assuming an annual wage of 25000 Euros and 1800 working hours per year. We used the assumption of 0.2 work hours per ton substrate digested in GAINS. The cost of labour per ton substrate is estimated by multiplying 0.2 work hours with the average hourly wage rate for the agricultural sector in each member state (EUROSTAT, 2023; ILO, 2010) and projected with the growth in value added in the agricultural sector as provided by the PRIMES model (E3modelling, 2023).

Measurements of leakage of fugitive methane emissions from farm AD plants suggest leakage rates between 3 and 4 percent of gas produced for well managed installations (Flesch et al., 2011; Groth et al., 2015). Considering that a biodigester enhances the conversion of coal into methane, a leakage rate of a few percent of the total generation of methane should be converted to a higher fraction of the methane generated had the manure not been treated in a digester but been subject to alternative manure management practices. Hristov et al. (2013a) mention removal efficiencies for farm AD plants of about 60 to 70% of methane emissions had the manure been treated in a conventional way. The assumed removal efficiency is in GAINS set to 60 percent of methane released from alternative manure management practices for farms of size 100-500 LSU. The assumed removal efficiency for plants installed on farms with more than 500 LSU is 80 percent as the very large farms are expected to be more efficient in controlling the methane slip throughout the process. Pellerin et al., (2013) estimate a removal efficiency of 88% for farm AD installations treating non-dairy cattle and pig manure in France. It is however not clear from Pellerin et al., (2013) if the 88% removal efficiency refers to the fraction removed of the methane generated in the digester or the methane removed in relation to a manure management system without anaerobic digestion.

Table 17 presents a summary of the assumptions that enter unit cost estimations of farm AD in GAINS.

Table 17: Summary of assumptions entering unit cost estimation for farm anaerobic digestion (AD).

Factors entering unit cost estimation	Unit	Reference scenario assumptions ^a	
		Farms 100-500 LSU (L)	Farms > 500 LSU (XL)
Volatile solids (VS)	% of Total solids (TS) in manure	80%	80%
Total solids	% of manure	15%	15%
Water content of manure	% of manure	85%	85%
Added organic substrate	% of manure	25%	25%
Water content of added organic substrate	% of organic substrate	85%	85%
Total wet substrate (manure+organic substrate)	% of manure	125%	125%
Investment cost -fixed initial investment	Euro per ton wet substrate loaded annually	200	100
Lifetime of investment	years	20	20
Organic substrate price	Euro per ton organic substrate	100	100
Labour hours	work hours per ton wet substrate per year	0.2	0.2
Average wage agricultural sector	Euro per year	Country-specific (ILO, 2010) projected by value added in agricultural sector (PRIMES, 2015)	
Energy generated	kWh per ton wet substrate per year	380	380
whereof electricity supplied at industry electricity price	kWh per ton wet substrate per year	190	190
whereof heat used on farm	kWh per ton wet substrate per year	152	152
whereof heat used in pasteurization process or lost	kWh per ton wet substrate per year	38	38
Electricity price	Euro per kWh	Industry sector by country (PRIMES, 2015)	
Heat price	Euro per kWh	50% of industry electricity price	
Organic fertilizer generated from slurry	Pure nutrients (N-P ₂ O ₅ -K ₂ O) as % of slurry	0.6%	0.6%
Organic fertilizer generated from organic waste	Pure nutrients (N-P ₂ O ₅ -K ₂ O) as % of waste	2.7%	2.7%
Organic fertilizer price	Euro per ton pure nutrients (N-P ₂ O ₅ -K ₂ O)	1000	1000
Emission removal efficiency	Reduction from no control	60%	80%

^aAssumptions presented are without effects of technological development (see Section 2.5.1.)

To identify the extent of the current adoption of farm AD in different member states, we first derive the maximum technically feasible output of energy from farm AD plants by animal category and farm-size in the respective member states on the basis of the assumptions summarized in Table 17. We then derive the total energy output produced in 2015 from manure-based anaerobic digesters in consistency with the farm-based biogas production as estimated by the PRIMES model for the same year. The conversion efficiency to electricity is assumed 0.375 and to heat 0.7 (and 50% of the energy output generated is in the form of electricity and 50% in the form of heat as specified in Table 17). The source of information for farm-based biogas production in historical years in the PRIMES model is Eur'Observer (2020). By relating the total energy output from manure-based anaerobic digestion in 2015 and 2020 (taking the reported values for 2019 as proxy for 2020) to the maximum technically feasible output of energy from manure-based systems, we obtain the percentage of the maximum potential currently exhausted. We exhaust the current potential using the same assumed adoption order for all member states, i.e., starting adoption on pig farms greater than 500 LSU. Once the potential in this category is exhausted, we move on to dairy farms greater than 500 LSU, then non-dairy cattle farms greater than 500 LSU, then pig farms 100 to 500 LSU, then dairy farms 100 to 500 LSU, and finally non-dairy cattle farms 100 to 500 LSU. The control strategy for 2020 was developed in consistency with actual application (Eur'Observer, 2020). The development in implied emission factors for manure management reported by member states to the UNFCCC (2022) for the years 2005, 2010, 2015 and 2020 was used as an indicator of the development in the uptake of farm AD technology between 2005 and 2020. For future years, the control strategy was developed so as to be consistent with the growth in farm-based biogas production projected by the PRIMES model (E3modelling, 2023).

3.3.2 Rice cultivation

CH₄ emissions from rice cultivation result from anaerobic decomposition of organic material in flooded rice fields. Emissions depend among other factors on the season, soil characteristics, soil texture, use of organic matter and fertilizer, climate, as well as on agricultural practices (IPCC, 2006, Vol.4, p. 5.45). The emission calculation methodology used in GAINS follows the IPCC guidelines (2006, p. 5.49) and adopts IPCC default emission factors for given water management regimes. The IPCC method is based on the annual harvested area with scaling factors for different water regimes. In GAINS, these are translated into three cultivation activities:

- *Continuously flooded cultivation area*: fields have standing water throughout the growing season and only drying out for harvest.
- *Intermittently flooded cultivation area*: fields have at least one aeration period of more than three days during the growing season. Compared with continuously flooded rice fields, IPCC suggests that intermittently flooded rice fields emit 27 to 78 percent of continuously flooded fields, where the range depends on if the fields are rainfed or irrigated. GAINS uses the assumption of 50 percent emissions per hectare from intermittently flooded compared with continuously flooded fields.
- *Upland rice cultivation area*: fields are never flooded for a significant period of time and are not assumed to emit CH₄.

CH₄ emissions from rice cultivation in country i in year t are calculated as follows:

$$E_{it} = \sum_{sm} A_{it} * ef_{i,flood}^{IPCC} * h_i * \beta_s * V_{is} * (1 - remeff_{sm}) * Appl_{itsm}, \quad (27)$$

where A_{it} is the rice cultivation area in country i in year t ,

$ef_{i,flood}^{IPCC}$ is the IPCC default emission factor for CH₄ emissions from flooded rice fields (1.3 kg CH₄ ha⁻¹ day⁻¹),

h_i is the duration of the growing season expressed in days per year (=185 days per year),

β_s is an emission scaling factor for water regime s (=1 for continuously flooded, =0.5 for intermittently flooded, and =0 for upland rice).

V_{is} is the fraction of rice cultivated land under water regime s ,

$remeff_{sm}$ is the removal efficiency of technology m when applied to water regime s , and

$Appl_{itsm}$ is the application rate of technology m when applied to water regime s .

Methane emissions from rice cultivation in Europe are in GAINS accounted for in Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania, and Spain. Activity data for rice cultivation is measured in million hectares of land and is taken from UNFCCC-CRF (2022) with projections based on OECD-FAO (2012) and with information on country-specific application of water regimes taken from UNFCCC-CRF (2022).

CH₄ mitigation options implemented in GAINS to control emissions from rice cultivation include employment of improved water management regimes, use of alternative rice hybrids increasing yields while suppressing methane generation e.g., through shorter stems, and use of soil amendments e.g., biochar or sulphate-containing amendments.

There are several ways to reduce CH₄ emissions through improved water management; single mid-season drawdown, alternative wetting and drying, aerobic rice production and dry direct seeding (WRI, 2014). A common feature of all water management options is that they reduce CH₄ emissions through decreasing the time that fields are flooded. Differences in local conditions e.g., climatic conditions, traditional farming customs and access to herbicides, water regulation mechanisms or fertilizers, will affect the impact of different water management regimes on yield, labour requirements and methane emissions (WRI, 2014). The choice of preferred water management regime is closely linked to these local conditions. Due to lack of information, we are not able to make a full-fledged assessment of the effectiveness of individual water management regimes in different regions of the world, but will have to resort to making broad assumptions about the effectiveness of water management regimes in general and their associated costs. According to a literature survey by WRI (2014), implementing improved water management regimes on continuously flooded fields have shown to achieve CH₄ emission reductions between 30-90%, with the higher relative reductions found for well-managed fields in the US. As a general assumption in GAINS across all flooded rice fields, an average abatement potential of 20% is assumed to be achievable in the next ten years, extending to 40% on an annual basis in 2050. If improved water management is combined with other options e.g., low-CH₄ hybrids or different soil amendments (see below for details), the average global abatement potential assumed in GAINS for continuously flooded fields extends to 50%. This estimate takes into account that some areas may be difficult to subject to improved water

management due to heavy rainfall during the wet season or due to unreliable water supply systems or fields that are not well levelled (WRI, 2014). These assumptions are somewhat conservative in comparison to Beach et al. (2015) who estimate an overall abatement potential for global rice cultivation in 2030 at 26.5% below baseline and Harmsen et al. (2019) who estimate 61% below baseline in 2050 for the same source.

A cost estimate of improved water management through drying out of continuously flooded rice fields will have to consider associated operation costs, including cost-savings from reduced water use and higher labour costs due to increased weed growth. In particular in poorer regions where farmers lack access to herbicides, longer periods of dry fields increase weed growth (WRI, 2014; Barrett et al. 2004; Ferrero and Nguyen 2004). According to estimates by Barrett et al. (2004), weed growth increases labour costs by an estimated 20 percent, which is equivalent to about 60 additional work hours annually per hectare in developing countries (Heytens, 1991) and 12 additional work hours annually per hectare in developed countries, where herbicides are used for controlling weed (Shibayama, 2001). Dry direct seeding of rice seedlings have shown to be very effective (45-90% reductions in emissions) for reducing CH₄ emissions in the US compared with transplanting seedlings into flooded fields (WRI, 2014; Linquist et al., 2015). The abatement effect is attributed to the one month shorter period of flooding as seedlings grow in dried out fields. The option also contributed to reduced labour input and costs, however, this result appears to be conditional on unrestricted access to herbicides and well managed water tables and may therefore be difficult to replicate in many developing countries. According to IRRI (2007), intermittent aeration of continuously flooded rice fields may reduce water use by 16 to 24 percent. Assuming that continuously flooded rice fields need 1000 mm water input per year (Bouman, 2001) and the average cost of irrigated water in Europe is 0.04 Euro per m³ (FAO, 2004), then saving 22 percent of water corresponds to a cost-saving of about 70 Euro per ha.

Certain rice hybrids may affect CH₄ emissions. By careful selection of low-CH₄ producing hybrids, emissions can be ten percent lower (ADB 1998). ADB (1998) estimates that Chinese rice yields may increase by as much as 10 to 20 percent from switching to low-CH₄ hybrids. In other parts of the world, where high yield rice hybrids are already in extensive use, potentials for additional yield increases are likely lower. In GAINS, the assumption is that the potential reduction in CH₄ emissions from switching to alternative rice hybrids is 10 percent with a 3 percent increase in crop yield, when applied as the sole option. When applied in combination with other options, like improved water management of continuously flooded fields, the removal efficiency of this option is set to 5 percent.

Application of sulphate-containing substrates to rice fields reduces CH₄ emissions because CH₄ producing bacteria compete for the same substrate as the sulphate reducing bacteria (van der Gon et al. 2001). Likewise, application of biochar to soils in rice fields improves soil fertility while contributing to reduced CH₄ emissions because carbon is added in a stabilized form, which inhibits the abundance and activity of methanogens (Han et al., 2016). The costs associated with these options are the costs of acquiring the sulphate-containing substrates or biochar and spreading them on the fields. In GAINS, a conservative assumption is that application of these types of CH₄ inhibitors can remove on average 20 percent of CH₄ emissions when applied as a stand-alone option and 5 percent when applied in combination with other options like improved water management.

3.3.3 Open burning of agricultural waste

Open burning of crop residuals on fields and other agricultural waste is forbidden in the European Union and regulated under the Council Regulation EC/1306/2013. Many EU member states do not report emissions from this activity. However, remote sensing data (e.g., from MODIS) consistently shows occurrence of hundreds of fires every year. Interpretation of the remote sensing data is associated with several uncertainties and depending on the instrument used, models and data (e.g., land use cover) applied, the results vary significantly. There are annual variability and multi-year trends. We attempt to represent the latter, although, it is largely indicative since the number of fires is not the only indicator that matters. Data is retrieved from the MODIS instrument as used in a GFED product (van der Werf et al., 2010; 2017) and reflect trends and changes in estimated biomass burned. In addition to the remote sensing information, we also compare estimates to bottom up estimates from Bond et al (2004), EDGAR FastTrack2000 data and information received through direct communication with national experts, who often have access to local data, e.g., on local management practices.

The emission factor used is the IPCC default emission factor for open burning of waste (IPCC, 2006, Vol.5, p.5.20) which corresponds to 6.5 kt CH₄ per Mt waste burned. Any further potential to reduce methane emissions from this source comes from stricter enforcement of the existing ban. The cost of mitigating methane through this option is set to zero, assuming stricter enforcement does not incur additional costs.

3.4 Waste sector

3.4.1 Solid waste

CH₄ from municipal and industrial solid waste is generated when biodegradable matter is digested under anaerobic conditions in landfills or during temporary storage of waste aimed for different types of treatment. CH₄ may also be released during loading or emptying of the reactor when organic waste is treated in anaerobic digesters to produce biogas or during treatment of organic waste in composts. The activity data used in GAINS is the total amount of waste generated before diversion to different types of treatment like recycling, energy recovery or landfill. Amounts of waste generated are first split by municipal or industrial solid waste and then by waste composition for municipal solid waste and by manufacturing industry sub-sector for industrial solid waste.

CH₄ from waste deposited on landfills is formed and released with a time delay of up to several decades. IPCC (2019 Refinement to the 2006, Vol. 5, Ch. 3) recommends the use of a First-order-decay model taking up to fifty years disposal into account. The GAINS model structure does not allow for implementation of a full First-order-decay model. Instead, a simplified structure is used, where the delay between waste disposal and CH₄ release is accounted for as a lag in the activity data of 10 years for fast degrading organic waste like food and garden waste and 20 years for more slowly degrading waste like paper, wood and textile waste. The lags correspond to approximate average half-life values for the respective waste types (IPCC, 2019 Refinement to the 2006 guidelines, Vol.5, Tables 3.3 and 3.4).

CH₄ emissions from municipal (or industrial) solid waste in country i in year t are estimated as the sum of emissions from a certain waste type s (or industry sector) summed over emissions from waste diverted to waste treatment option m :

$$E_{it} = \sum_s \sum_m A_{i,(t-y_s);s} * ef_s * (1 - remeff_{sm}) * Appl_{it sm} \quad (28)$$

where $A_{i,(t-y_s);s}$ is amount of waste type (or industry sector) s generated in year $t-y_s$, where y_s is the average lag in CH₄ release assumed for waste type (or industry sector) s ,

$remeff_{sm}$ is the removal efficiency of waste treatment option m , and

$Appl_{it sm}$ is the application of waste treatment option m to waste type (or industry sector) s in country i in year t , and

ef_s is the IPCC default emission factor for waste type (or industry sector) s deposited in a landfill without recovery of landfill gas.

From IPCC (1997, Vol.3, Ch.6, Equation 1) the following expression for the waste type specific emission factor ef_s is obtained:

$$ef_s = DOCm_s * DOCf * MCF * F * \frac{16}{12} * (1 - OX) \quad (29)$$

Where

$DOCm_s$ is the fraction of Decomposable Organic Carbon (DOC) in waste type/sector s ,

$DOCf$ is the fraction of DOC that can decompose (default used is 0.5),

MCF_i is the Methane Correction Factor correcting for aerobic decomposition and vary with the management standard of the landfills,

F is the fraction of CH₄ in generated landfill gas (default used is 0.5),

$16/12$ is the molecular weight ratio CH₄/C,

OX is the oxidation factor correcting for increased oxidation from covering of landfills (default used is 0.1).

IPCC (2006, Vol.5, Tables 2.4 and 2.5) default factors are used for the content of decomposable organic carbon ($DOCm$) in different types of biodegradable waste as well as for the Methane Correction Factor (MCF) applied to different management standards of landfills.

It can be expected that waste generation is positively related to income (World Bank, 2012) and that relative changes in income have a relatively larger effect on waste generation in high income groups than in low income groups. We used country-level data to estimate waste generation elasticities for different average income intervals using annual data on income and historical MSW generation amounts and composition taken from EUROSTAT (2019) for 31 countries (EU-27, Iceland, Norway, United Kingdom and Switzerland) and spanning the time period 1995-2017. To estimate elasticities, the relationship between the relative impact of GDP

per capita and urbanization rate (UNstat, 2019) on the per capita MSW generation was formulated as a log-linear function:

$$\log(MSWcap_{it}) = \alpha + \beta_1 * \log(GDPcap_{it}) + \beta_2 * \log(urbrate_{it}) + \varepsilon_{it}, \quad (30)$$

where

$MSWcap$ is kg MSW per capita per year,

$GDPcap$ is the average annual Gross Domestic Product in Euro per capita,

$urbrate$ is the fraction of the total population living in urban areas,

$\varepsilon_{it}=u_i+v_{it}$ is an error term which is separated into an individual effects term and a residual omitted variables term, and

$\varepsilon_{it} \sim IID(0, \sigma_\varepsilon^2)$ is an error term which is independent and identically distributed, and

β_1 and β_2 are estimated elasticities for income and urbanization rate, respectively.

The MSW waste composition categories considered are Food and garden, Paper, Textile, Wood, Plastics, Glass, Metal, and Other.

Elasticity estimates were generated separately for three different levels of average GDP per capita; < 20000 Euro, 20000 to 40000 Euro, and above 40000 Euro. The results of the elasticity estimates are presented in Table 18. Projections of future generation of total MSW, as well as generation of waste in the period prior to 1995, are estimated applying the elasticities presented in Table 18. When projecting the development in the composition of the MSW, priority was first given to drive generation of food waste using an elasticity estimated only for MSW food waste generation. Thereafter, non-food waste categories were attributed proportionally to the 2010 attribution until constrained by the estimated total MSW generated. This approach take consideration of the inferiority nature of food in relation to other goods, i.e., as income increases we are likely to increase our consumption of food relatively less than we increase consumption of non-food goods.

Table 18: Elasticity estimates for drivers of Municipal Solid Waste (MSW) generation.

Dependent Variable	Unit	Income Group	Number of Observations	Explanatory variable	OLS	Fixed Effect	Random Effect	LM test	Hausman test
Municipal solid waste -total	Mt per capita	< 20000	203	Constant	-0.001 (-1.00)	n.a	-0.01 (-0.80)	1.41	9.9
				GDP per capita	0.14 (3.20)***	0.21 (4.75)***	0.16***		
				Urbanization rate	0.14 (0.36)	-0.76 (-1.69)~	0.004 (3.66)		
				R-square	0.07	0.06	n.a		
		>=20000 - <40000	221	Constant	0.0001 (0.20)	n.a	-0.002 (-0.22)	2.81	1.25
				GDP per capita	0.33 (7.62)***	0.29(4.48)***	0.33*** (6.79)		
				Urbanization rate					
				R-square	0.2	0.009	n.a		
		>=40000	235	Constant	-0.002 (-0.52)	n.a	-0.005 (-0.77)	0.17	6.68
				GDP per capita	0.58 (7.61)***	0.67(8.07)***	0.61 (7.74)***		
				Urbanization rate	-0.85 (-3.91)***	-0.95(-4.24)***	-0.89 (-4.05)***		
				R-square	0.11	0.18	n.a		
MSW Food waste	Mt per capita	All income groups	156	Constant	4.05 (9.32)***	n.a	2.78 (4.29)***	40.54	9.78
				GDP per capita	0.05 (1.33)	0.428 (4.22)***	0.18 (2.85)**		
				R-square	0.01	0.12	n.a		
Food, beverages and tobacco industry waste	Mt	All income groups	70	Constant	0.77 (0.90)	n.a	0.78 (0.72)	18.7	0.01
				Value added	0.83 (7.73)***	0.83 (3.27)**	0.81 (5.82)***		
				R-square	0.47	0.71	n.a		
Pulp and paper industry waste	Mt	All income groups	70	Constant	-0.12 (0.20)	n.a	-1.35 (1.72)	54.4	0.24
				Value added	0.85 (9.85)***	1.07 (7.84)***	1.03 (9.56)***		
				R-square	0.59	0.95	n.a		
Textile, leather and footwear industry waste	Mt	All income groups	71	Constant	-1.38 (1.99)	n.a	-0.53 (0.48)	67.8	6.4
				Value added	0.88 (9.26)***	-0.32 (0.72)	0.74 (4.74)***		
				R-square	0.55	0.89	n.a		
Wood and wood products industry waste	Mt	All income groups	71	Constant	3.12 (4.79)***	n.a	3.64 (2.66)**	173.3	0.78
				Value added	0.47 (4.44)***	0.23 (1.39)	0.33 (4.58)***		
				R-square	0.22	0.83	n.a		

Detailed information on historical uptake of waste treatment measures in 1990, 1995, 2000, 2005, 2010, 2015 and 2020 were collected from National reporting to the UNFCCC (submissions from April 2022) and EUROSTAT (2022 and 2023). From the Common Reporting Format (CRF) tables, we take information on amounts of waste allocated to various types of landfills, composting and anaerobic digestion in biogas facilities as well as the Methane Correction Factor (MCF) for the different types of landfills used. From EUROSTAT (2022 and 2023) we take data on overall recycling rates and specific recycling rates for paper waste and other waste materials. In consistency with the reported treatment information and emission factors derived for each waste category and treatment stream applying default IPCC (2006, 2019) methodology, the emission generation potential of waste is determined for every 5 years. The simplified version of the IPCC First-Order-Decay method explained above is then used to shift the timing of the release of emissions 10 or 20 years into the future, depending on if the waste is fast-decaying (food and garden waste) or medium-to-slow decaying (paper, wood, textile, other). Composting and anaerobic digestion are assumed to give rise to limited CH₄ emissions, while no CH₄ emissions are assumed from recycling of paper, wood or textile waste. Accounting for the decay time of waste in landfills means that to come up with emission estimates from 1990 onwards, we must also estimate the generation and treatment attribution of MSW for the period 1970 to 1990. For this purpose, an extrapolation was made which assumes that in year 1970 all MSW is landfilled except a small fraction that is scattered or openly burned (fractions as reported for 1990 kept constant in years 1970 to 1990). Between 1970 and 1990, a linear transition to the 1990 treatment attribution is assumed.

Projections for future waste treatment streams start from the treatment structure identified for year 2020 and assumes countries meet the targets of the amended EU Waste Directive from

2018, i.e., maximum 10% of total MSW being landfilled in 2035, with a five years grace period granted to Bulgaria, Croatia, Cyprus, Greece, Hungary, Latvia, Romania, Slovakia and Iceland. These countries must meet a target of maximum 25% MSW landfilled in 2035. A linear phase-in of the targets is assumed for the period 2020 to 2035. The targets are met by moving increasing amounts of MSW away from landfill disposal and towards other treatment options (recycling, anaerobic digestion, incineration with energy recovery) following the principles of the EU waste hierarchy.

Figure 5 illustrates resulting EU-27 and EU-27+UK estimates of CH₄ emissions from solid waste disposal using the consistent methodology of GAINS and as reported by countries in the CRF tables to the UNFCCC (submissions as of April 2022 and August 2023). Figure 6 illustrates the same estimates by EU member state and the UK. Note that Figures 5 and 6 illustrate the sum of emissions from MSW and industrial solid waste as only the sum of these emissions are reported in the CRF tables. However, emissions from MSW dominate total solid waste CH₄ emissions.

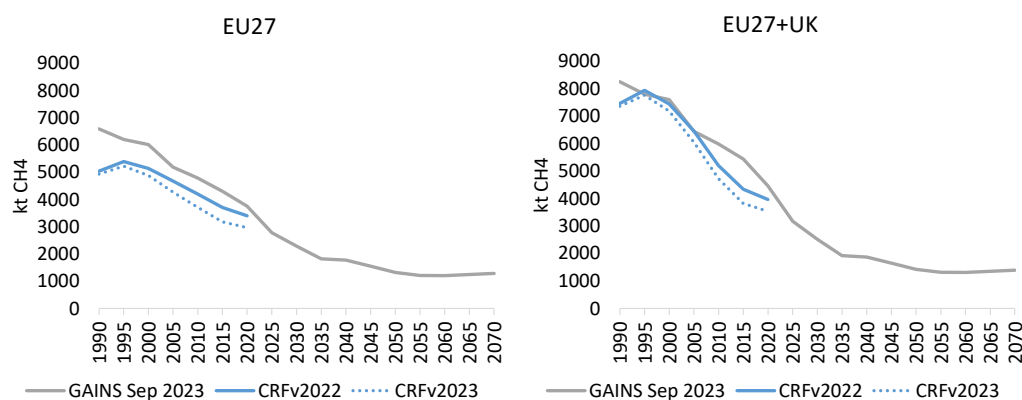


Figure 5: CH₄ emissions from solid waste disposal and treatment as estimated in the GAINS model 2023 and reported in National submissions to the UNFCCC (submissions as of April 2022 and August 2023) for EU-27 and EU27+UK.

As shown in Figure 5, GAINS estimates somewhat higher emissions from solid waste sources for the EU-27 in the period 1990-2020, however, converging towards the reported level in year 2020. Figure 6 shows that GAINS estimates match quite closely the reported emission trend of Austria, Finland, Germany, Netherlands, and Sweden. For a number of countries (Belgium, Estonia, Ireland, Lithuania, Poland (in CRF 2023), Portugal, Slovenia, and Spain), the reported emissions fall more rapidly in the period 2010-2020 than in GAINS. For these countries, the GAINS estimate often converges to the 2020 national estimate with a delay of five to ten years. Hence, this may be an effect of these countries being more optimistic than GAINS about how fast landfilled waste decay and accordingly how fast an effect will be seen on emissions from the measures undertaken to fulfill the 1999 EU Landfill Directive targets (-65% of organic waste landfilled between 1995-2020).

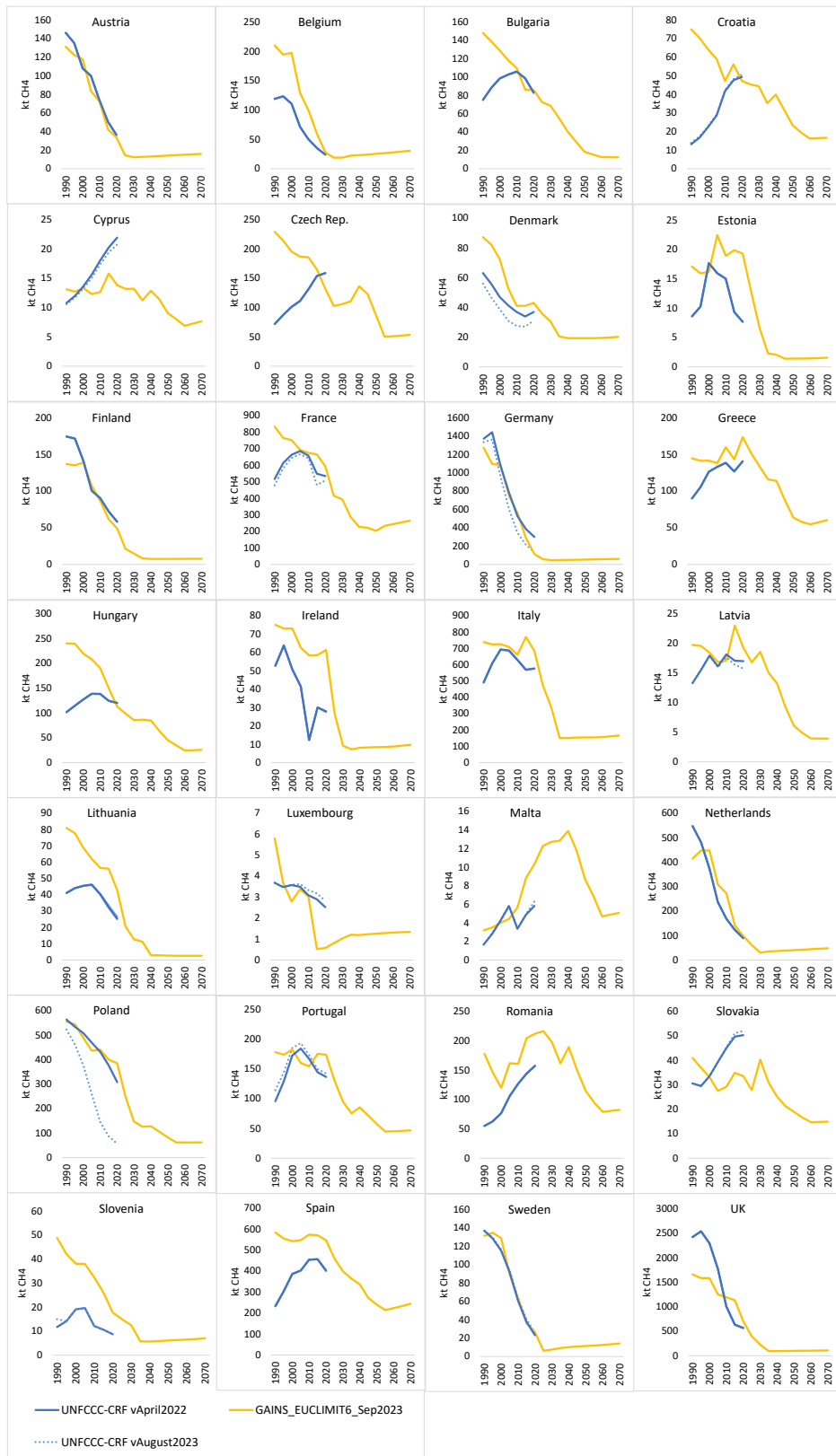


Figure 6: CH₄ emissions from solid waste disposal and treatment as estimated in the GAINS model September 2023 and in comparison to emissions reported in the National submissions to the UNFCCC CRF tables, versions submitted as of April 2022 and August 2023.

In GAINS, the maximum feasible reduction of CH₄ emissions in the waste sector is modelled as an “optimal” waste treatment path as defined by the EU waste hierarchy. Source separation of waste for recycling or energy recovery purposes is preferred to landfill disposal with gas recovery. In the optimal case, all biodegradable waste is source separated from the waste stream and none is disposed of to landfills. Some EU member states (Austria, Belgium, Denmark, Germany, Netherlands and Sweden) are close to this optimum and have already implemented a complete ban on landfilling of untreated biodegradable waste.

Costs for waste treatment options are derived as the opportunity cost of switching from managed landfills to higher-order treatment options. Assumptions on cost parameters used to derive the unit cost for the treatment of different types of waste are presented in Table 19. The costs considered include the upfront capital investment cost, the non-labour operations and maintenance costs, labor-related operational costs as well as opportunity costs for households spending time source-separating waste,

Table 19: GAINS model assumptions for the opportunity costs of switching from managed landfills to higher-order waste treatment in the EU27.

Type of waste	Treatment option	Fixed investment cost	Lifetime of fixed investment	Operation and maintenance cost	Cost-saving from forgone landfill and sales/use of recycled material	Source separation labour (for households)		Electricity recovery	Biogas recovery
		Euro/t waste	years	Euro/t waste	Euro/t waste	Fraction of 1800 annual labor hours per ton waste	Corresponding minutes per ton waste	kWh/t waste	GJ/t waste
Food & garden	Anaerobic digestion with biogas recovery	471	15	42.9	22.4	0.002083	225	0	4
	Large-scale composting	215	15	24.1	22.4	0.002083	225	0	0
	Household composting	637	5	0	57.3	0.002894	314	0	0
	Incineration of mixed waste with energy recovery	748	20	26.7	22.4	0	0	2083	0
Paper	Recycling	0	0	208.2	134.4	0.001822	199	0	0
	Incineration of mixed waste with energy recovery	748	20	26.7	22.4	0	0	5700	0
Textile	Incineration of mixed waste with energy recovery	748	20	26.7	22.4	0	0	4105	0
Wood	Recycling (for chipboards)	842	15	219.0	457.7	0.002894	314	0	0
	Incineration of mixed waste with energy recovery	748	20	26.7	22.4	0	0	5900	0
Other (mixed)	Incineration of mixed waste with energy recovery	748	20	26.7	22.4	0	0	351	0

Sources: Table based on information from Arcadis (2009), Van Leeuwen (2020), AEAT (2001), Persson (2003), IPPC (2006), Wilson (2003).

3.4.2 Wastewater

Wastewater treatment plants serve to decompose compounds containing nitrogen and phosphorus as well as carbon from the wastewater before discharge. Main gaseous products are CO₂ and molecular nitrogen, but during the process also CH₄ is released. CH₄ is formed whenever wastewater with high organic content is handled under anaerobic conditions.

In the GAINS model, wastewater from households and industry are accounted for separately. The activity data used for estimation of emissions from domestic wastewater is number of people connected to centralized or decentralized collection of wastewater. This basically refers to wastewater from urban and rural population, except for most industrialized countries where

wastewater collection services often include some rural areas as well. Country-specific data on fractions of wastewater collected centrally is taken from UNFCCC (2022 submission), EUROSTAT (2022) and OECD (2022).

Uncontrolled emissions are defined as emissions when wastewater is emitted directly to a water body without prior collection and treatment. As anaerobic conditions are formed when large quantities of wastewater are collected and stored, CH₄ formation in the uncontrolled case are likely to be limited and to increase for any form of organized wastewater collection. Collection is however a prerequisite for treatment, which is important for combating water pollution from excessive nitrogen and phosphor. Uncontrolled CH₄ emission factors are derived following the IPCC guidelines (2006, Vol.5, Equations 6.1 to 6.3):

$$E_{it} = \sum_s A_{it} * h_s * ef_i * (1 - remeff_m) * Appl_{itm} \quad (31)$$

where A_{it} is total population in country i and year t ,
 h_s is fraction of total population connected to treatment system s (centralized or decentralized treatment)
 $remeff_m$ is the removal efficiency of technology m ,
 $Appl_{itm}$ is the application of technology m in country i and year t , and

The methanogenic process in the treatment of wastewater is sensitive to daily/seasonal temperature variations as temperature affects the microbiological community and the degradation rate of organic matter (Dhaked, Singh and Singh, 2010). Temperature is therefore a relevant factor for the formation of methane during treatment of domestic wastewater, where the lower the temperature, the lower the methane formation (Luostarinen et al. 2007). In GAINS a country-specific temperature correction factor was included when deriving emission factors for domestic wastewater, i.e.,

$$ef_i = BOD_i * B_0 * MCF_0 * TCF_i \quad (32)$$

where BOD_i is amount of biochemical oxygen demand per person in country i ,
 B_0 is maximum CH₄ producing capacity,
 MCF_0 is the methane correction factor, i.e. the fraction of BOD converted to CH₄, and
 TCF_i is the temperature correction factor in country i .

The temperature correction factor is derived by weighing the rate of methanogenesis at different temperature intervals with the number of days per year in respective temperature interval, i.e.,

$$TCF_i = \frac{\sum_{j=1}^4 \alpha_j D_{ij}}{365}, \quad (33)$$

where α_j are the rates of methanogenesis (0, 0.1, 0.6, and 0.9) at the four respective temperature intervals $\leq 5^\circ\text{C}$, 5 to 15°C , 15 to 30°C and $> 30^\circ\text{C}$, and
 D_{ij} are the average number of days (over years 2000, 2005 and 2010) when the maximum temperature in a country falls within the respective temperature intervals.

Data on the rates of methanogenesis at different temperature intervals is adopted from Lettinga, Rebac, and Zeeman (2001), while daily data of the maximum temperature for years 2000, 2005 and 2010 at 25km resolution was taken from the Agri4 Cast Data Portal (Biavetti, et al., 2014).

Country-specific values for the biochemical oxygen demand per person (BOD) are used when available from UNFCCC-CRF (2022). When unavailable, an IPCC (2019 Refinement of the 2006 guidelines, Vol.5, Table 6.4) default factor for the EU of 31.0 kt CH₄/million people is used for the maximum CH₄ producing capacity (B_0). Methane correction factors (MCF_0) of 0.1 for uncontrolled decentralized collection and 1 for uncontrolled centralized collection apply.

Industry sectors identified by IPCC (2019 Refinement to the 2006 guidelines, Vol.5, p.6.19) as potential sources for CH₄ emissions from wastewater are food, pulp- and paper industry and other manufacturing industries generating wastewater with an organic content, i.e., textile, leather, organic chemicals etc.

The activity data for estimating methane emissions from industrial wastewater is the amount of COD present in untreated industrial wastewater. These amounts are derived from production volumes combined with COD generation factors as specified in Table 20. Production volumes in ton product are taken from FAOSTAT (2015). Growth in value added by industry is used as driver for future projections.

For pulp- and paper industry, wastewater and COD generation rates reported in literature differ considerably between processes and between developed and developing countries. By comparing reported values from different sources, process specific generation rates are derived as presented in Table 20. For the EU countries, default rates derived for developed countries apply. It should be noted that when using process specific generation rates, the estimated amounts of COD and CH₄ generated from this industry come out several times lower than if using the IPCC default factor (2006, Vol.5, Table 6.9) for some food industries and pulp- and paper industry.

$$E_{it} = \sum_{sm} A_{its} * COD_i * ef_i * (1 - remeff_m) * Appl_{itm} \quad (30)$$

where A_{its} is the amount of product A produced in country i in year t ,
 COD_i is the chemical oxygen demand in untreated wastewater generated per tonne product produced in country i ,
 $remeff_m$ is the removal efficiency of technology m ,
 $Appl_{itm}$ is the application of technology m in country i and year t , and where

$$ef_i = B_0^{COD} * MCF_0, \quad (35)$$

where B_0^{COD} is maximum CH₄ producing capacity,
 MCF_0 is the methane correction factor, i.e., the fraction of CH₄ generated which is not oxidized but released as CH₄.

Values for the maximum methane production capacity (B_0^{COD}) of wastewater from different industrial sectors are based on a literature review presented in Table 20. Weighted averages of the values for each process/product for the year 2010 were used to calculate the methane production capacity by sector and country. An IPCC (2019 Refinement to the 2006 guidelines, Vol.5, Table 6.2) default factor of 0.25 kt CH₄/kt COD is applied for the maximum CH₄

producing capacity (B_0^{COD}) when no value was available from literature. A methane correction factor (MCF_0) of 0.5 is applied for the uncontrolled case.

There are no wastewater options available that primarily target CH_4 emissions. There are, however, several different ways of treating wastewater, which have different implications for CH_4 emissions (Pohkrel and Viraraghavan, 2004 and Thompson et al., 2001). When domestic wastewater is centrally collected and emitted to a water body with only mechanical treatment to remove larger solids, plenty of opportunities for anaerobic conditions and CH_4 formation are created. For this type of treatment, the methane correction factor (MCF) used in GAINS is 1. With well managed aerobic or anaerobic treatment, the CH_4 formation is effectively mitigated and CH_4 emissions can be kept on a negligible level. MCF used in GAINS is 0.01 for aerobic treatment and 0.005 for well managed anaerobic treatment. With less well managed systems the occurrence of anaerobic conditions increase as well as CH_4 formation (IPCC 2019 Refinement to the 2006 guidelines, Vol.5, Tables 6.3 and 6.8). Anaerobic treatment has advantages over aerobic treatment like lower costs, smaller volumes of excess sludge produced, and the possibility of recovering useful biogas, which can be upgraded to gas grid quality (Lettinga 1995, Thompson et al. 2001). For industrial wastewater, it is assumed that the most effective way to reduce CH_4 emissions is to apply a two-stage process where the water is treated anaerobically with recovery of the biogas in a first stage, which is then followed by an aerobic treatment in a second stage (Latorre et al., 2007). The assumed MCF for this type of treatment is 0.05. In rural areas, domestic wastewater can be collected and treated in latrines, septic tanks or similar anaerobic treatment (USEPA, 1999).

Current applications of different treatment practices for domestic and industrial wastewater in EU countries are taken from UNFCCC (2022 submission) CRF tables complemented with information from EUROSTAT (2022), OECD (2022) and IPCC (2006, Vol.5, Table 6.5). Investment costs for sewage treatment are taken from EEA (2005) and operation and maintenance costs from Hernandez-Sancho and Sala-Garrido (2008). Rural wastewater treatment costs are from USEPA (1999).

In GAINS, the CH_4 mitigation scenario builds upon the Waterbase – UWWTD: Urban Wastewater Treatment Directive – reported data (EEA, accessed 2022). The dataset contains data reported by Member States under UWWTD Articles 15 and 17 (EEA, 2022). GAINS considers the age distribution and capacity of the wastewater treatment plants currently in operation at a country level when building the Maximum Feasible Reduction (MFR) scenario assuming an average plant lifetime of 30 years (Risch et al., 2015). The MFR assumes full adoption of two-stage anaerobic – aerobic treatment with energy recovery and use. If the technology is adopted at the end of plant lifetime as part of natural capital turnover, then no additional fixed investment costs are accounted for and the additional cost of switching to the MFR technology is limited to the costs for the higher electricity demand of the two-stage process compared to conventional aerobic treatment. Pre-mature implementation of the MFR technology means there will be a sunk cost in the form of the initial fixed investment cost scaled to the length of the remaining plant lifetime. Figure 7 presents the distribution of wastewater treatment types in the EU27 and the assumed phase in of the MFR technology in the future mitigation scenario.

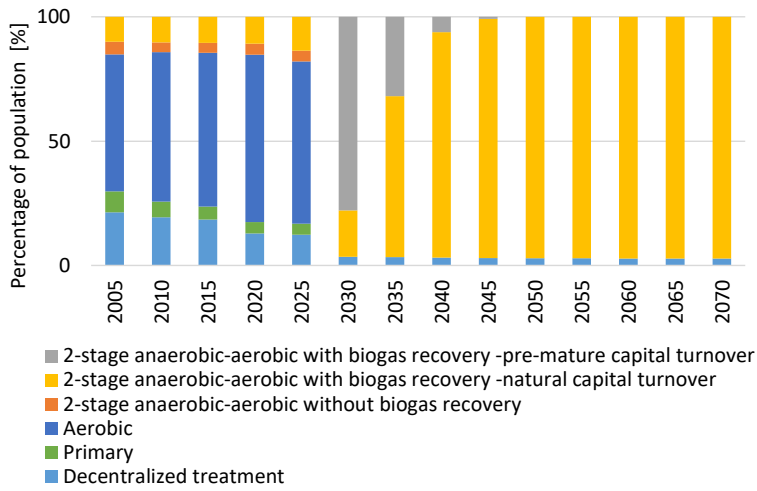


Figure 7: Attribution of EU27 population to different wastewater treatment standards, including the future pathway for moving to the MFR technology (i.e., two-stage anaerobic-aerobic treatment with biogas recovery).

Table 20: Literature review of factors used in calculation of industry wastewater emission factors.

Industry	Product	Wastewater generation in m ³ /ton. (range over different studies)	[COD] in kg/m ³ Untreated wastewater. (range over different studies)	Maximum CH ₄ producing capacity in kg CH ₄ /kgCOD. (range over different studies)	References
Food	Beer	4.95 ^a (1.98 - 7.92)	4 ^a (2-6 /1.2 - 125 UK)	0.23 ^a (0.19-0.27)	Debik and Coskun 2009; Kobya, Senturk, and Bayramoglu 2006; Fountoulakis et al. 2008; Şentürk, İnce, and Onkal Engin 2010; AZBAR et al. 2004; Azbar et al. 2009; Healy, Rodgers, and Mulqueen 2007; Brito et al. 2007; Rodgers, Zhan, and Dolan 2004; Sharda, Sharma, and Kumar 2013; Shivayogimath and Jahagirdar 2015; Maya-Altamira et al. 2008.
	Vegetables oils ^c	0.8 ^a (0.4 - 1.2)	45.5 ^a (5 -804)	0.17 ^a (0.11 -0.24)	
	Wine	2 ^b (0.8-14)	30.4 ^b (3.1-150)	0.18 ^d	
	Sugar Refining	0.69 ^a (0.16-1.0)	6.15 ^a (2.3 -10)	n.a.	
	Meat	13 (IPCC)	5.4 ^b (3 -11)	0.22	
	Dairy Products ^e	3.05 ^{b f} (0.19-10)	8.8 ^b (0.18 -25.6)	0.22 ^b (0.16 -0.27)	
Pulp	Bleached sulphate pulp	70 ^a (30 -110)	1.55 ^a (0.10-3.0)	n.a.	Janssen et al. 2009; Ekstrand et al. 2013; Larsson et al. 2015; Karlsson et al. 2011; Tezel et al. 2001; Chaparro and Pires 2011; Dufresne, Liard, and Blum 2001; N H and others 2012; Thompson et al. 2001.
	Unbleached sulphate pulp	50 ^a (20 -80)	1.43 ^b (1.35 -2.44)	n.a.	
	Bleached sulphite pulp	70 ^a (40-100)	2.10 ^b (0.62 - 8)	0.22 ^b (0.20-0.24)	
	Unbleached sulphite pulp	70 ^a (40-100)	0.80 ^a (0.20 - 1.4)	n.a.	
	Mechanical wood pulp	20 ^a (5-50)	6.9 ^b (2.71 - 10.37)	0.19 ^a (0.12 - 0.27)	
	Semi-Chemical pulp	50 ^a (20-80)	2.19 ^a (0.67 -3.71)	0.19 ^a (0.11-0.27)	
	Recovered pulp ^g	20	3	n.a.	
	Other fibre pulp	20 ^h	8.20 ^a (7.7 -8.7)	n.a.	
Paper	Newsprint	9 ^a (5-15)	3.5	n.a.	
	Printing and writing paper	60 ^b (60-227)	0.81 ^a (0.5-1.11)	n.a.	
	Recovered paper	12 ^a (8 - 16)	0.51 ^a (0.43 -0.58) ⁱ	0.22 ^a (0.16-0.27)	
	Household/sanitary/tissue	8.50 ^a (5-12)	1.02 ^a (0.05-2)	n.a.	
	Wrapping papers ^g	20	0.08	n.a.	
	Paper and paperboard othe	12 ^a (8 - 16)	0.95 ^b (0-11)	n.a.	

- a Average
- b Median
- c Olive oil (primarily centrifugation and pressing production processes), sunflower and cotton seed oil
- d Based only on one study
- e Including milk production, cheese, cheese whey, ice cream and butter
- f Most of the data (11 total) are below 4.0 (8)
- g based on Höglund-Isaksson, 2012
- h 60 m³/ton for UK and 227 m³/ton for Thailand
- i Collected after the clarifier

4 N₂O emission sources

4.1 Overview of N₂O emission sources and mitigation options in GAINS

N₂O emission sources in the GAINS model include anthropogenic emissions from agricultural soils, handling of livestock manure, combustion, chemical industry (adipic and nitric acid production, caprolactam production), direct use of N₂O in hospitals and food industry, composting and wastewater treatment (Winiwarter et al., 2018). Table 21 provides an overview of the included N₂O emission sources with corresponding mitigation options. Following the requirements of the amendment (EC/29/2009) of the EU-ETS Directive, nitrous oxide emissions from production of nitric acid, adipic acid, glyoxal and glyoxylic acid are included in the EU-ETS emission cap and subject to emission permits under the EU-ETS system (see Table 22). Caprolactam production, which is not part of the EU-ETS, is considered separately.

Table 21: Overview of N₂O emission sources and mitigation options in the GAINS model.

Emission source	GAINS sector	Sector description	GAINS mitigation technology	Technology description
Combustion	CON_COMB -DC/ GSL/ LPG/ MD	Other combustion sources: various fuels	none	No mitigation option identified
	CON_COMB -BC1/ BC2/ HC1/ HC2/ HC3	Other combustion sources: brown coal/hard coal	ISFCSN	NO _x abatement option - <i>increases</i> N ₂ O emissions
	CON_COMB -GAS/HF	Other combustion sources: gas/heavy oil	IOGCSN	NO _x abatement option - <i>increases</i> N ₂ O emissions
	CON_COMB2 -BC1/ BC2/ HC1/ HC2/ HC3	Other combustion sources: fluidized bed -brown coal/hard coal	FBC_CM	Combustion modification in fluidized bed combustion
	DOM -BC1/ BC2/ DC/ GAS/ GSL/ HC1/ HC2/ HF/ LPG/ MD/ OS1/ OS2	Domestic -various fuels	none	No mitigation option identified
	IN_BO -DC/ GSL/ HF/ LPG/ MD/ OS1/ OS2	Industry boilers -various fuels	none	No mitigation option identified
	IN_BO -BC1/HC1/HC2	Industry boilers -brown coal/hard coal	ISFCSN	NO _x abatement option - <i>increases</i> N ₂ O emissions
	IN_BO -GAS	Industry boilers -gas	IOGCSN	NO _x abatement option - <i>increases</i> N ₂ O emissions
	IN_BO -BC1/HC1/HC2/ OS1/ OS2	Industry boilers: solid fuels	FBC	Fluidized bed combustion - <i>increases</i> N ₂ O emissions
			FBC_CM	Combustion modification in fluidized bed combustion

Table 21 Cont.: Overview of N₂O emission sources and mitigation options in the GAINS model.

Emission source	GAINS sector	Sector description	GAINS mitigation technology	Technology description
Combustion	IN_OC -DC/ GSL/ HF/ LPG/ MD/ OS1/ OS2	Industry other combustion - various fuels	none	No mitigation option identified
	IN_OC -BC1/HC1	Industry other combustion - brown coal/hard coal	ISFCSN	NO _x abatement option - <i>increases</i> N ₂ O emissions
	IN_OC -GAS	Industry other combustion -gas	IOGCSN	NO _x abatement option - <i>increases</i> N ₂ O emissions
	IN_OC2 -BC1/HC1	Industry other combustion: fluidized bed -brown coal/hard coal	FBC_CM	Combustion modification in fluidized bed combustion
	PP_EX & PP_NEW -DC/ GAS/ GSL/ HF/ MD	Power plants: existing or new - gaseous and liquid fuels	none	No mitigation option identified
	PP_EX & PP_NEW -BC1/ BC2/ HC1/ HC2/ HC3/ OS1/ OS2	Power plants: existing or new - solid fuels	FBC	Fluidized bed combustion - <i>increases</i> N ₂ O emissions
			FBC_CM	Combustion modification in fluidized bed combustion
	PP_IGCC, PP_MOD, PP_ENG	Power plants: Integrated Gasification Combined Cycle; Modern (ultra-, supercritical steam of combined cycle); Internal Combustion Engines	none	No mitigation option identified
	TRA_OT_AGR/ AIR_DOM/ CNS/ INW/ LB/ RAI - GSL/MD	Non-road transport: various modes -gasoline/diesel	EU-I to EU-VI	Switching to higher Euro standards
TRA_RD_HDB/ HDT/ LD4C/ LD4T/ M4 -GSL	Road transport: bus/trucks/cars/vans/two-wheels: gasoline/diesel	EU-I to EU-VI	Switching to higher Euro standards	
Industry	PR_ADIP	Adipic acid production	CR	Catalytic or thermal reduction
			TWIN_RED	Twin reduction technology
	PR_NIAC	Nitric acid production	CR	Catalytic or thermal reduction
			BAT	Best available technology
	PR_CAPR	Caprolactam production	CR	Catalytic or thermal reduction
BAT			Best available technology	
Direct N ₂ O use	N ₂ O_USE	Direct use of N ₂ O as anaesthetic gas in medicin and as unreactive propellant in food industry	REDUCE	Apply N ₂ O in combination with other (liquid) anaesthetics
			REDUCE2	Apply even less N ₂ O in combination with other (liquid) anaesthetics
			REPLACE	Replace N ₂ O with alternative: e.g., Xe
Waste	COMPOST	Composting	none	No mitigation option identified
Wastewater	WW_DOM	Domestic wastewater handling	OPTIM	Process optimization to increase the N ₂ /N ₂ O ratio in effluent gases
Livestock	MANURE-DL/ DS/ OL/ OS/ PL/ PS/ HO/ SH/ LH/ OP	Manure management - solid/liquid systems for various animal categories	none	No mitigation option identified

Table 21 Cont.: Overview of N₂O emission sources and mitigation options in the GAINS model.

Emission source	GAINS sector	Sector description	GAINS mitigation technology	Technology description
Soils	APPLIC - MANURE_N	Application of manure nitrogen on soils	FERT_RED	Set of good practice measures to reduce fertilizer input (note: considered to be covered in fertilizer projections)
			FERTTIME	Adjusting fertilizer application to the periods of agricultural demand (note: option superseded by more efficient and cost-effective options)
			VRT_L, VRT_M, VRT_H	Variable rate technology to minimize fertilizer need (three cost levels)
			INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
			PRECFARM	Optimization of agricultural nitrogen efficiency by "precision farming"
	APPLIC - SOIL_N	Application of mineral fertilizer nitrogen on soils, including crop residues	FERT_RED	Set of good practice measures to reduce fertilizer input (note: considered to be covered in fertilizer projections)
			FERTTIME	Adjusting fertilizer application to the periods of agricultural demand (note: option superseded by more efficient and cost-effective options)
			VRT_L, VRT_M, VRT_H	Variable rate technology to minimize fertilizer need (three cost levels)
			INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
			PRECFARM	Optimization of agricultural nitrogen efficiency by "precision farming"
	APPLIC - RICE_N	Application of mineral fertilizer nitrogen and crop residues on rice fields	FERT_RED	Set of good practice measures to reduce fertilizer input (note: considered to be covered in fertilizer projections)
			FERTTIME	Adjusting fertilizer application to the periods of agricultural demand (note: option superseded by more efficient and cost-effective options)
			VRT_L, VRT_M, VRT_H	Variable rate technology to minimize fertilizer need (three cost levels)
			INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)
			PRECFARM	Optimization of agricultural nitrogen efficiency by "precision farming"
GRAZE - EX_C TTL	Grazing-related emissions from cattle, pigs, poultry excreta	INHIB_L, INHIB_M, INHIB_H	Nitrification inhibitors to reduce emission rates (three cost levels)	
GRAZE - EX_SH	Grazing-related emissions from sheep excreta	none	No mitigation option identified	
HISTOSOLS	Area of organic soils used for agricultural purposes	FALLOW	Abandonment of agricultural use	

Table 22: Current legislation affecting N₂O emissions in EU member states.

Sector	Policy	Regional coverage	Policy description and implementation in GAINS
Agriculture	EU Common Agricultural Policy (CAP) and EU Nitrate Directive (EEC/676/1991) with revisions	EU-wide	Reflected in GAINS through input of CAPRI model data on trends in livestock numbers, milk yield and fertilizer use.
Waste & wastewater	Legislation to replace current composting with anaerobic digestion of food waste	Germany	In GAINS, the current composting of organic waste is phased-out linearly and replaced with anaerobic digestion between 2020 and 2050.
Industry	EU ETS Directive (EC/29/2009): Production of nitric acid, adipic acid, glyoxal and glyoxylic acid.	EU-wide	Industry needs to acquire tradable emission permits under the EU emission trading system (EU-ETS).
Energy	FuelEU Maritime regulation adopted by the EU Council in July 2023. Regulation on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC	EU-wide	CH ₄ and N ₂ O emissions from use of bunker fuels included in GAINS as an ETS (Emissions Trading System) sector.

4.2 Energy sector

4.2.1 Combustion in stationary sources

N₂O is formed as a combustion by-product, similar to the formation of NO_x. Available activity data is energy consumption by sector and fuel, which for the EU countries is provided by the PRIMES model (E3modelling, 2023). Stationary combustion sources include emissions from power plants, industry boilers, other combustion in industry, and residential and commercial sector (see Table 21). Emission factors are specified by sector and type of fuel used and taken from IPCC (2006) and de Soete (1993).

No specific mitigation options have been identified for control of N₂O emissions from stationary combustion sources. However, the use of fluidized bed combustion (FBC) and abatement of NO_x (through selective non-catalytic reduction of flue gas) in power plants and industry boilers increases emission factors for N₂O. This may in some cases lead to increasing emissions over time, even if starting from a very low level. For FBC, emission factors used in GAINS have been adopted following Tsupari et al. (2007) and Rentz et al. (2002).

Fluidized bed combustion (FBC) is a technology that allows for an extended contact of solid fuels with air oxygen, minimizing the need to crush or pulverize fuels, while at the same time hampering particle formation. Also, combustion temperatures are kept below the optimum for formation of NO_x. Lower NO_x emissions are accompanied with strong increases in N₂O emissions. FBC requires advanced methods to properly regulate combustion air flow and fuel intake to achieve a stable fluidized bed. The GAINS database contains expert estimates of the implementation of FBC, including their future development, in combustion of solid fuels in European countries. This data has been specifically addressed at previous country consultations in order to allow for improvement according to national information. Following information from PRIMES (personal communication with Alessia De Vita, 2013) that FBC is not cost efficient for future power plants, its degree of implementation has been set at the 2005 values

for existing power plants and zero for new power plants such that we expect FBC to fade out. In industry, we remain with the GAINS database supplemented with country information.

Methods have been developed and implemented in pilot plants, which allow minimizing N₂O formation connected with the use of FBC, i.e., the GAINS technology “combustion modification in fluidized bed combustion”, see Table 21. Data presented by Winiwarter (2005) indicate that 80 percent of N₂O can be removed (Hendriks et al. 2001). Also cost data was taken from this source. No discrimination has been made for applicability or costs in different countries (considered to be 100 percent).

4.2.2 Combustion in mobile sources

N₂O emissions from mobile sources are known to be affected by NO_x abatement applied to the vehicle exhausts. N₂O emissions are linked to the NO_x abatement technology applied in the form of catalytic converters or SCR-technology applied in diesel vehicles. Activity data for the EU countries is adopted from the PRIMES model (E3modelling, 2023). Emission factors depend on several factors like fuel, technology and operating characteristics. GAINS uses default emission factors from the European transport emission database COPERT4 (EMISIA, 2013 <http://www.emisia.com/copert/General.html>). Emission factors are specified by vehicle category, type of fuel used and the emission control standard of the vehicles (EURO I to EURO VI), while averaging for road types and driving conditions. NO_x abatement may lead to increased N₂O emissions, as were observed in the early generations of catalysts. To reflect this, N₂O emission factors are differentiated by the emission control standard. Apart from this, no N₂O specific mitigation options are identified for mobile combustion sources in GAINS.

4.3 Industry sector

4.3.1 Adipic acid production

The industrial process generating adipic acid (a compound required in the production of Nylon 66 or polyurethane) involves treating the raw material with concentrated nitric acid, at which large quantities of N₂O are released. Typically, for each ton of product 300 kg of N₂O are formed, making the process an important contributor to overall N₂O emissions, although the amount of production is fairly low compared to production of standard chemicals.

Adipic acid production occurs in only a handful of countries, and since only very few production plants are involved (as of 2010, there were 5 plants operational in EU-28), the CRF tables usually list production data as “confidential”, but the exact sites and production capacities are known (Schneider et al., 2010). Therefore, we supplement activity data with capacity and derive future development by country from PRIMES model (E3modelling, 2023) outputs, specifically by scaling according to the value added in chemical industry.

The small number of producers also allows observing general structural changes efficiently. Industry have made voluntary agreements after a cost-efficient method (catalytic reduction) had been developed to take advantage of the high N₂O concentrations in plume to efficiently remove and even convert back into nitric acid (with 95% efficiency). Most plants had been retrofitted by 2000, with the exception of one in Novara, Italy, where this modification started to be fully operative from 2006 only.

As the method in principle is able to reduce 99.9 percent of the emissions, and the remaining emissions are mainly released during operational shutdown of the abatement device, one of the smaller European plants in Krefeld, Germany, recently installed a backup device. This backup device is expected to reduce 80 percent of the remaining emissions (LANXESS, 2008), such that total abatement of 99 percent (95% +80% of 5% remaining) can be achieved, allowing for some system failure still. Costs for the installations have been estimated to be identical to the original system, but the marginal cost of abating the additional 4%-points (considering the much smaller reductions) is of course considerably higher. The option termed “twin reduction technology” is not available in 2015, but with the expected carbon price level of the ETS system (see Section 2.3), we assume full implementation of this option from 2020 onwards.

In this sector, we also cover emissions from Glyoxal/glyoxylic acid production as the underlying chemical process is similar. Glyoxal production employing the nitric acid pathway (thus causing N₂O emissions) is reported from one plant in EU28 only (in France).

4.3.2 Nitric acid production

The oxidation of ammonia to nitric acid is one of the large scale industrial processes. Nitric acid is needed both for the production of fertilizer and of explosives. Nitric acid production occurs in many EU countries, often in several installations, but some countries keep activity data confidential. In such cases, production amounts were inferred using emission results and the default unabated emission factor for the base year. Future production development has been scaled according to the value added in chemical industry, taken from the PRIMES model (E3modelling, 2023) outputs.

As a by-product in the oxidation, nitrous oxide is formed. While the amount lost is by far smaller than with adipic acid production, the level of production makes this an important emission source. In nitric acid production also the concentration of the released gas is considerably smaller, making it more difficult to reclaim. Still, industrial scale production has been proven successful in applying catalytic reduction also to nitric acid production (de Soete 1993; de Beer 2001; Kuiper 2001), leading to emission reductions of 80%. The use of information from a demonstration plant in Linz, Austria, as published in the BREF report (EC, 2007) allows for reasonable estimates of the additional costs incurred. Recent information from the same plant (Muik, 2009) demonstrates that a second level of abatement has been made available allowing to reduce emissions by 94%. As the plant operates under commercially favourable conditions, we assume that this more stringent “best available technology” reduction option is available at no extra costs.

As a consequence of the general introduction of emission reduction technologies across EU, between 2007 and 2012 N₂O emissions from nitric acid production dropped to one quarter (UNFCCC, 2022), presumably at least in part in connection with introduction of the EU emission trading scheme. We use this UNFCCC data to establish, by country, the respective abated emission factor to assess the level of control already established in a historic year. As the marginal cost of using catalytic reduction to control emissions from nitric acid production is estimated at less than the expected carbon price in the ETS market, thus full adoption of the “best available technology” option seems reasonable in all Member States from 2020.

4.3.3 Caprolactam production

The production of caprolactam, which in a similar manner as adipic acid is used to create the polymer Nylon 6, occurs only in five EU countries at a rather limited scale. As with nitric acid production, nitrous oxide is formed as a by-product during the oxidation of ammonia. Information on abatement technology is scarce, also as the contribution to overall emissions are not large. Only with the decline in emissions from nitric acid production, caprolactam becomes the remaining source of industrial N₂O, in some countries arriving at or even exceeding the emissions of nitric acid production.

Due to the similarities in process, GAINS uses the same control technologies, emission reduction efficiencies and costs as for nitric acid production. Caprolactam is dealt with separately as it is not included in the ETS.

4.3.4 Direct use of N₂O

The specific properties of N₂O are taken advantage of in medicine as an anaesthetic gas, in the food industry as an unreactive propellant, and in specific combustion engine applications providing additional oxygen to the combustion process. At least for the first two applications, virtually all of the N₂O used will eventually be emitted to the atmosphere. In both cases, N₂O enters the human body, where it remains only for a short time and is not metabolised. Based on a handful of assessment to support national emission inventories, Winiwarter (2005) extracted an emission factor by population of a country (i.e., GAINS sector N2O_USE).

Methods to reduce application of N₂O have been derived in hospitals, mostly due to concerns about workplace security for hospital personnel. Medical research allows to supplement or even to fully replace the use of N₂O (Spakman et al. 2003; Nakata et al. 1999). While the use of combined anaesthetics to supplement N₂O application can be observed in practice following national sale statistics, data on replacement are highly speculative.

4.4 Waste and wastewater sector

Microbial processes are responsible for conversion of nitrogen compounds contained in waste or wastewater, during which process also N₂O is released. GAINS uses default emission factors derived by IPCC (2006) to quantify these emissions. Specifically, emissions occur during composting and in wastewater treatment. Both emission sources are small sources.

For composting, this default factor refers to the amount of wet waste entering treatment. No differentiation is being made for specific process or type of material. Also, no options are known to mitigate such emissions.

In sewage treatment, the amount of nitrogen added depends on the number of people connected. In consequence, emissions can be estimated by population number on a country scale. GAINS uses a simple emission factor per inhabitant for assessing wastewater related emissions (Behrend et al., 2004). In line with Hendriks et al. (1998), it is assumed that an optimization of process parameters will lead to a decrease of emissions by 40%, without compromising on any of the other operating requirements of the facility, specifically not affecting downstream N content. This measure is assumed to not need any specific investment or operation cost.

4.5 Agriculture sector

4.5.1 Agricultural and grassland soils

Microbial processes in soil convert ammonia into nitrate (nitrification) and further to molecular nitrogen (denitrification). The processes occur in soil under aerobic and anaerobic conditions, respectively, and both release N_2O as a side product. Soil processes are by far the most important source of N_2O .

Despite a considerable amount of on-going research, there are still important gaps in knowledge about N_2O release from soils. Especially, the amount of N_2O formed and converted while still in the soil (during diffusion to the surface) seems difficult to assess, but is needed to obtain the overall release rate in a process based approach. Chamber measurements on top of the soil yield highly variable results. As a consequence, uncertainty associated with the emission figures has been estimated as an order of magnitude, when emissions are related to the input of nitrogen (IPCC 2006). Despite of contributing only a minor fraction to overall greenhouse gas emissions, soil N_2O emissions are typically responsible for the major part of uncertainty in a national greenhouse gas inventory (Winiwarter and Rypdal, 2001; Winiwarter and Muik, 2010). Lately there has been some evidence that, averaged over long time periods and large areas, inventories using IPCC methodology provide a very useful tool to understand the real world emissions. On a global scale, Mosier et al. (1998) proved that emissions are in agreement with observed trends of N_2O accumulation in the atmosphere. Using inverse modelling, Bergamaschi et al. (2015) demonstrated in general reasonable agreement between observations on tall towers in Europe, and European inventories. Moreover, assessments of global N_2O developments based on more generic parameters (freshly created reactive nitrogen, or total mineral fertilizers and total manure only) note that the IPCC total “is not inconsistent with the total derived by the top-down methodology” developed therein (Crutzen et al., 2008; Davidson, 2009).

Nitrous oxide emissions are typically assessed as a fraction of the nitrogen deposited on soils. Nitrogen input in GAINS is derived from nitrogen contained in mineral fertilizer, animal manure and crop residue left on the field. Information on mineral fertilizer use and projections till 2070 derive from results of the CAPRI (EuroCare, 2023) model, which also provides numbers of animals on farms. Assessing the amount of animal manure also requires nitrogen excretion rates, data that are available in the national reports (UNFCCC, 2019) and have been integrated in the GAINS model with the help of national experts during consultations. The amount of crop residues and their nitrogen content is again taken from national reports (UNFCCC, 2022), with no temporal trend assumed.

As from 2015, countries change reporting methodology in their national greenhouse gas inventory. With completion of the Kyoto period, using the IPCC (2006) guidelines has become mandatory. One major difference for agricultural N_2O emissions is a different treatment of indirect emissions due to nitrate leaching. Nevison (2002) discovered and described in detail these issues that lead to a reevaluation of the situation by IPCC (2006), which under default conditions decreases indirect emissions due to leaching by a factor of more than 3, such that overall soil-related N_2O emissions (direct & indirect) are reduced by about a third.

Consequently, also the algorithm for assessing soil N₂O emissions in GAINS has been updated. As previously, there is no differentiation between direct and indirect emissions. Instead, IPCC default data has been used to assess the level of indirectly produced N₂O (as a result of atmospheric redeposition of ammonia, or nitrate leaching) and aggregated into an overall emission factor. IPCC (2006) reports distinctively different emissions from grazing (of which sheep have distinctively lower emissions than cattle) and from direct application of fertilizers (mineral fertilizers, animal manure and crop residue nitrogen have largely similar impacts) to soils. Wetland rice production is associated with a lower emission factor. Avoiding a category split not supported by data, the following activity clusters having the same emission factor were created in GAINS: grazing (all animals except sheep), sheep grazing and manure application, mineral fertilizer and crop residues application on soil and grassland, and fertilizer application on wetland rice (see Table 23).

Table 23: Emission factors of N₂O from soils as used in GAINS. Default release rate (given in % of N applied), shares of re-emissions and leaching were taken from IPCC (2006), the conversion to total N₂O emitted uses a stoichiometry factor of 1.57

IPCC 2006	manure / grazing (sheep)	grazing (all other animals)	urea	other mineral fertilizer	crop residues	flooded rice
direct soil emissions [%]	1.000	2.000	1.000	1.000	1.000	0.300
indirect / atmos deposition [%]	0.200	0.200	0.150	0.030	0.000	0.150
indirect leaching [%]	0.225	0.225	0.225	0.225	0.225	0.225
Total N ₂ O-N [%]	1.425	2.425	1.375	1.255	1.225	0.675
Total N ₂ O [kg N ₂ O/kg N applied]	0.022	0.038	0.022	0.020	0.019	0.011
GAINS emission factors [kg N ₂ O/kg N applied]						
	0.022	0.038		0.020		0.011

Technological options to reduce N₂O emissions may target either on the nitrogen input, or on the release rate of N₂O. Following the tier 1 level of the IPCC (2006) methodology, reducing nitrogen input (increasing NUE) is the only applicable way to get emission reductions accepted, thus the majority of measures available in the literature focusses on reduced inputs. Increased NUE's have been observed in Europe (OECD, 2008), in part as a consequence of fertilizer savings also triggered by environmental considerations. Further such changes are implemented in the CAPRI (EuroCare, 2023) fertilizer projections, improvements deemed technologically possible may in part be factored in already as part of the projections. Using CAPRI's Nitrogen budgets, it is evident that an improvement of NUE takes place over the projected period. Measures implicitly assumed by CAPRI in part reflect reduction technologies and are therefore accounted for when assessing additional potentials for N-input reductions in future abatement in the GAINS model.

Thus, with the update of the algorithm to assess soil N₂O emissions, GAINS also updates abatement technologies. Based on a thorough review of available scientific literature (Winiwarter and Sajeev, 2015), emission reductions have been reassessed and technologies available in agriculture have been updated. The resulting reduction efficiencies are described in detail below. Using further literature with a specific focus on the European situation (e.g., Tavella et al., 2010, from the "FutureFarm" research project), cost information has been further refined. Cost data are now split into investments, operation costs and (financial) benefits derived from implementing a given technology.

As with emissions generally, there are two directions abatement could take: controlling emissions, or reducing activities. In the case of N₂O from soil, lowering fertilization rate (i.e., reducing input activities) is clearly a chance to also reduce emissions wherever the nitrogen use efficiency is low. Obviously such measures would not change the amount of manure or crop residues available to deliver nutrients, but if used more effectively such organic nutrients would be able to further reduce mineral fertilizer application. Further technology options exist to reduce emissions while maintaining fertilizer levels. While combination of both types of technologies is conceivable, evidence seems not to suffice for inclusion in GAINS.

The concept of abatement technology used here basically follows the concept developed by Gale and Freund (2002) and updated for use in GAINS according to Winiwarter (2005). It describes, for the same set of “activity”, N application on agricultural soils, subsequent abatement stages of increasing stringency and at the same time increased costs. In addition to the original approach, now also improvements in nitrogen use efficiency are considered, and the cost-dependence (“economy of scale”) of the size of farms has been investigated. In this new structure, the three technologies effectively considered are: “variable rate” application of fertilizers, agrochemical “inhibitors” (limiting the microbial processes that release N₂O) and “precision farming” (as a high-tech tool to minimize and optimize agricultural production).

The simplest and cheapest form of reducing excess fertilizer application is to reduce its wastage. “Fertilizer reduction” subsumes a set of good practice approaches to avoid fertilizer losses to ditches and to set-asides, or excess application by inappropriate or misadjusted spreaders. Following previous studies, Winiwarter (2005) assumed 6% of fertilizer could be saved this way.

As GAINS obtains external information on future fertilizer application, specifically using the results of the CAPRI model (EuroCare, 2023; Britz and Witzke, 2014), it is important to provide consistent assumptions. CAPRI internally estimates fertilizer demand in part from plant requirements, and it also projects agronomic improvements based on past trends. On an EU average, the modelled improvement between 2005 and 2030 amounts to 6.6%, which comes close to the 6% reduction expected from the simple measures to reduce fertilizer application. We thus conclude that improvements expected by CAPRI largely refer to measures defined as simple improvements, and “fertilizer reduction” should therefore be assumed to be already fully implemented without costs in the baseline scenario by 2030. No emission reductions will result as implicitly the reduced fertilizer consumption rates will cover these reductions.

Choosing agronomic practice and developing economically viable strategies for farms will often also depend on the farm size. This is also the case for emission abatement. In the case of air pollutants (ammonia, specifically), an elaborate scheme has been worked out to assess abatement costs on the basis of animal numbers per farm averaged by country (Klimont and Winiwarter, 2015). The same “economy of scale” principle also applies to agronomy, but in

contrast to animal husbandry it is the farm area that will determine the scale of activities. Especially for one-time costs that can be distributed over a large area on large economic units, such as investments or one-time training costs, cost advantages may occur for larger units. Smaller units, however, do also have opportunities to take advantage of expensive technology etc., which they can more easily share as needed only for a short time period to cover the smaller area. Traditionally this has been organized in machinery rings or by using the service of a contractor.

We use here farm sizes as collected by EUROSTAT in their agricultural data on farm structure, specifically those for arable crops (Table ef_alarableaa, available at <http://ec.europa.eu/eurostat/data/database>). For each EU member country, the shares of arable area in a given size class of utilized agricultural area (>150 ha, 30-150 ha, and <30 ha) have been extracted and used for further differentiation. We apply these shares also to grassland and permanent crops as arable land constitutes the largest share of fertilized agricultural area in almost all countries, and we understand that the farm size structure of a country is well represented. An alternative EUROSTAT table (ef_oluaareg) only provides differentiation up to 100 ha utilized agricultural area per farm and was therefore not selected. In contrast to the methods adopted to describe increasing animal numbers per farm (see section 3.3), the agricultural area of 2010 has been used throughout to depict farm sizes, even if data from different years indicate a consistent trend towards increased size could be derived here, too.

Precision agriculture provides nutrients to plants only to the extent they need it. At high prices of agricultural commodities and technical progress, there is a long-standing discussion (see e.g. Auernhammer, 2001) whether saving fertilizer at a certain point would not compensate any expenditure for technology, such that precision agriculture might become profitable. Looking into the lower-cost options of precision agriculture, here we consider the use of sensors and yield maps to estimate the fertilizer requirements on the scale of square meters, combined with applicators that individually regulate the dose spread according to the locally optimized needs (Variable rate technology, VRT). Winiwarter and Sajeev (2015) compile the results of ten individual studies and reviews which, using sensor technology, on the average allow to reduce nutrient inputs by 24% to arrive at comparable yields. In a situation of 2030, assuming general efficiency improvements having taken place (6%, see above), implementation of such a technology still would decrease application rates by 19%. It is interesting to note that some authors (Sehy et al., 2003) observed N₂O emission reductions clearly higher than the fertilizer application decrease (34% at 18% less fertilizer) which could be explained by less excess nitrogen available – but has not been used here. Instead, emissions remain to be considered proportional to N fertilizer application.

Very little information is available on costs, even while the technology actually exists and is on the market. Cost assessment, in some cases, referred also to different farm sizes, or at least was provided for a given farm size. Operation costs and investment for sensor and spreaders have been made available from U.S. studies (ICF, 2013; Koch et al., 2004). In order to apply instrumentation for a European situation, here we decided to apply the cost estimates of the “FutureFarm” project (Tavella et al., 2010), who (for a 500 ha farm) require one set of sensor & spreader. Moreover, in order to maintain consistency with the emission reductions derived

from our literature survey from the sensor system, we include also costs of an “auto guidance” system. This systems provides detailed information on the location of agricultural machinery and allows, by precise GPS guidance, to fully prevent overlaps in spreading. One system is needed per 250 ha (Tavella et al., 2010). Applying this to a 250 ha farm (which we use as representative for all farms at >150 ha), we arrive at total investments of EUR 56000, annualized over ten years, plus 5% maintenance costs and flat costs for the precision GPS signal. Note this investment is about 2-3 times that assumed in U.S. studies (ICF, 2013; Koch et al., 2004). Benefits are fertilizer savings due to a 19% lower application rate, which we estimate at 1.11 €/kg N (following an estimate by KTBL, personal information transmitted to JRC). With costs and benefits closely matching, results are volatile with respect to assumptions taken – i.e., under certain real conditions costs may be higher while for other situations VRT may actually be profitable (see detailed emission factors and cost data provided in Table 24).

Basically the same considerations apply to the use of VRT for manure spreading. As manure cannot be saved, we understand that it can be distributed to a larger area and so save mineral fertilizer elsewhere. Savings, however, are estimated only at 80% of the N content.

For farms smaller than 150ha, investments needed would soon render VRT very costly, while the equipment would remain idle for most of the year. Sharing of equipment, under such conditions, seems a viable option. While some studies (ICF, 2013) have ignored that “because 70–80% of farmers who currently use [a specific VRT] technology purchase it”, the current market situation cannot be seen representative for the costs of a future activity. We use the additional costs estimated by Koch et al. (2004) for contracting, scale it by the significantly higher investments assumed for the European situation, and apply the resulting costs to farms between 30 and 150 ha size. For even smaller farms, we understand an organization overhead of 20% is needed in addition. Revenues in both cases are reduced fertilizer application, and again resulting costs reflect an average condition and may be different in individual situations as local variation cannot be adequately modelled here.

Enhanced efficiency fertilizers have been developed to allow a continuous supply of nutrients during the growth phase of plants. As urease inhibitors and nitrification inhibitors, key compounds of the so-called “stabilized fertilizers”, prevent processes that release N_2O , we specifically looked into the effect of reduced emissions as a consequence of such inhibitors. Following the literature survey by Winiwarter and Sajeev (2015), 14 studies were evaluated covering different parts of the world and often several types of enhanced efficiency fertilizers. Inhibitors were among the most efficient, by average demonstrating an emission reduction of 38%. Here we do not account for possible simultaneous fertilizer reductions, and we also will not consider the resulting economic benefit – consistent with the way emission reductions are being reported in the background literature. Compared to an improved 2030 situation due to improved nitrogen use efficiency already in the baseline (see above), emission reductions are still as high as 34%.

The effectiveness and considerable achievable emission reductions have been noted before (see e.g. the review by Snyder et al., 2014). However, inhibitors are substances that affect the soil

microflora (Freibauer, 2001) and may exhibit possible unintentional side effects, which call for monitoring programs.

Limited information on costs is available, which basically is a consequence of the incremental cost charged to treated fertilizer – inhibitors typically will be applied in combination with or as compounds of fertilizers. Estimates from fertilizer industry indicate costs to be clearly below 10% of the original fertilizer. Costs derived from market prices (Carson and Ozores-Hampton, 2014) matched both the industry quote and the estimate used by Winiwarter (2005). We apply this estimate and add 10% training and other transaction costs (for a 250 ha farm). The same training costs in absolute terms, also applied to smaller farm sizes, lead to cost increases for smaller farms, such that the training element for 20ha farms exceed the fertilizer cost increments. Training costs alone have been quoted at 300 GBP per farm every 5 years (Godwin et al., 2003), as annual costs less than an order of magnitude smaller than training and transaction costs of 365 EUR per farm and year which have been derived as above. Resulting emission factors and cost data are provided in Table 24.

Inhibitors can be generally used, also for manure and even animal droppings and urea patches. While use during application is rather straightforward, additional labor is needed to treat animal excreta on pasture. O'Brien et al. (2014b) estimate inhibitors are applicable to urine (60% of N excreted) in 50% of cases, reducing direct & indirect emissions by 50%, while Di and Cameron (2022) report reductions of direct emissions by 80%. Here we use 80% generally, applicable to half of the urine excreted, thus total reductions amount to 24% ($0.6 \times 0.5 \times 0.8$). This reduction applies to pastures and thus is unaffected by the improved nitrogen use efficiency relevant in other cases. Costs were converted from data provided by O'Brien et al. (2014b), reflect the tedious additional work needed and thus represent an upper level of the cost curve (see Table 24).

Soil testing, yield mapping, additional sensors including airborne equipment all have been discussed as means to further optimize nutrient supply to plants. Both efficiency in emission reduction and costs exceed those of VRT. While little information is available, we allow abatement marginally higher than inhibitors, and unit costs as already selected by Winiwarter (2005) and Gale and Freund (2002). Precision farming thus appears at the top of the cost curve (Table 24).

Resulting from the above assumptions, Table 24 displays the detailed emission factors and cost assumptions used in agriculture, based on IPCC (2006) guidelines.

Table 24: Emission factors and abatement costs in agriculture (except histosols), expressed as € of 2010. Large farms (>150, nominal average set at 250 ha), Medium farms (30-150, nominal average set at 80 ha) and Small farms (<30, nominal average set at 20 ha) are considered separately for some abatement measures. Default fertilizer input used is 170 kg N/ha, the effectiveness of manure as fertilizer has been set to 80%.

Sector	Abatement	Cost structure	Investment [M€/ (kt N/yr)]	Lifetime [yr]	O&M [M€ / kt N]	Savings [M€ / kt N]	Uncontrolled emissions [kt N ₂ O / kt N]	Controlled emissions [kt N ₂ O / kt N]
Mineral fertilizer	VRT	Large farms	1.32	10	0.034	0.21	0.020	0.0162
		Medium farms			0.249	0.21	0.020	0.0162
		Small farms			0.299	0.21	0.020	0.0162
	Inhibitors	Large farms			0.095		0.020	0.0132
		Medium farms			0.113		0.020	0.0132
		Small farms			0.194		0.020	0.0132
	Precision Farming				0.302		0.020	0.0132
Manure	VRT	Large farms	1.32	10	0.034	0.17	0.022	0.0178
		Medium farms			0.249	0.17	0.022	0.0178
		Small farms			0.299	0.17	0.022	0.0178
	Inhibitors	Large farms			0.095		0.022	0.0145
		Medium farms			0.113		0.022	0.0145
		Small farms			0.194		0.022	0.0145
	Precision Farming				0.302		0.022	0.0140
Grazing (cattle)	Inhibitors	grazing (all except sheep)			0.810		0.038	0.0289

VRT – Variable Rate Technology

O&M – Operation and Maintenance

Note that in GAINS no emission abatement options are foreseen for the categories “grazing sheep” and “flooded rice” production, hence they have been excluded from the table above.

4.5.2 Organic soils

Soil processes in organic soils do not differ from those in other soils, but the larger amount of carbon available provides “feed” for micro-organisms which become more productive. Organic soils (histosols) are thus treated separately in national greenhouse gas inventories (IPCC, 2006). Thus the area of histosols used for agricultural purposes (HISTOSOL, presented in Mha area) is taken from the national submissions to the UNFCCC (2022). A link was established between IIASA’s GAINS and GLOBIOM models to align in a consistent manner the GAINS projections of Mha histosols used for cultivation with the land-use change of restoring histosols, e.g., into wetlands through rewetting, as modelled in GLOBIOM.

As emissions are large compared to other soils, and the overall area of organic soils under cultivation is fairly low in all countries, the obvious abatement option is to stop utilizing these soils for agricultural purposes. This option has been implemented in GAINS, even if studies on abandoned Finnish histosols (Maljanen *et al.*, 2004) indicate that banning cultivation may in reality not return the emission situation to the natural background. Emission reductions are taken as the difference between natural background and cultivated histosols according to IPCC (2006) which indicate 94% reductions, and costs have been estimated as lost revenues from agricultural production of 500 €/ha (e.g. Riester *et al.*, 2002).

4.5.3 Livestock

When the organic content in livestock manure decomposes, emissions of CH₄ and N₂O are released. While CH₄ release occurs when manure is handled under anaerobic conditions, formation of N₂O occurs during aerobic conditions, i.e., with access to oxygen. Activity data is number of animals by animal category and type of manure management system (solid/liquid). Sources for historical animal numbers are EUROSTAT (2022) for EU countries with projections based on future trends taken from the CAPRI model (EuroCare, 2023).

Emissions of N₂O from manure handling are calculated as a fraction of the total nitrogen excretion, where the size of the fraction depends on the type of manure management. Both animal number and nitrogen excretion rates required for this calculation are elements of the national submissions to UNFCCC (2019), projections of animal numbers are available from the CAPRI (EuroCare, 2023) model.

For dairy cows, both enteric fermentation emissions and manure management emissions per animal are affected by the milk productivity of the cow. This effect is particularly accentuated for highly productive milk cows. To capture this, the no control emission factor for dairy cows is specified as the sum of a fixed emission factor per animal for cows producing up to 3000 kg per head per year and an additional term describing the emission factor per milk yield for milk production exceeding the productivity level 3000 kg per animal per year, i.e.,

$$ef_{it,cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * (x_{it} - 3000) \quad (36)$$

where ef_i^{animal} is the default emission factor for cows in country i producing 3000 kg milk per year,

ef_i^{milk} is the emission factor per kt milk produced above the threshold level 3000 kg milk per animal per year, and

x_{it} is the average milk yield per animal in country i and year t .

Increased nitrogen excretion associated with high milk yields (above 3000 kg/hd) is considered at an increase rate provided by national experts during consultations (Klimont, pers. communication).

Methodology and default emission factors specified by animal categories and manure management system (liquid vs. solid) follow IPCC (2006) guidelines (Table 25). No emission abatement technologies are considered in GAINS for N₂O emissions from manure handling.

Table 25: Emission factors for manure handling following IPCC (2006), Vol. 4, Table 10.21. The conversion to total N₂O emitted (from originally N₂O-N) uses a stoichiometry factor of 1.57.

GAINS manure system	Emission factor [kg N ₂ O/kg N excreted]	IPCC characterization
poultry	0.0016	Poultry manure with/without litter
solid manure systems	0.0157	Cattle and Swine deep bedding
liquid manure systems	0.0079	Liquid/slurry with cover

Changes over time occur, however, in terms of the manure systems, with general trends towards an emission reduction due to liquid manure systems becoming more prevalent. Information on such a change over time derived from country experts during consultations (for a few countries only), or from the extrapolated trend in increasing animal numbers per farm (see section 3.3). As large farms (with a high number of animals) tend to be on liquid systems, it is assumed that the separation between liquid and solid systems is strictly along a given number of animals on a farm, and that farms above a certain (country specific) size automatically will use liquid systems. This allows deriving a liquid/solid share for any future scenario, which is applicable for pigs, dairy cows and other cattle, for which such solid/liquid share information is available.

5 F-gas emission sources

5.1 Overview of F-gas emission sources and mitigation options in GAINS

The GAINS model framework accounts for the F-gas emissions hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). For the emission scenarios produced for the EUCLIMIT5 project, only HFCs, PFCs and SF₆ emissions are considered as these were regulated under the Kyoto Protocol during its first commitment period. In the post-2012 period, nitrogen trifluoride (NF₃)³ –a potent greenhouse gas- was added to the ‘basket’ of greenhouse gases covered by the Kyoto Protocol. NF₃ is manufactured by the reaction of hydrochloric acid (HCL) and ammonia (NH₃) and primarily used in the cleaning of silicon wafers in semiconductor applications (Arnold et al., 2013). In the EUCLIMIT6 project, NF₃ emissions are reported separately in addition to the other F-gases.

F-gas emissions have increased significantly in recent years and are estimated to rise further in response to increased demand for cooling services and a phase out of ozone-depleting substances (ODS) under the Montreal Protocol (Gschrey et al. 2011, Velders et al. 2015; Purohit and Höglund-Isaksson, 2017; Purohit et al., 2020). In compliance with the Montreal protocol (UNEP, 2007), many applications that formerly used chlorofluorocarbons (CFCs) for cooling and refrigeration purposes changed rapidly to applications employing HCFCs with lower ozone-depleting effects or to HFCs with no ozone-depleting effects. Later amendments to the Montreal protocol require a complete phase-out of all ozone-depleting substances including HCFCs (UNEP, 2007). In GAINS, all use of CFCs in mobile air conditioners in the EU-27 is assumed phased out by 2005, while in stationary sources about 20 percent of the total demand for HFCs/HCFCs is still covered by HCFCs in 2005 followed by a gradual phase-out completed by 2020.

The Kigali Amendment (KA) to the Montreal Protocol (UNEP, 2016) went into force in January 2019 and is expected to phase-down global HFC consumption by 80-85% by the late 2040s, thereby significantly reducing HFC emissions over the period leading up to 2050 (Purohit et al., 2020). The EU F-gas regulations (EC) No 517/2014 and (EC) No 842/2006 together with the EU Mobile air conditioners (MAC) Directive are expected to overachieve on the commitments EU have under the KA (Garry, 2019). In the EUCLIMIT6 scenarios, effects on baseline emissions from adopted F-gas regulation are therefore reflecting EU F-gas regulation, thereby also fulfilling commitments under the KA.

Table 26 presents the structure of F-gas emission sources (for the Kyoto protocol gases HFCs, PFCs and SF₆) in GAINS with corresponding mitigation options. HFCs are primarily used as cooling agents in refrigeration and air-conditioning appliances, as solvents in industrial processes, as fire-extinguishing agents, for foam blowing and as aerosol propellants. Emissions of HFCs from these sources can be reduced through good practices like leakage control and end-of-life recollection and recycling. For more substantial removal of emissions, the HFCs need to be replaced by alternative substances with low or no global warming potential (GWP). The production of HCFC-22 for feedstock use in industry also gives rise to HFC emissions

³ GWP₁₀₀ = 16,100 as per IPCC/AR5

unless these are controlled through incineration. Sources of PFCs accounted for in the GAINS model are primary aluminium production and the semiconductor industry. The SF₆ sources considered are high and mid- voltage switches, magnesium production and casting, soundproof windows and some small sources like tyres and sports equipment. For more details on activity data, emission factors, mitigation options, and emissions estimation methodology applied in GAINS, see respective sector descriptions below.

An overview of the EU legislation currently in place to control the release of F-gas emissions is presented in Table 27. Baseline scenario emissions are in GAINS estimated under the assumption that all EU Member States at least meet the requirements of the regulations adopted EU wide. From 1st January 2015 the placing on the market and use of F-gases within the EU has to follow the rules given in Regulation (EU) No 517/2014. This Regulation has repealed Regulation (EC) No 842/2006 with effect from 1st January 2015.

The EU F-gas Regulation (EC 842/2006) was implemented in 2006 to control the release of F-gases from stationary cooling and refrigeration equipment as well as from aerosols, foams and a few other minor sources. Emissions from air conditioners in motor vehicles are regulated in the EU MAC Directive (2006/40/EC) and in the EU Directive on end-of-life vehicles (EC 53/2000). These F-gas regulations stipulate e.g., that good practice measures like leakage control and end-of-life recollection of refrigeration and air-conditioning equipment should be put into place by 2008. Allowing for a certain phase-in period in countries with no prior F-gas regulation, GAINS assumes the full effect of good practice measures is attained from 2015 onwards. From 2011, the use of HFC-134a in mobile air conditioners should be replaced by a cooling agent with a GWP of less than 150 in all new vehicle models placed on the market (Minjares, 2011). In addition, the EU MAC directive (2006/40/EC) bans the use of HFC-134a in mobile air-conditioners in all new cars and vans from 2017.

The new EU F-gas regulation (517/2014) came into force from 1st January 2015, replacing the previous version EC (842/2006). Key changes include: product and equipment bans, service and maintenance bans, cap and phase down and responsible supply. The regulation puts restrictions on the placing on the market of certain refrigeration and air conditioning equipment, foams and propellants using F-gases, and of SF₆ in small magnesium foundries. It limits the use of higher GWP gases, such as HFC-404A and HFC-507A, in existing refrigeration equipment from 2020. Further, the new regulation puts a cap on the placing on the market of F-gases and phase down on the supply of HFCs. Only companies with EU quotas will be able to supply HFCs to the EU market. Numerous additional changes include requirements for leakage control, checks and detection systems, end-of-life recovery, training and certification programmes, labelling and reporting (EC 517/2014).

In addition, the new F-gas Regulation requires an increased use of alternative blowing agents for one-component foams, use of alternative propellants for aerosols, leakage control and end-of-life recollection and recycling of high- and mid- voltage switches, SF₆ replaced by SO₂ in magnesium production and casting, and a ban of use of SF₆ in soundproof windows, sports equipment etc. The EU's 2006 regulation only restricted use of SF₆ in magnesium die casting operations. The bans on the use of SF₆ in the recycling of magnesium die casting alloys are new to the 2014 regulation.

The new EU F-gas regulation (517/2014) phases out the total amount of HFCs that can be sold from 2015 to one fifth of today's sales by 2030. This is expected to reduce the EU's F-gas emissions by some two-thirds in 2030 compared to the 2014 level. Table 28 summarizes how different control options have been implemented in the GAINS baseline scenario in order to meet the F-gas emission reduction target specified in the 2014 F-gas regulation.

On April 5, 2022, the EU Commission proposed regulations concerning fluorinated greenhouse gases and ozone-depleting substances. Following this, the Parliament adopted its stance on March 30, 2023, and on April 5, 2023, the Council reached a general agreement. The revised regulation extends and strengthens the free allocation quota system for HFCs in the market beyond 2030 and introduces a new quota system for their production. Furthermore, it imposes additional restrictions on various equipment and products containing F-gases, enhancing provisions for implementation and enforcement, including penalties. These measures are aligned with the EU's 2030 climate targets, aiming for at least 55% emission reductions, and are a step towards achieving climate neutrality in Europe by 2050.

The EU Council and the European Parliament have reached a provisional agreement on October 5, 2023, to gradually reduce fluorinated gases that contribute to global warming and substances harmful to the ozone layer (European Council, 2023). The agreement outlines a plan to phase out the consumption of hydrofluorocarbons (HFCs) entirely by 2050. Additionally, the production of these substances will be limited to a minimum of 15% by 2036, along with other restrictions.

Following the requirements of the amendment (EC/29/2009) of the EU-ETS Directive, PFC emissions from the primary aluminium industry are included in the EU-ETS emission cap.

There is a voluntary agreement among semiconductor producers worldwide to reduce release of PFC emissions to 10 percent below the 1995 emission level by 2010 (WSC 2008). The European semiconductor industry has signed up to this agreement (ESIA, 2006). HFCs used in the manufacture of semiconductors are excluded from the phase-down in the new F-gas regulation (EC 517/2014).

In addition to EU wide legislation, there is national legislation targeting F-gases in Austria, Belgium, Denmark, Germany, Netherlands and Sweden. These regulations were put in place earlier or go further in their stringency or address more sources than the EU wide regulation.

Table 26: Overview of F-gas sources and mitigation options in the GAINS model.

Gas	GAINS sector	Sector description	GAINS technology	Technology description
HFCs	CAC_SMALL_B/ CAC_SMALL_S	Small commercial air conditioning. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components
			ALT_HC	Alternative refrigerant: Propane (R290)
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a, HFC-32, HFC-446A, HFC-447A)
			ALT_CO2	Alternative technology: pressurized CO ₂
			ALT_WATER	Water chillers
			LOW_GWP	Alternative refrigerant: HFO-1234yf, HFO-1234ze
	CAC_LARGE_B/ CAC_LARGE_S	Large commercial air conditioning. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: end-of-life recollection
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a, HFC-32, HFC-446A, HFC-447A)
			ALT_CO2	Alternative technology: pressurized CO ₂
			ALT_WATER	Water chillers
	COMM_SMALL_B/ COMM_SMALL_S	Small commercial refrigeration. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components
			ALT_HC	Alternative refrigerant: Hydrocarbons (e.g., HC-600a, HC-290, HC-1270)
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a, HFC-32, HFC-446A, HFC-447A)
	COMM_LARGE_B/ COMM_LARGE_S	Commercial refrigeration, emissions banked in equipment. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-152a, HFC-32, HFC-446A, HFC-447A)
			ALT_CO2	Alternative technology: pressurized CO ₂
	DOM_S	Domestic small hermetic refrigerators, emissions from scrapped equipment	GP	Good practice: end-of-life recollection
			ALT_HC	Alternative refrigerant: Isobutane (HC-600a)
	IND_SMALL_B/ IND_SMALL_S	Small industrial refrigeration, including food and agricultural sectors. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components
			ALT_HC	Alternative refrigerant: Hydrocarbons (e.g., HC-290, HC-1270)
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-446A, HFC-447A)
			ALT_HFO	Alternative refrigerant: HFO-1234ze
			ALT_CO2	Alternative technology: pressurized CO ₂
	IND_LARGE_B/ IND_LARGE_S	Large industrial refrigeration, including food and agricultural sectors. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components
			ALT_HC	Alternative refrigerant: Hydrocarbons (e.g., HC-290, HC-1270)
			ALT_HFC	Alternative HFC refrigerant (e.g., HFC-446A, HFC-447A)
			ALT_HFO	Alternative refrigerant: HFO-1234ze
			ALT_NH3	Alternative technology: Ammonia (NH ₃)
RAC_B/ RAC_S	Residential air conditioning. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components	
		ALT_HC	Alternative refrigerant: Hydrocarbons (e.g., HC-290, HC-1270)	
		ALT_HFC	Alternative HFC refrigerant (e.g., HFC-32)	
		ALT_CO2	Alternative technology: pressurized CO ₂	
		LOW_GWP	Placeholder for speculative future HFO alternative refrigerant	
TRA_REFB/ TRA_REFS	Refrigerated transport, emissions banked in equipment. Emissions banked in equipment ("_REFB") and at end-of-life ("_REFS") are modelled separately.	GP	Good practice: leakage control, improved components	
		ALT_HC	Alternative refrigerant: Hydrocarbons (e.g., HC-290, HC-1270)	
		ALT_HFC	Alternative HFC refrigerant (e.g., HFC-32)	
		ALT_CO2	Alternative technology: pressurized CO ₂	
TRA_RD_HDB_B/ TRA_RD_HDB_S	Mobile air conditioning in buses. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components	
		ALT_HFO	Alternative refrigerant: HFO-1234yf	
		ALT_CO2	Alternative technology: pressurized CO ₂	
TRA_RD_LD4C_B/ TRA_RD_LD4C_S	Mobile air conditioning in cars. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components	
		ALT_HFO	Alternative refrigerant: HFO-1234yf	
		ALT_CO2	Alternative technology: pressurized CO ₂	
TRA_RD_LD4T_B/ TRA_RD_LD4T_S	Mobile air conditioning in light duty trucks. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components	
		ALT_HFO	Alternative refrigerant: HFO-1234yf	
		ALT_CO2	Alternative technology: pressurized CO ₂	

Continued: Table 26: Overview of F-gas sources and mitigation options in the GAINS model.

Gas	GAINS sector	Sector description	GAINS technology	Technology description
HFCs	AERO	Aerosols	ALT_HFC	Alternative propellant HFC-152a
			ALT_HC	Alternative propellant: Propane (R290)
			ALT_HFO	Alternative propellant HFO-1234ze
	OC	Polyurethane one component foams	ALT_HFC	Alternative blowing agent: HFC-152a
			ALT_HC	Alternative blowing agent: c-pentane, iso-pentane, n-pentane, etc.
			ALT_CO2	Alternative technology: CO2 and supercritical CO2
			ALT_HFO	Alternative blowing agent: HFO-1234ze, HFO-1233zd, HFO-133
	OF	Other foams	ALT_HFC	Alternative blowing agent: HFC-152a
			ALT_HC	Alternative blowing agent: c-pentane, iso-pentane, n-pentane, etc.
			ALT_CO2	Alternative technology: CO2 and supercritical CO2
			ALT_HFO	Alternative blowing agent: HFO-1234ze, HFO-1233zd, HFO-1336mzz
	GSHP_SMALL_B/ GSHP_SMALL_S	Heat pumps, small. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components
			ALT_HC	Alternative refrigerant: Propane (R290)
			ALT_HFC	Alternative HFC refrigerant: HFC-152a
			ALT_HFO	Alternative blowing agent: HFO-1234ze, HFO-1233zd, HFO-1336mzz
	GSHP_LARGE_B/ GSHP_LARGE_S	Heat pumps, large. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: end-of-life recollection
			ALT_HC	Alternative refrigerant: Propane (R290)
ALT_HFC			Alternative HFC refrigerant: HFC-152a	
ALT_HFO			Alternative blowing agent: HFO-1234ze, HFO-1233zd, HFO-1336mzz	
FEXT_B/ FEXT_S	Fire extinguishers. Emissions banked in equipment ("_B") and at end-of-life ("_S") are modelled separately.	GP	Good practice: leakage control, improved components	
		FK	Alternative agent: Fluoro-ketone (FK-5-1-12)	
SOLV_PEM	Solvents	ALT_HFO	Alternative agent: HFO-1233zd(E)	
		BAN	Ban of use	
HCFC22_E	HCFC-22 production for emissive use	INC	Post combustion of HFC-23	
HCFC22_F	HCFC-22 production for feedstock use	INC	Post combustion of HFC-23	
MAGNPR	Magnesium production and casting	NOC	No abatement option identified	
HFC_OTH	Other use of HFCs	ALT_HFC	Alternative low-GWP HFC refrigerant	
PFCs	ALU_SWPB	Primary aluminium production using side-worked prebake technology (SWPB)	RETSWPB	Retrofitting SWPB technology
			CONVSWPB	Conversion of SWPB to PFPB technology
			NEWSWPB	Conversion to speculative new technology eliminating emissions ^a
	ALU_VSS	Primary aluminium production using vertical stud Söderberg technology (VSS)	RETVSS	Retrofitting VSS technology
			CONVVSS	Conversion of VSS to PFPB technology
			NEWVSS	Conversion to speculative new technology eliminating emissions ^a
	ALU_CWPB	Primary aluminium production using center-worked prebake technology (CWPB)	RETCWPB	Retrofitting CWPB
			CONVCWPB	Conversion of CWPB to PFPB technology
			NEWCWPB	Conversion to speculative new technology eliminating emissions ^a
	ALU_PFPB	Primary aluminium production using point-feeder prebake technology (PFPB)	NEWPFPB	Conversion to speculative new technology eliminating emissions ^a
SEMICOND	Semiconductor industry	PFC/ NF3	Switch from PFC to NF ₃ with post-combustion	
PFC_OTH	Other use of PFCs	BAN	Ban of use	
SF ₆	HMOVES	High -and mid voltage switches	AIR	Low-GWP alternative of SF ₆ in electrical switchgear: pressurized air
			NOVEC4710	Low-GWP alternative of SF ₆ in electrical switchgear: NOVEC-4710
			NOVEC5110	Low-GWP alternative of SF ₆ in electrical switchgear: NOVEC-5110
	MAGNPR	Magnesium production and casting	ALT_MAGN	Alternative protection gas: SO ₂
			NOVEC612	Sustainable cover gas for magnesium casting.
	WIND_B	Soundproof windows	BAN	Ban of use
	SF ₆ _OTH	Other SF ₆ sources	BAN	Ban of use

a New technologies refer to either of the following technologies mentioned in IEA's Energy Technology Perspectives 2010 (IEA/OECD 2010): wetted drained cathodes, inert anodes, carbothermic reduction or kaolinite reduction.

Table 27: Current legislation regulating F-gas emissions in EU member states.

Sector	Gas	Policy	Regional coverage	Policy description and implementation in GAINS
Industry	PFCs	EU ETS Directive (EC/29/2009): Primary aluminum production	EU-wide	Industry needs to acquire tradable emission permits under the EU emission trading system (EU-ETS).
	PFCs	Voluntary agreement in semiconductor industry	EU-wide	Semiconductor producers to reduce PFC emissions by 2010 to a level at 10 percent of 1995 emissions. Accounted for in GAINS to the extent it is reflected in national emission inventories to the UNFCCC.
F-gases	HFCs, PFCs, SF ₆	EU F-gas regulation (EC 517/2014)	EU-wide	Phase-down of F-gas sold on the market, banning of use in applications where alternatives to F-gases are readily available, and preventing emissions from existing use of F-gases through leakage control and end-of-life recovery.
	HFCs, PFCs, SF ₆	Commission proposal for a Review of the regulation of the fluorinated greenhouse gases 2022/0099 (COD)	EU-wide	Accelerated reduction of HFC production and import, banning F-gases in select applications, stricter equipment maintenance rules, anti-illegal trading measures, and support for low-GWP alternatives like natural refrigerants (i.e., water, ammonia, carbon dioxide, hydrocarbons) and HFOs.
	HFCs	EU MAC Directive (EC 40/2006)	EU-wide	Mobile air conditioners: replacing the use of high GWP HFCs with cooling agents GWP ₁₀₀ < 150 in all new vehicle models placed on the market.
	HFCs	EU Directive on end-of-life vehicles (EC 53/2000)	EU-wide	Scrapped mobile air conditioners: recovery and proper handling
	HFCs, PFCs, SF ₆	National F-gas regulations more stringent than EU regulation	Austria ("HFKW-FKW-SF ₆ -Verordnung"), Belgium (end-of-life regulation from 2005 for large-scale refrigeration), Denmark (deposit-refund scheme since 1992, tax since 2001 and ban on import, sale and use since 2002), Germany ("Chemikalien-Klimaschutzverordnung" specify maximum leakage rates), Netherlands ("STEK" since 1992), Sweden (environmental fees since 1998, specific regulation since 2007)	

Table 28: Summary of assumptions on the control adopted to meet implemented EU and national F-gas regulations.

Gas	Sector	Control adopted in the Reference scenario 2023 to meet implemented and proposed F-gas regulations
HFCs	Aerosols	Alternative substance propane (HC-290) and HFO-1234ze implemented to 20% in 2025 and 40% in 2030 in all EU-27 countries. The consumption of HFCs in metered dose inhalers (MDIs) is exempted according to Article 15 (2) of the F-gas Regulation.
	Commercial air conditioning -small	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative low-GWP refrigerants (i.e., HFC-32, HC-290 and CO2) implemented to 50% in 2025 and 75% in 2030 in EU-27.
	Commercial air conditioning -large	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative low-GWP refrigerants (i.e., water (R-718), HFC-32 and HFO-1234yf) implemented to 35% in 2025, while an increased implementation of water (R-718) and HFO-1234yf up to 75% is aimed for in large units by 2030 in EU-27.
	Commercial refrigeration -small	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance hydrocarbons (e.g., HC-290) implemented to 20% in 2025 and to 60% in 2030 in EU-27. Alternative substances HFCs with low-GWP (e.g., HFC-32) implemented to 40% in 2025 and to 25% in 2030 in EU-27.
	Commercial refrigeration -large	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance pressurized CO2 (R-744) implemented to 35% in 2025 and to 70% in 2030 in EU-27. Alternative HFC refrigerant (e.g., HFC-32) implemented to 35% in 2025 and to 15% in 2030 in EU-27.
	Domestic refrigeration	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance hydrocarbons (e.g., HC-600a) implemented to 80% in 2025 and to 100% in 2030 in EU-27.
	Fire extinguishers	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Fluoro-Ketons implemented to 40% in 2025, 70% in 2030 and 100% in 2050 in all EU-27 countries.
	Heat pumps -small	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative low-GWP refrigerants (i.e., HFC-32) implemented to 60% in 2025 and 32% in 2030, while an increased implementation of propane (HC-290) and HFO-1234ze up to 58% is aimed for in large units by 2030 in EU-27.
	Heat pumps -large	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative low-GWP refrigerants (i.e., HFC-32) implemented to 60% in 2025 and 32% in 2030, while an increased implementation of HFO-1234ze(E) up to 58% is aimed for in large units by 2030 in EU-27.
	HCFC-22 production	Post-incineration of HFC-23 is 100% implemented from 2005 onwards (except Greece but plant has been closed).
	Industrial refrigeration -small	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance ammonia (NH3), HFO-1234ze, and CO2 implemented to 40% in 2025, 65% in 2030 and 100% in 2050 in all EU-27 countries.
	Industrial refrigeration -large	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative low-GWP substances (o.e., ammonia (NH3), HFO-1234ze) implemented to 40% in 2025, 65% in 2030 and 100% in 2050 in all EU-27 countries.
	One component foams	Alternative substances (i.e., propane, pressurized CO2, HFC-152a and HFO's (e.g. HFO-1234ze, HFO-1233zd, HFO-1336mzz)) implemented to 50% in 2025 and to 65% in 2030 in all EU-27 countries.
	Other foams	Alternative substances (i.e., propane, pressurized CO2, HFC-152a and HFO's (e.g. HFO-1234ze, HFO-1233zd, HFO-1336mzz)) implemented to 50% in 2025 and to 65% in 2030 in all EU-27 countries.
	Residential air-conditioning	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance propane (HC-290) implemented to 10% in 2025, 60% in 2030 and 100% in 2050 in all EU-27 countries. Alternative substance HFC-32 implemented to 50% in 2025 and 30% in 2030 in all EU-27 countries.
	Solvents	Alternative substance HFO's (e.g., HFO-1336mzz (Z), HFO-1233zd(E)) implemented to 100% from 2025 onward in all EU-27 countries.
	Mobile air-conditioning	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance HFO-1234yf implemented to 60% in 2025, extending to 90% in 2030 and 100% in 2040 in all EU-27 countries.
	Transport refrigeration	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Alternative substance pressurized CO2 implemented to 10% in 2025, 30% in 2030 and extending to 50% from 2045 onward in all EU-27 countries. Alternative substance propane implemented to 10% in 2025, 35% in 2030 and extending to 50% from 2040 onward in all EU-27 countries. Alternative substance HFCs with low-GWP (i.e., HFC-32) implemented to 30% in 2025 and 25% in 2030 in all EU-27 countries.
PFCs	Primary Al production	Only point-feeder pre-bake (PFPB) technology in use from 2025 onwards.
	Semiconductor industry	Emissions consistent with national reporting to the UNFCCC (2022)
SF6	High and mid- voltage switches	Good practices (GP) implemented to 100% in all years (except Bulgaria and Romania in 2005 and Croatia in 2005/10) Low-GWP alternative of SF6 in electrical switchgear (i.e., pressurized air, NOVEC-4710, NOVEC-5110) 30% in 2035, 47% in 2050 and 100% by 2070 in all EU-27 countries.
	Magnesium prod. and casting	No alternative gas (i.e., SO2, NOVEC-612) are considered in the baseline scenario
	Soundproof windows	Use of sound-proof windows with SF6 phase-out in 2030.

5.2 HFC emission sources

5.2.1 Air conditioning and refrigeration

To estimate emissions from stationary air conditioners in the residential sector, we apply a method similar to what has been used in a model described by McNeil and Letschert (2007). HFC use for air conditioning depends both on the average HFC consumption per household using air conditioning (kg HFC/unit) and on the fraction of households who own air conditioners (penetration).

$$\text{HFC consumption} = \text{Households} \times \text{Penetration} \times \text{Average charge size} \quad (37)$$

The number of households was calculated by dividing total population by average household size. Data and scenario values for average household sizes are taken from the UN Global Report on Human Settlements 2005 (UN-HABITAT 2005).

We assume that both energy consumption per appliance and the proportion of households owning air conditioners (penetration) depend on climate and income, being higher in warmer and richer places. Penetration in a certain region is formulated as a function of the climate maximum saturation for that region and of the percentage of the climate maximum saturation achieved at that time in the region (availability).

$$\text{Penetration} = \text{Availability} \times \text{Climate Maximum Saturation} \quad (38)$$

The climate maximum saturation is derived from the assumption that current penetration rates in the USA are the maximum for a climate with a given amount of cooling degree days (CDD's). The relationship between maximum saturation and CDD is exponential, as developed by Sailor and Pavlova (2003) and corrected to give a maximum of 100 percent by McNeil and Letschert (2007) whose equation we have used here. Availability of air conditioners as a function of income is assumed to develop along a logistic function, with a threshold point beyond which ownership increases rapidly. Using data on present day air conditioner penetration in various countries from McNeil and Letschert (2007) we find availability as a function of income.

$$\text{Availability} = \frac{1}{1 + e^{4.152 \times e^{-0.237 \times \frac{\text{Income}}{1000}}}} \quad (39)$$

where income is defined as GDP per capita in purchasing power parity (PPP) and converted to constant Euro 2015.

GDP and population data is taken from the GAINS model in consistency with the relevant external macroeconomic scenario, i.e., EC (2023). Data on cooling degree days along with the expected future increase in regional CDDs and household size is taken from IEA (2018) and UN-HABITAT (2005), respectively. Once the number of stationary air conditioners is estimated, the HFC consumption is estimated assuming the average size of each appliance is 2.62 kW (Adnot et al. 2003) and the average refrigerant charge is 0.25 kg/kW (UNEP 2011a). An annual leakage rate of 10 percent is assumed from equipment in use mainly due to losses during refill (Schwartz and Harnisch 2003). The emission factor has been estimated as a product of leakage rates and country/sector specific GWPs, taken from the national communication to the UNFCCC (2022). Figure 8 presents the share of HFC's used in stationary air-conditioning sector as reported by EU-27 countries for 2020 (UNFCCC, 2022). For countries not reporting

HFC consumption in this sector, the German shares have been adopted as default. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery through recycling or destruction.

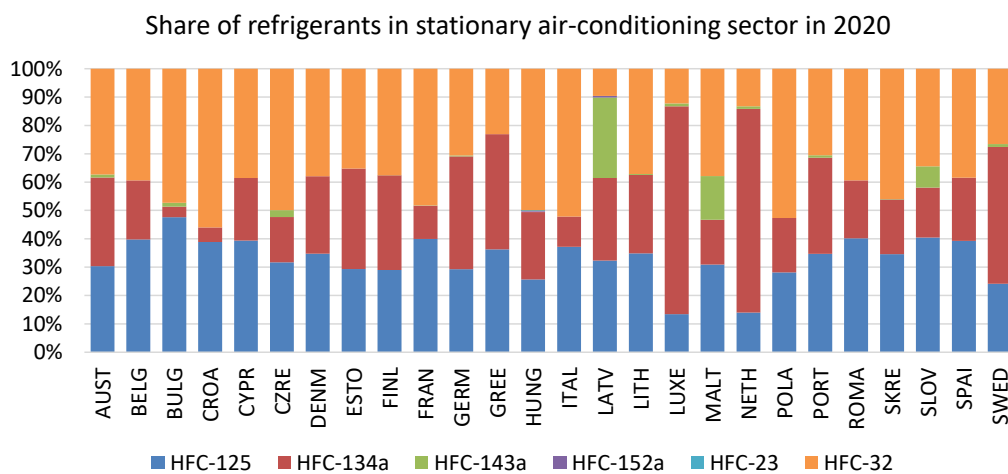


Figure 8: Share of refrigerants in stationary air-conditioning sector in 2020 as reported to UNFCCC (2022).

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 30 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions. Good practice options are being implemented in the EU as part of the different regulations controlling F-gases (see Table 27). In countries with no prior national F-gas regulation, full adoption of good practice options is assumed from 2015 onwards. For substantial further emission reductions, the use of HFC-410A (50% HFC-125 and 50% HFC-32) and HFC-134a (GWP₁₀₀=1300) using IPCC (2013) and other high GWP blends need to be replaced by an alternative low GWP refrigerant such as HFC-32 (GWP₁₀₀=677), propane (GWP₁₀₀=0.02⁴) or pressurized CO₂ (GWP₁₀₀=1) (see Table 26).

A problem with the HFC alternatives with low GWPs is that they often suffer from poorer performance, e.g., in terms of flammability or efficiency (IPCC/TEAP, 2005; USEPA, 2008b; Minjares, 2011). In recent years, companies like Honeywell© and Dupont© have developed and marketed alternative substances with better performances and very short lifetimes of less than a few months. These are known as hydrofluoroolefins (HFOs) (or unsaturated HFCs). E.g., HFO-1234ze with a GWP₁₀₀ of less than 1 can be used in foam products and HFO-1234yf with a GWP₁₀₀ of less than 1 can be used in mobile air-conditioners (IPCC, 2013). The suitability of these substances for stationary air conditioners has not yet been confirmed and they are therefore currently not applied in GAINS for this source.

Another option would be to use other non-HFC substances with low or zero GWP like hydrocarbons, CO₂, dimethyl ether and other diverse substances used in various types of foam products, refrigeration, air-conditioning and fire protection systems. In view of the new EU F-

⁴ The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) stated that propane (HC-290) has a 100-year GWP of only 0.02 compared to previous assumptions of a 100-year GWP of 3 (IPCC, 2021).

gas regulation (EC517/2014), HFC's with a GWP above 750 will be banned from 2025 in 'single split' systems that contain less than 3 kg of refrigerant. A recent study by the European Commission concluded that propane in split air conditioners up to 7 kW can be classified as a technically valid alternative to HFC-driven split air-conditioners (European Commission, 2020) however, some national regulations prohibit their use, primarily due to regulations restricting the use of refrigerants with higher flammability (Purohit et al., 2022b). Split air-conditioners using propane as a low-GWP alternative to HFC-410A (or HCFC-22) are commercially available in the Chinese and Indian markets (UNEP-IEA, 2020; Wang et al., 2020; Sharma et al., 2015). Notably, the International Electrotechnical Commission (IEC) has recently given its approval for higher charge limits of propane and other flammable refrigerants in household air conditioners, heat pumps, and dehumidifiers, as indicated in the IEC's 2023 update (IEC, 2023). The latest proposal from the European Commission (European Commission, 2022), which seeks to amend the EU F-Gas Regulation, includes measures aimed at reducing the utilization of HFCs within the EU. This proposal creates possibilities for the adoption of natural refrigerants, including appliances based on hydrocarbons like propane (HC-290), such as heat pumps and air conditioners, within the residential market in the European Union. Therefore, in the baseline scenario, we make the assumption that HC-290 will be adopted 60% by 2030, and 100% by 2050 across all 27 EU countries (Table 28).

The GAINS model stores data on commercial floor space area for Annex-1 countries (Cofala et al., 2009). The primary data source for this data is the PRIMES (2015) model. For year 2005 the data on commercial floor space area was correlated with GDP/capita as illustrated in Figure 9.

Fitting a linear trend line, the following relationship was retrieved:

$$\left[\left(\frac{\text{Commercial floor space}}{\text{Capita}} \right) = 0.0003 \left(\frac{\text{GDP}}{\text{Capita}} \right) + 7.1984 \right] \quad (R^2 = 0.6737) \quad (40)$$

Using GDP per capita as driver, projections for future growth in commercial floor space area were obtained for each country. To estimate the HFC consumption in commercial air conditioning, a sector specific HFC consumption value of 0.02 kg/m² was applied. In the GAINS model, it is assumed that around 80% of HFC consumption in the commercial air-conditioning sector will occur in medium and large air-conditioning units, while the remaining 20% will be in smaller units.

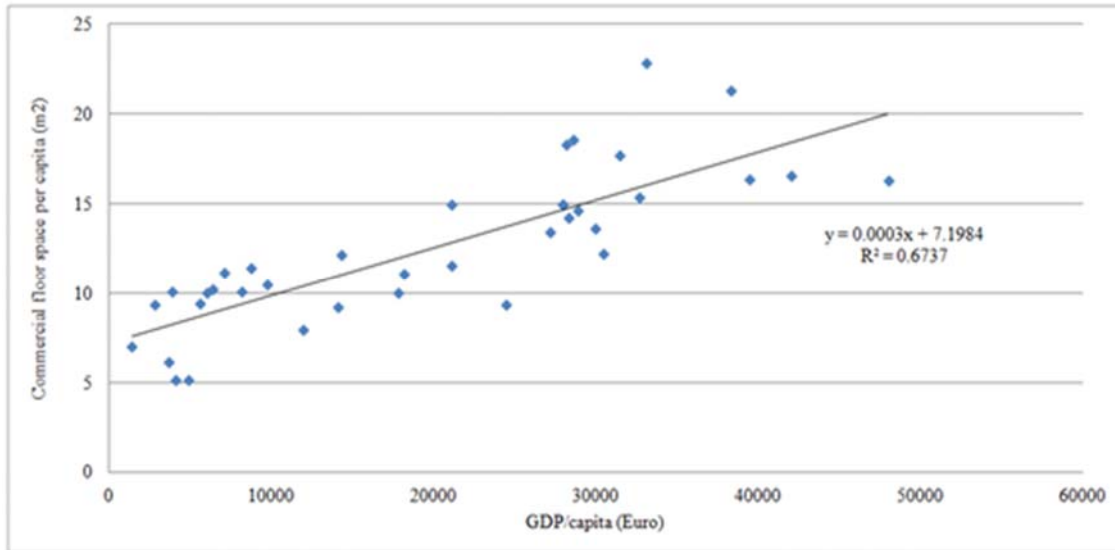


Figure 9: Variation of commercial floor space per capita w.r.t. GDP per capita in year 2005. Source: PRIMES model (2015).

An annual leakage rate of 10 percent is assumed from equipment in use mainly due to losses during refill (Schwartz and Harnisch, 2003).

Figure 10 shows the default GAINS leakage rate applied to all EU-27 countries in comparison to the different leakage rates reported by member states to UNFCCC (2022) for 2020. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

The GAINS model provides control options for commercial air conditioning systems in the small and medium size units category, which encompass CO₂, HC-290, HFOs (i.e., HFO-1234ze), and other low-GWP HFC alternatives (i.e., HFC-454C, HFC-455A, HFC-32). In contrast, for larger units, the available control options consist of water, HFOs (i.e., HFO-1234ze) and other low-GWP HFC alternatives (i.e., HFC-32).

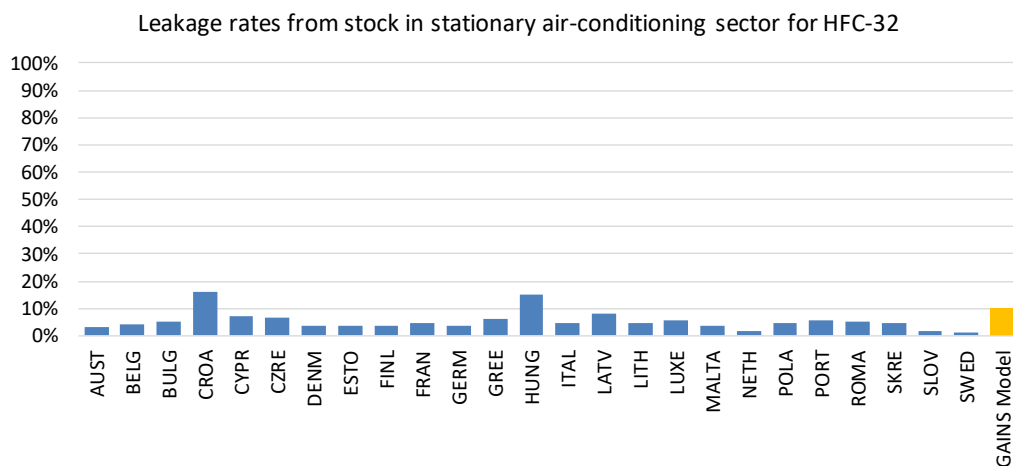
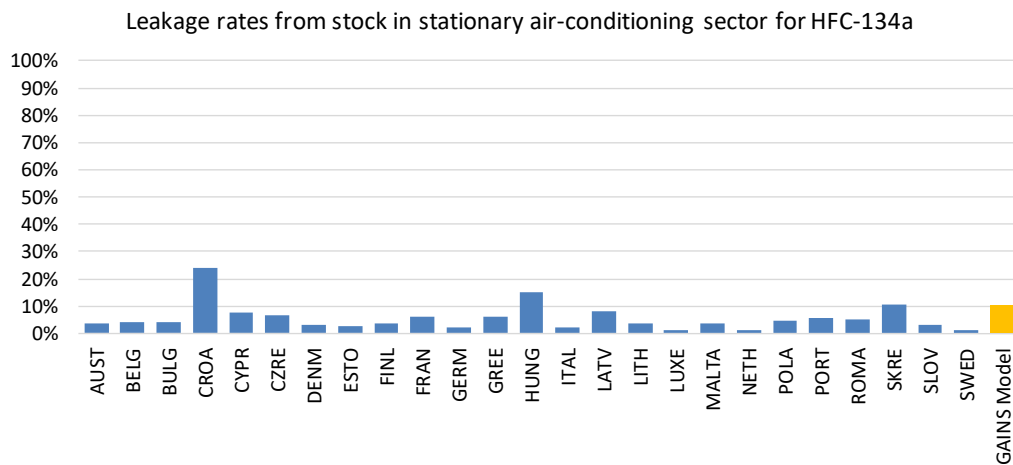
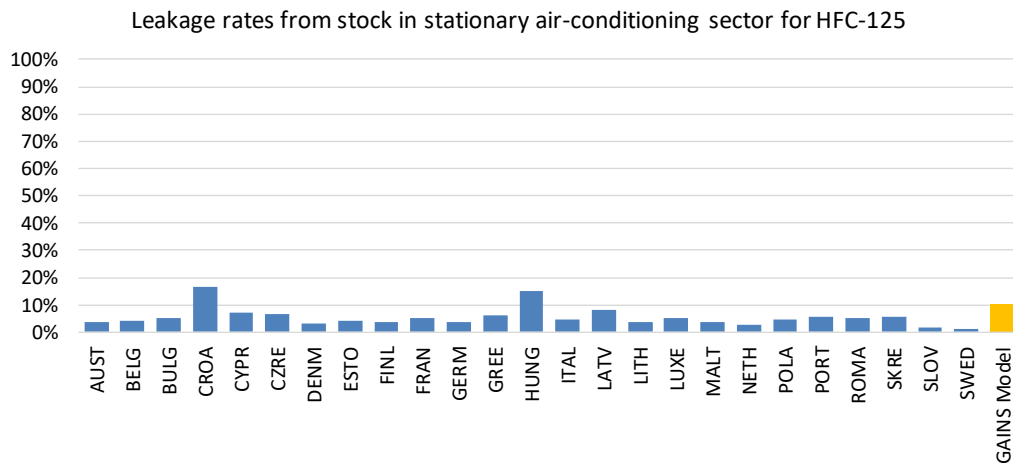


Figure 10: Leakage rates from stock in stationary (residential and commercial) air-conditioning in 2020 for different HFCs as reported to UNFCCC (2022) and adopted as assumptions in GAINS.

The activity data for refrigeration in the domestic sector is number of refrigerators owned by households. The rate of ownership of refrigerator(s) per household is derived using a function estimated by the PAMS model (2012). The general form of the function for the rate of refrigerator ownership per household is given by:

$$Sat_{DOM} = (K \times I_t)^{\lambda_a} \times \left[1 - e^{-(bE_t^{\lambda_b} + cU_t^{\lambda_c})} \right]^a \quad (41)$$

where Sat_{DOM} represents the saturation (rate) of domestic refrigerator ownership, I is the monthly household income given by GDP per household in the country, U is the national urbanization rate, E is the national electrification rate, and t is the year of the projected saturation. The econometric parameter estimates from the PAMS model were applied to derive the rate of refrigerator ownership per household in GAINS. The number of refrigerators in a country was calculated by multiplying the ownership rate by the number of households in a country (UN-HABITAT, 2005). GDP and population data is taken from the GAINS model in consistency with the relevant external macroeconomic scenario, i.e., EC (2022) whereas data on household size is taken from UN-HABITAT (2005). Growth in number of refrigerators is driven by population growth and trends in appliance ownership as estimated above. Once the number of refrigerators is estimated, an average refrigerant charge of 0.125 kg HFC per unit (Schwartz et al., 2011) is used to estimate the HFC consumption in domestic refrigerators.

As domestic refrigerators are hermetic there is no risk of leakage during use, but there is a risk of emission release during the scrapping phase. At the end-of-life, the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

The control option available for this source is good practice during end-of-life scrapping, which is assumed to remove 85 percent of emissions. The option is already in place in the EU through the F-gas Regulation 2006 (see Table 27). For substantial further emission reductions, the use of HFC-134a (GWP₁₀₀=1300) need to be replaced by alternative low GWP refrigerants such as iso-butane (GWP₁₀₀=0.02). HFCs with GWPs above 150 are banned in domestic fridges and freezers as per new F-gas regulation (EC 517/2014).

Commercial refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments (Giroto et al. 2004). Equipment in this end-use typically lasts approximately 15–20 years. The commercial refrigeration sector accounts for approximately 32 percent of global HFC consumption, or 40 percent of HFC consumption in the refrigeration/AC sector (USEPA 2010c).

Starting point for the estimation of emissions from commercial refrigeration in EU-27 in GAINS is the HFC consumption reported by member states to the UNFCCC (2022) for this sector for the years 2005, 2010 and 2015. As we are not able to fully explain the variations in the reported consumption, e.g., by having access to information on consumption patterns for refrigerated goods, we adopt HFC consumption as reported. Projections for future HFC consumption are driven by growth in service sector value added. For countries not reporting HFC consumption in this sector, the German consumption per service sector value added has been adopted as default. Projections for service sector value added are adopted from the

macroeconomic scenario by EC (2022). Within the GAINS model, it is presumed that roughly 25% of HFC consumption within the commercial refrigeration sector will be in small and medium units, with the remaining 75% attributed to large units.

A uniform application of an annual leakage rate of 6 percent from small and medium equipment in use, along with a 15 percent rate for large equipment, is consistently applied across all member states (Birchby et al., 2022) since no evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector. The leakage from this source mainly reflects losses during refill (Schwartz and Harnisch 2003). Figure 11 presents the share of HFC's used in commercial refrigeration sector as reported by EU-27 countries for 2020 (UNFCCC, 2022). It is observed that HFC-134a (42%), HFC-143a (22%), HFC-125 (27%), and HFC-32 (8%) are mostly used for commercial refrigeration sector in the EU. Country/sector specific GWPs are derived from the national communication to the UNFCCC (2022).

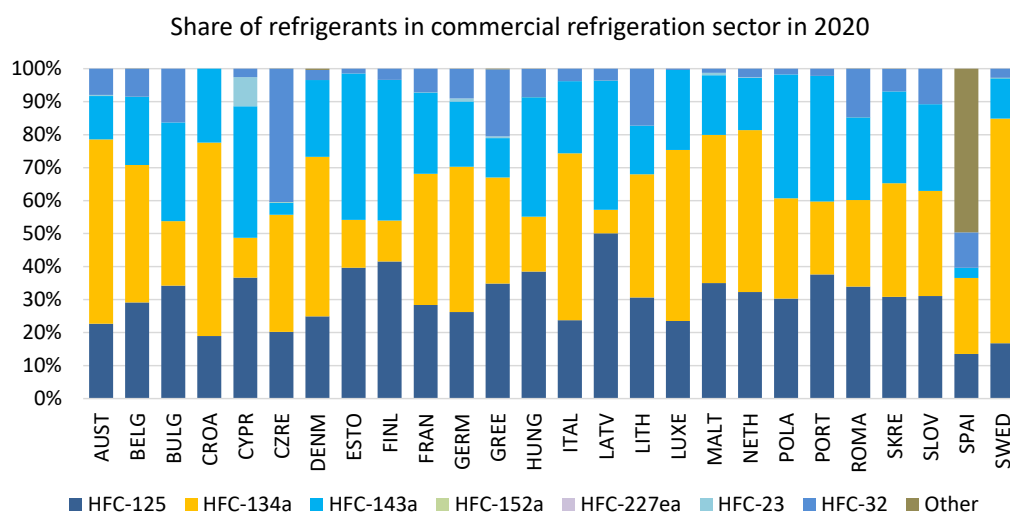


Figure 11: Share of refrigerants in commercial refrigeration sector in 2020 as reported to UNFCCC (2022).

Figure 12 shows the default GAINS leakage rate applied to all EU-27 countries in comparison to the different leakage rates reported by member states to UNFCCC (2022) for 2020. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 42 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions (Tohka, 2005). Good practice options are already implemented in the EU as part of the different regulations controlling F-gases (see Table 27). For substantial further emission reductions, the use of HFC-134a ($GWP_{100}=1300$), HFC-125 ($GWP_{100}=3170$), HFC-143a ($GWP_{100}=4800$) and other high GWP blends need to be replaced by alternative low GWP refrigerants such as HFC-152a ($GWP_{100}=138$), HC-290 ($GWP_{100}=0.02$) or pressurized CO_2 ($GWP_{100}=1$) using IPCC (2013). HFCs with GWPs of more than 2,500 will be banned in commercial refrigeration systems as per new F-gas regulation (EC 517/2014).

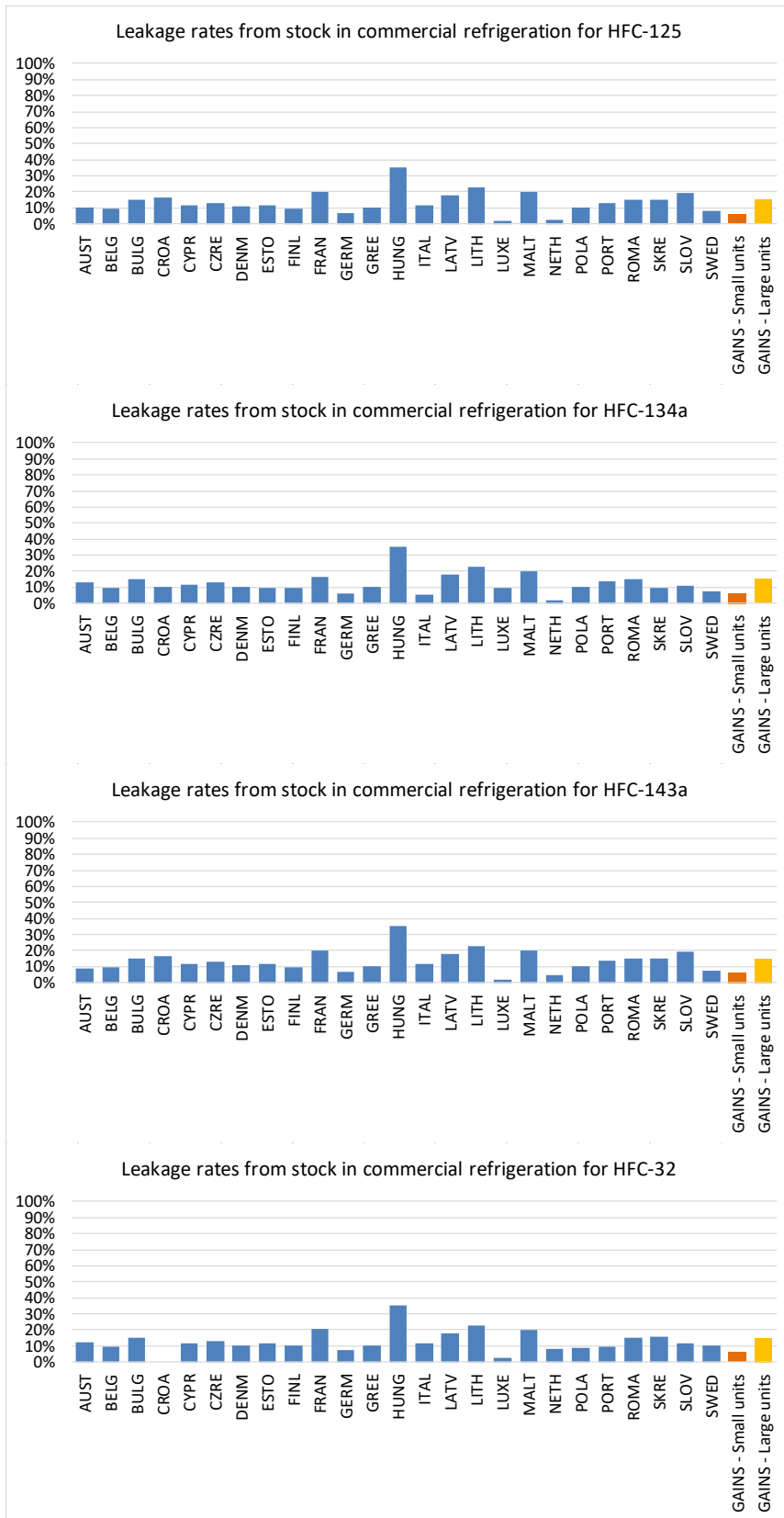


Figure 12: Leakage rates from stock in commercial refrigeration in 2020 for different HFCs as reported to UNFCCC (2022) and assumption adopted in GAINS.

Food processing and cold storage is an important application of industrial refrigeration used for preservation and distribution of food while keeping nutrients intact. On a global scale this application is very significant in size and economic importance (Mohanraj et al. 2009). The application includes cold storage (at temperatures from -1°C to 10°C), freezing (-30°C to -35°C) and the long-term storage of frozen products (-20°C to -30°C). The preferred HFCs used are HFC-134a and HFC blends with a small temperature glide such as HFC-404A, HFC-507A and HFC-410A. Ammonia/ CO_2 cascade systems are also being used, as are hydrocarbons as primary refrigerants in indirect systems (IPCC/TEAP 2005).

Starting point for the estimation of emissions from industrial refrigeration in EU-27 in GAINS is the HFC consumption reported for this source by member states to the UNFCCC for the years 2005, 2010, 2015, and 2020. As we are not able to explain the variations in the reported consumption, we adopt it as activity data as reported. Projections for future HFC consumption are driven by growth in value added for manufacturing industry. For countries not reporting HFC consumption in this sector, the German consumption per value added has been adopted as default. Projections for manufacturing industry value added are adopted from the macroeconomic scenario by EC (2022). It is assumed that approximately 25% of HFC consumption in the industrial refrigeration sector will take place in small and medium units, while the remaining 75% will be associated with large units.

An annual leakage rate of 11 percent is applied consistently across member states (Gschrey et al., 2011) from equipment in use mainly due to losses during refill (Schwartz and Harnisch 2003). No evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector. Country/sector specific GWPs are taken from the national communication to the UNFCCC (2022). Figure 13 presents the share of HFC's used in industrial refrigeration sector as reported by EU-27 countries for 2020 (UNFCCC, 2022). It is observed that HFC-134a (41%), HFC-125 (31%) and HFC-143a (18%) are mostly used for industrial refrigeration sector in EU-27 countries. For countries not reporting HFC consumption in this sector, the German shares has been adopted as default.

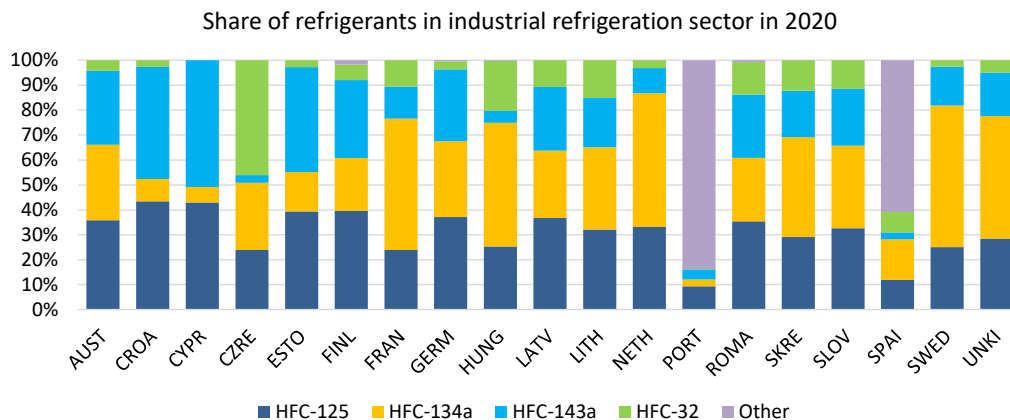


Figure 13: Share of HFC’s in industrial refrigeration sector of EU countries in 2020 as reported to UNFCCC (2022).

Figure 14 shows the default GAINS leakage rate applied to all EU-27 countries in comparison to the different leakage rates reported by member states to UNFCCC (2022) for year 2020. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery with recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 42 percent of emissions banked in equipment in use and almost 90 percent of scrapping emissions (Tohka, 2005). Good practice options are already implemented in the EU as part of the different regulations controlling F-gases (see Table 27). For substantial further emission reductions, the use of HFC-134a ($GWP_{100}=1300$), HFC-125 ($GWP_{100}=3170$), HFC-143a ($GWP_{100}=4800$) and other high GWP blends need to be replaced by alternative low GWP refrigerants such as ammonia ($GWP_{100}=0$), HFO’s (i.e., HFO-1234ze), alternative HFCs (i.e., HFC-446A ($GWP_{100}=461$), HFC-32 ($GWP_{100}=677$) or pressurized CO_2 ($GWP_{100}=1$)) (see Table 26).

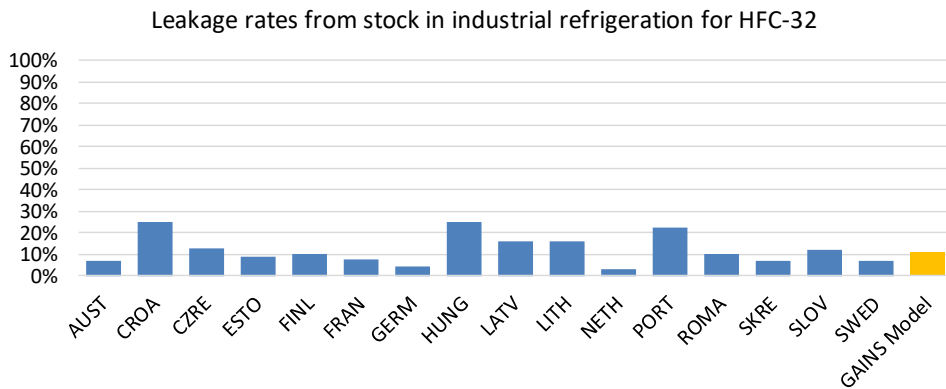
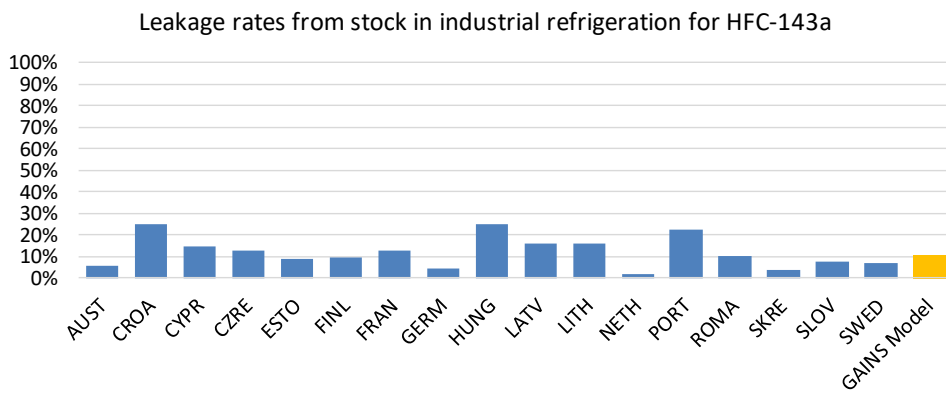
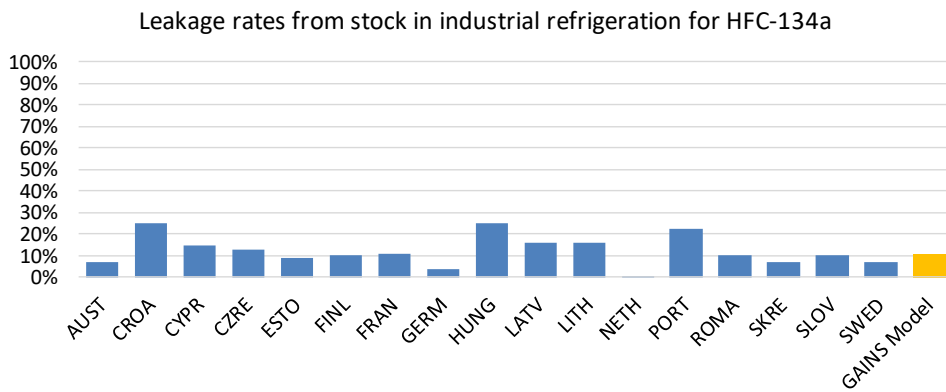
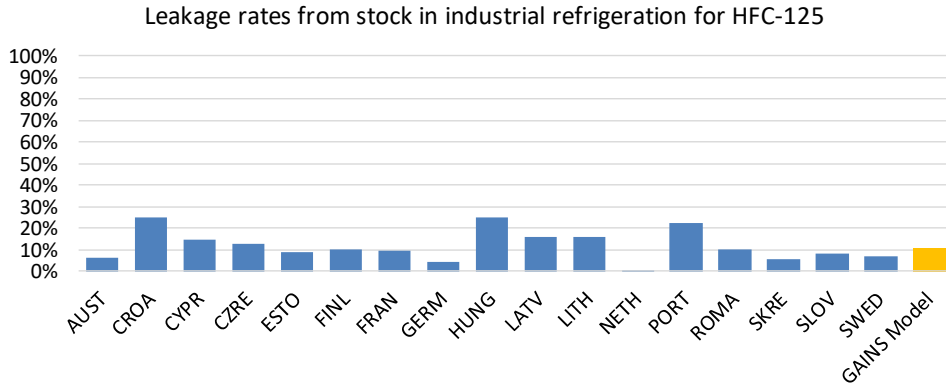


Figure 14: Leakage rates from stock in industrial refrigeration in 2020 for different HFCs as reported to UNFCCC (2022) and assumption adopted in GAINS.

Refrigerated road transport includes transportation of food products (fresh, frozen or chilled), pharmaceutical products, and plants/flowers. The type of vehicles used for such transportations are trailers, heavy and small trucks, and vans. Refrigerated road transport vehicles have different capacities; vans are typically below 3.5 tonnes, small trucks and trailers vary between 3.5 to 7.5 tonnes, and heavy trucks have a capacity of more than 7.5 tonnes.

Approximately 650,000 refrigerated road vehicles were used within the EU during 2003-04 (Tassou et al. 2009; 2010) that has increased up to one million in 2014-15 (Dearman, 2015). These units predominantly use HFC-404A and HFC-410A as refrigerants. HFC-134a is also used for chilled distribution only vehicles. It is reported that the emission leakages from transport refrigeration systems are higher than those from stationary refrigeration because the former operate under more severe conditions (IIR, 2003). The operating environment involves vibration, which will depend on road surface and a wide range of weather conditions and operating temperatures. Annual leakage figures reported are 10–37 percent of the refrigerant charge (IPCC/TEAP 2005). A study reported by Koehler et al. (2003), which assumed a 10 percent leakage rate showed the direct emissions (refrigerant leakage) from the refrigeration system to be 21 percent of indirect emissions (engine fuel consumption) for HFC-404A and 13 percent for HFC-410A.

Due to the country-specific variation in the amount of freight transported as well as the type of vehicles used (see UNECE 2010; Eurostat 2010; USDOT 2010), GAINS derive HFC consumption per unit of freight transportation in 2005, 2010, 2015, and 2020 based on the consumption reported by countries for this source to the UNFCCC (2022). For countries not reporting HFC consumption specific for this sector, the rate reported for Germany (0.32, 0.40, 0.44, and 0.42 t HFC per unit GDP for 2005, 2010, 2015 and 2020, respectively) is adopted as default. Projections of HFC consumption in refrigerated transport have been assumed to follow proportionately the growth in GDP (EC, 2022).

An annual leakage rate of 20 percent from equipment in use is adopted consistently across all member states (Birchby et al., 2022). This leakage is mainly due to losses during refill (Schwartz and Harnisch 2003). Figure 15 presents the share of HFC's used in transport refrigeration sector as reported by EU-27 countries for 2020 (UNFCCC, 2022). It is observed that HFC-134a (35%), HFC-125 (29%), HFC-143a (25%) and HFC-32 (11%) are mostly used for transport refrigeration sector in EU-27 countries.

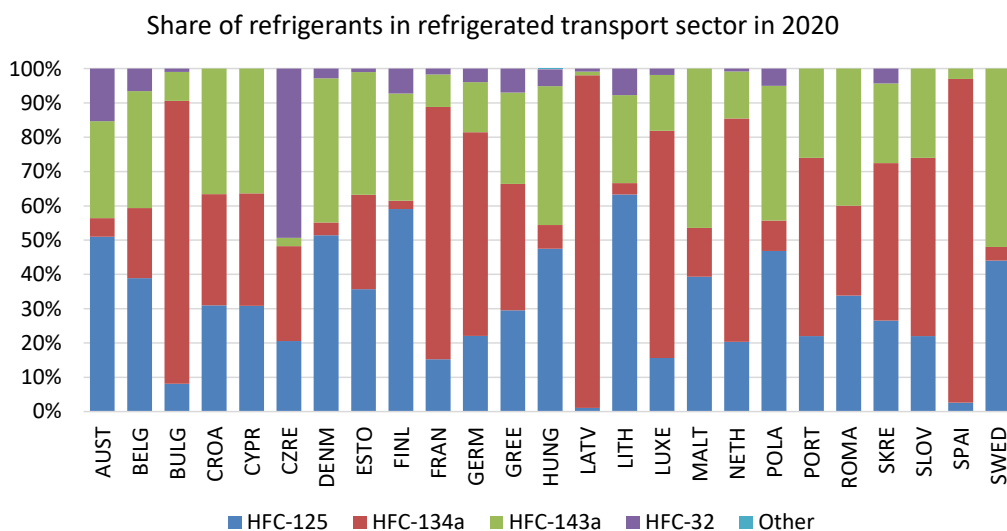


Figure 15: Share of HFC's in transport refrigeration sector of EU countries in 2020 as reported to UNFCCC (2022).

No evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector. Figure 16 shows the default GAINS leakage rate applied to all EU-27 countries in comparison to the different leakage rates reported by member states to UNFCCC (2022) for 2020. At the end-of-life the scrapped equipment is assumed to be fully loaded with refrigerant which needs recovery, recycling or destruction.

The control options available for this source are different good practise options including leakage control, improved components and end-of-life recollection. These options are assumed to remove 33 percent of emissions banked in equipment in use and 80 percent of scrapping emissions. The latter emissions are controlled in the EU through the end-of-life vehicles Directive (see Table 27). Control of leakage from equipment in use for refrigerated transport was not part of the EU F-gas regulation but assumed to be adopted with full effect from 2015 in Germany, Denmark and the Netherlands due to national F-gas regulations. Further emission reductions from this source can be achieved through switches to alternative refrigerants like HFC-32 or pressurized CO₂ (see Table 26). HFCs with GWP of more than 2,500 will be banned in transport refrigeration systems as per new F-gas regulation (EC 517/2014).

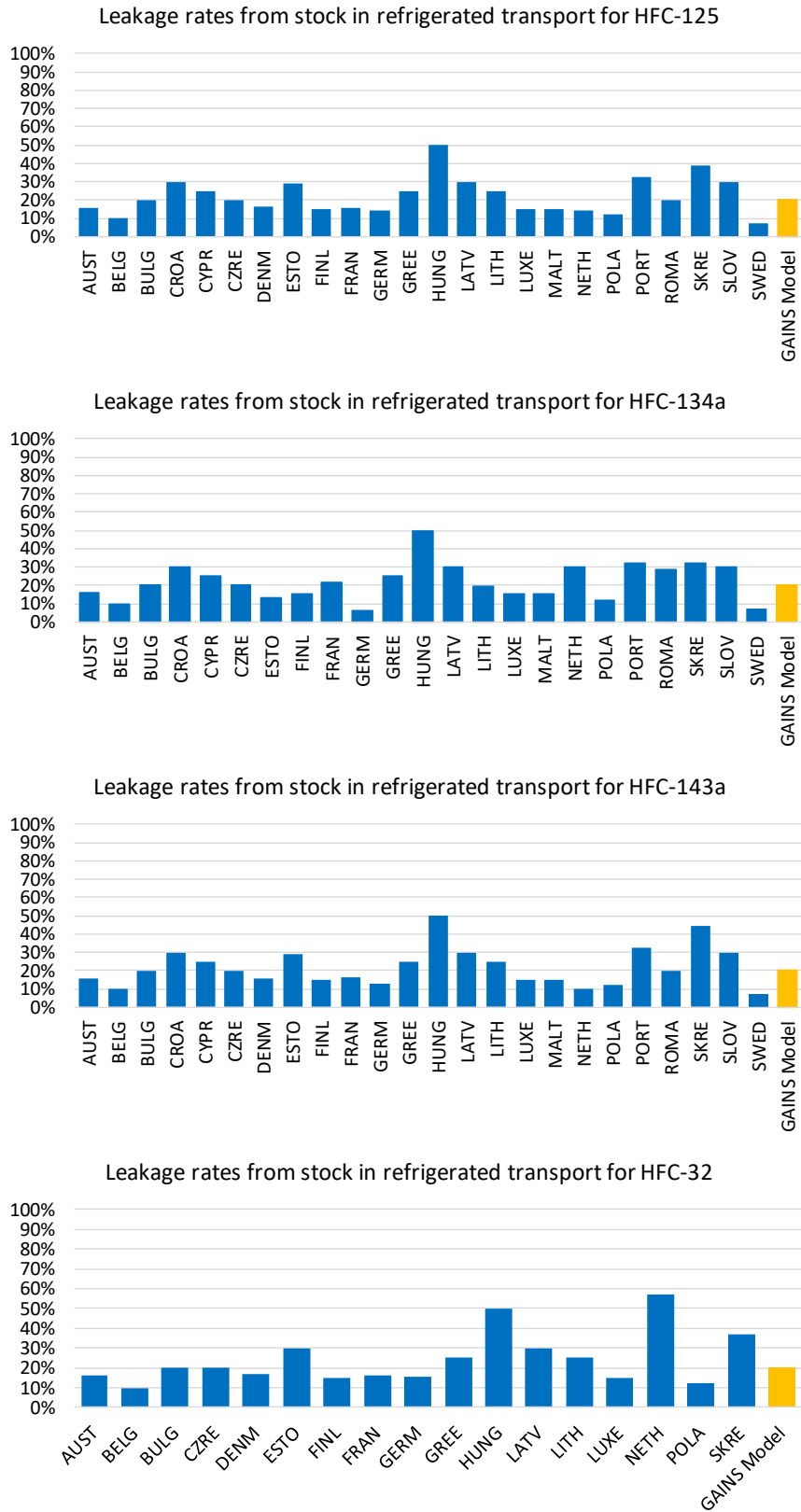


Figure 16: Leakage rates from stock in refrigerated transport in 2020 for different HFCs as reported to UNFCCC (2022) and assumption adopted in GAINS.

A major source of F-gas emissions from the transport sector is emissions from mobile air-conditioners (MAC). Air conditioning in cars became common in the United States in the 1960s. Mass installation in Europe and developing countries started only later, around 1995. The most commonly used refrigerant MACs in the EU is HFC-134a. The emissions of HFC-134a take place during accidents, through leakage and servicing and at disposal. Global recovery rates are generally low (DeAngelo et al. 2006), except for the EU where end-of-life recollection has been mandatory since 2000 due to the Directive on end-of-life vehicles (EC 53/2000).

In the GAINS model, emissions from MAC are accounted for in cars, light and heavy-duty trucks, and buses, as shown in Table 26. The number of vehicle types in different GAINS regions is extracted from the GAINS model and for EU member states consistent with transport fuel use in the PRIMES model (E3modelling, 2023). The penetration rates for air-conditioners in different vehicle types were derived from a literature survey (IPCC/TEAP 2005; Kanwar 2004; Hu et al. 2004; CSI 2009; Uherek et al. 2010). The adopted penetration rates for MAC in EU-27 in 2005 are applied consistently across all member states assuming 75 percent in cars and 60 percent in buses, light and heavy duty trucks. By 2020 all vehicles are assumed equipped with MAC. Using the average charge size for different vehicle types, the HFC consumption from MACs is estimated (Repice and Schultz 2004; Tohka 2005). Average charge sizes used are 0.67 kg for cars and light duty trucks, 1.34 kg for heavy duty trucks (Tohka, 2005) and 12 kg for buses (Schwarz et al., 2011). The leakage rate assumed from MAC in use is 10 percent and at the end-of-life the scrapped MAC is assumed to be fully loaded with coolant which needs recovery, recycling or destruction. Figure 17 shows the default GAINS leakage rate from equipment in use applied to all EU-27 countries in comparison to the different leakage rates reported by member states to UNFCCC (2019) for 2015. No evidence has been found available from direct measurements which would suggest that leakage rates differ substantially between EU countries for this source sector.

Following adherence to the MAC Directive (see Table 27), HFC-134a ($GWP_{100}=1300$) is expected to be replaced by a low GWP substance ($GWP_{100} < 150$) in all new models put on the market from January 2011 onwards. Moreover, new vehicles fitted with air conditioning cannot be manufactured with fluorinated greenhouse gases having GWPs greater than 150 from January 2017 onwards. There are a few possible alternatives to HFC-134a including replacement with CO₂, HFO-1234yf (GWP_{100} is less than 1) or HFC-152a (GWP_{100} is 138). The modelling of additional future potential for adoption of CO₂-based systems versus the use of HFO-1234yf in mobile air conditioners, depends in GAINS on the marginal cost of the respective alternatives when implemented in different types of vehicles.

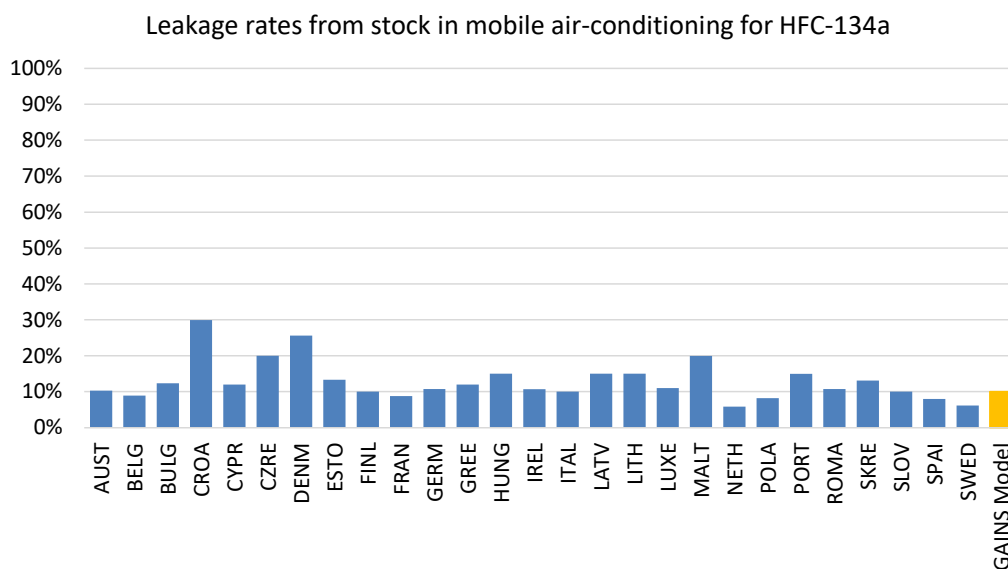


Figure 17: Leakage rates from stock in mobile air-conditioning in 2020 for HFC-134a as reported to UNFCCC (2022) and assumption adopted in GAINS

5.2.2 Foams

Foams became a significant application for HFCs as part of the phasing-out of CFCs under the Montreal Protocol. HFCs are used as blowing agents in a solidifying matrix of a polymer (UNEP, 2006). The main application of polyurethane (PU) one component (OC) foam is to fill cavities and joints when installing inner fixtures in housing constructions. Since one component foams come in pressurized canisters and cylinders, they are also called aerosol foams. One component blowing agents are typically gaseous and function as propellant for the foam. They volatilize upon application, except for small residues that remain for at most one year in the hardened foam (Schwarz and Leisewitz 1999).

To estimate emissions from one component foams we adopt HFC consumption in one component foams as reported by member states to the UNFCCC (2022) for years 2005, 2010, 2015 and 2020. Projections of blowing agents for the one component foam sector follow growth in GDP (EC, 2022). The annual release of HFCs from foams is assumed 15 percent of the stock banked in foams. Figure 18 presents the share of HFC's used in foam sector as reported by EU-27 countries for 2020 (UNFCCC, 2022).

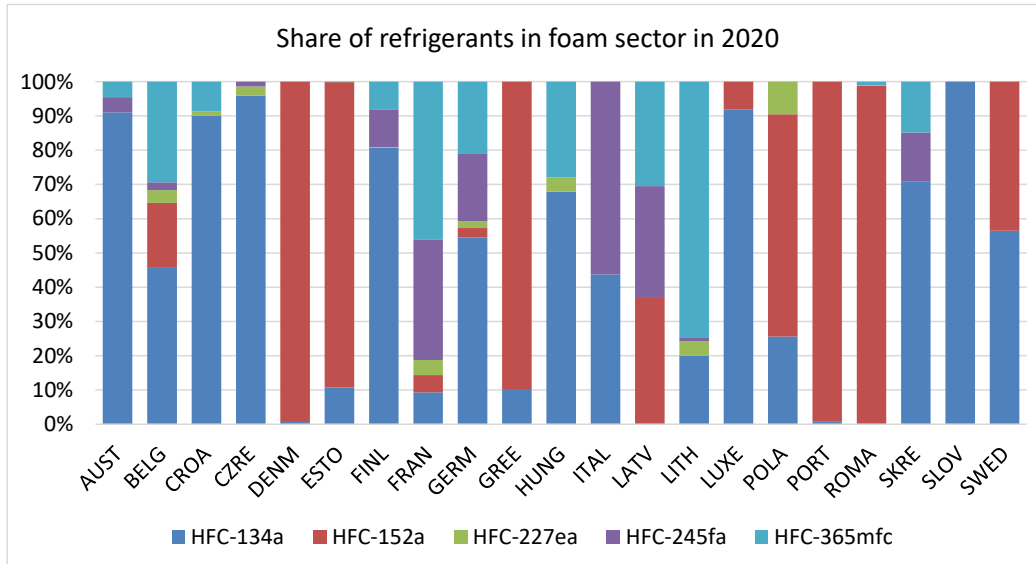


Figure 18: Share of HFC's in foam sector of EU countries in 2020. Source: UNFCCC (2022)

Emissions from foams can be controlled by replacing HFC-134a and other high GWP blends with alternative low GWP blowing agents, like hydrocarbons or CO₂. A recent mitigation option for applications where high pressure is essential is the replacement with HFO-1234ze (GWP₁₀₀ of less than 1). According to the manufacturer Honeywell© it is already available for use as blowing agent for one component foams (<http://www51.honeywell.com/sm/lgwp-uk/applications.html>) however the cost is unclear.

The F-gas Regulation (see Table 27) requires that all EU member states from 2008 stop using HFCs in one component foams unless this is required to meet national safety standards. According to Kaschl (2012) the most common current replacement options for HFCs in foams is CO₂. For some applications the performance of CO₂ in foam blowing is limited (UNEP/TEAP 2010). In GAINS the options considered available for replacement of HFCs in one component foams are CO₂, different hydrocarbons like propane, butane (i.e., i-butane, n-butane), pentane (i.e., isopentane, cyclopentane) and HFO-1234ze.

The sector for other foams (OF) in the GAINS model includes about 10 different polyurethane foam types (viz. PU appliances, PU/PIR/Phen laminates, PU disc panel, PU cont panel, PU blocks, PU spray, PU pipe, XPS) and extruded polystyrene (XPS). It is difficult to estimate product life emissions and lifetime of the foam product. End of life emissions depend greatly on the end of life treatment. If the product is land filled, the emission factor depends mainly on the properties of the plastic. If the product is recycled, all gases can be emitted into the atmosphere if fugitive emissions during the recycling process are not incinerated or collected. If the product is incinerated, the emission factor can be close to zero, depending on the incineration temperature. To estimate emissions from the other foam sector we adopt HFC consumption in other foams as reported by member states to the UNFCCC for years 2005, 2010,

2015, and 2020. Projections of refrigerants for one component foam sector follow GDP as taken from (EC, 2022). The annual release of HFCs from foams is assumed 6 percent of the stock banked in foams. The share of HFCs used in foam sector as reported by EU-27 countries for 2020 (UNFCCC, 2022) is presented in Figure 18.

Emissions from foams can be controlled by replacing HFC-134a and other high GWP blends with an alternative blowing agent like CO₂ or hydrocarbons (propane, butane, pentane) or HFO-1234ze. According to Harvey (2007) a water/CO₂ mixture has been used in Europe (with a 10 to 20 percent market share by 2000) for solid PU in building applications. The use of HFO's (i.e., HFO-1234ze, HFO-1336mzz, HFO-1233zd) with a GWP₁₀₀ of less than 1 is also available for use as blowing agent for foams.

According to Kaschl (2012) 80 percent of XPS board foams in the EU use CO₂. However, CO₂ has some limitations with respect to thermal resistance and product thickness (UNEP/TEAP 2010). The remaining 20 percent will therefore need to use some other alternative, e.g., a mix of HFCs, HCs and water could be possible, but also HFO-1234ze is an interesting possible option (UNEP/TEAP 2010). In GAINS the options considered available for replacement of HFCs in other foams are CO₂, different hydrocarbons like propane, butane and pentane, and HFO's (i.e., HFO-1234ze, HFO-1336mzz, HFO-1233zd).

All F-gases with GWPs of more than 150 will be banned as the refrigerant or foam blowing agent in any hermetically sealed system. This will mainly affect the use of HFC-134a as a refrigerant and HFCs-245fa and HFC-365mfc as foam blowing agents (EC 517/2014). From 2020, HFCs with GWPs of more than 150 will be banned in extruded polystyrene foam (XPS). From 2023 HFCs with GWPs of more than 150 will be banned in all other foams, including polyurethane.

5.2.3 Aerosols

HFC is used as propellant for aerosols released from cans and metered dose inhalers (MDIs), e.g., medical asthma inhalers. In the EU, the use of HFCs as propellant for aerosols in all applications for entertainment and decorative purposes has been prohibited since 2008 (see Table 27). From 2018 HFCs with a global warming potential above 150 will be banned in technical aerosols (EC 517/2014). The release from this source is therefore mainly from MDIs, where high pressure is essential and the approval of new medical drugs is very expensive and time-consuming (UNEP/TEAP 2010). In 2020, approximately 84% of HFC-134 reported for the aerosol sector was used in MDIs (UNFCCC, 2022) We assume that for the EU, the current use of HFCs in MDIs is limited to severe cases and that the primary gases used are HFC-134a with some use of HFC-152a (Schwarz et al., 2011). To estimate HFC consumption in aerosols, we adopt the HFC consumption reported by member states to the UNFCCC for years 2005, 2010, 2015 and 2020 (UNFCCC, 2022). For countries not reporting HFC consumption in this sector, the German consumption per person has been adopted as default. Population growth is used as driver for future HFC use in aerosols. Figure 19 presents the share of HFC's used in aerosol sector as reported by EU-27 countries for 2020 (UNFCCC, 2022).

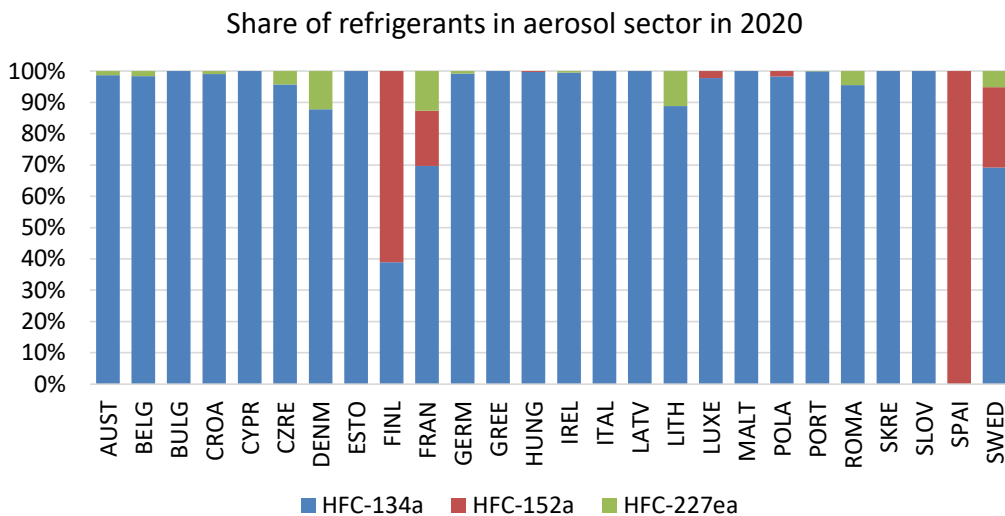


Figure 19: Share of HFC's in aerosol sector of EU countries in 2020 (UNFCCC, 2022).

The primary alternatives to HFC-134a as propellant in medical dose inhalers are dry powder inhalers (DPI) or HFC-152a, which has a GWP_{100} of 138. The relative cost of these options is similar to the cost of MDIs in developed countries (UNEP/TEAP 2010), however, for medical reasons MDIs are still preferred in severe cases.

For severe cases, where high pressure is essential, there is the option to replace HFC-134a with HFO-1234ze (GWP_{100} of less than 1), which according to the manufacturer Honeywell© is already available for use as propellant for aerosols (<http://www51.honeywell.com/sm/lgwp-uk/applications.html>). As no cost information is available for this option, GAINS assumes that the cost is about 50 percent higher than the cost of using HFCs.

5.2.4 HCFC-22 production

HCFC-22 (chlorodifluoromethane) is a gas used in refrigeration and air-conditioning systems, in foam manufacturing as a blend component of blowing agents, and in the manufacturing of synthetic polymers. Since it is an ozone-depleting substance its release is regulated in the Montreal Protocol (MP). The phase-out schedule of HCFCs in the latest revision of the MP (UNEP, 2007) is presented in Table 29 for Article 5 (mostly developing countries) and non-Article 5 (mostly industrialized countries) countries. In addition to the phase-out of the use of HCFCs, the MP also requires the production and sales of HCFC-22 for emissive use to end completely after 2040.

In contrast to production of HCFC-22 for emissive use, the production and use of HCFC-22 as feedstock in industry is not regulated in the MP as it does not contribute to emissions of HFC-23. Production of HCFC-22 is however a source of HFC-23 emissions, which is a strong greenhouse gas with GWP_{100} of 12400 times that of CO_2 (IPCC, 2013).

Table 29: Phase-out schedule of HCFCs for emissive use in the Montreal protocol (UNEP 2007).

	Article 5 (developing countries)		non-Article 5 (developed countries)
	Pre 2007 revision of MP	Post 2007 revision of MP	Pre- and post 2007 revision of MP
1996			freeze in emissions
2004			-35%
2010			-75%
2013		freeze at average of 2009 & 2010 levels	
2015	freeze in emissions	-10%	-90%
2020	-35%	-35%	-99.50%
2025		-67.5%	
2030		-97.5%	-100%
2035			
2040	-100%	-100%	

To calculate HFC-23 emissions from HCFC-22 production in the EU, GAINS applies an IPCC default emission factor of 3 percent related to the volume of HCFC-22 production for emissive (HCFC22_E) and feedstock (HCFC22_F) applications (IPCC, 2006). Activity data are based on reported production levels for historic years (UNEP, 2022) and UNEP’s phase out schedule for HCFC products for future years (UNEP, 2007). Projections of HCFC-22 production for feedstock use are assumed to grow proportionately with value added in manufacturing industry.

HFC-23 emissions from HCFC-22 production can be almost eliminated through post combustion during which HFC-23 is oxidized to carbon dioxide, hydrogen fluoride (HF) and water. The removal efficiency of incinerators in HCFC-22 production facilities is assumed to 95%.

The marginal abatement cost for destruction of HFC-23 emissions from HCFC-22 production is very low, less than 1 Euro/tCO₂eq (Schneider 2011; IPCC/TEAP 2005).

HCFC-22 production in the EU is recorded in the emission inventories submitted to the UNFCCC and takes place in France, Germany, Greece, and the Netherlands. All countries except Greece are in the baseline scenario assumed to have full post-incineration of emissions in place already in 2005. Greece has full control from 2010 onwards.

5.2.5 Heat pumps

Heat pumps represent a category of heating, ventilation, and air conditioning (HVAC) systems employed to provide both heating and cooling in buildings. They are seen as a key technology for reducing greenhouse gas emissions in the HVAC sector (IEA, 2022b) because they are much more efficient than traditional HVAC systems. Heat pumps work by transferring heat from one place to another (using refrigerants), rather than generating heat themselves. This makes them much more efficient than traditional HVAC systems, which rely on combustion to generate heat. There are three main types of heat pumps: air-source heat pumps, water-source heat pumps, and ground-source heat pumps. Air-source heat pumps are the most common type of heat pump. They use the heat in the outside air to heat and cool buildings. Water-source heat pumps use the heat in bodies of water, such as lakes and rivers, to heat and cool buildings.

Geothermal heat pumps or ground source heat pumps (GSHP) are systems combining a heat pump with a ground heat exchanger (closed loop systems) or being fed by ground water from a well (open loop systems). The earth is used as a heat source when operated in heating mode, with a fluid as the medium which transfers the heat from the earth to the evaporator of the heat pump, thus utilizing geothermal energy (Sanner et al., 2003). In cooling mode, heat pumps use the earth as a heat sink. With borehole heat exchangers (BHE), geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet demands.

The EU Strategy for Energy System Integration identifies heat pumps as a key technology for the decarbonization of space heating and domestic hot water production, as well as for cooling in buildings and the industry (European commission, 2021). In Figure 20, annual heat pump sales data for the years 2005-2021 in countries surveyed by the European Heat Pump Association (EHPA 2008; 2010; 2022) is displayed. In 2022, about 3 million units were sold in these surveyed countries, showing a remarkable 39% growth compared to the already impressive 34% increase in the previous year's annual sales (EHPA, 2022). As a result, the total number of connected heating heat pumps (including air-to-air and water-based) and hot water heat pumps in Europe has now reached approximately 20 million units. These 20 million heat pumps are currently providing heating to approximately 16% of Europe's residential and commercial buildings.

Heat pump sales in Europe

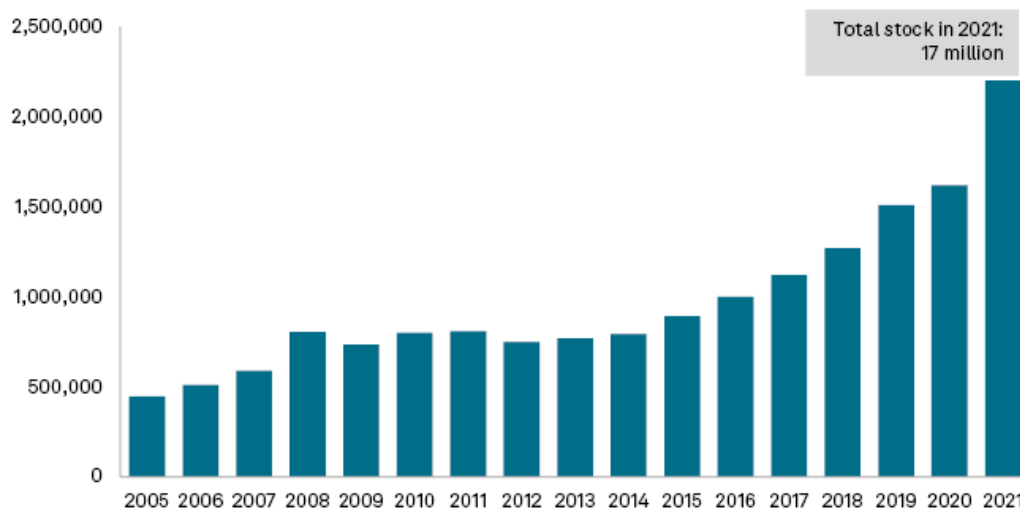


Figure 20: Annual heat pump sales in markets surveyed by European Heat Pump Association: Austria, Belgium, Switzerland, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Sweden, Slovakia and the UK. Source: EHPA (2022)

Direct uses of geothermal energy are traditional and well established world-wide. One of the main advantages of the direct use of geothermal energy is that it can use low-to-moderate resource temperatures. The other advantage is that it can be found, often at shallow depths, almost anywhere in the world. The installed capacity and thermal energy available worldwide today are 107.8 GWh and 1,021 PJ/year (283.6 TWh/year), respectively (Lund et al., 2022; Lund and Toth, 2021) distributed in 82 countries. The previous estimates from the same research group estimated installed capacity of direct use geothermal in 2014 at 71 GW_{th},

distributed in 82 countries (Lund and Boyd, 2016), 51 GWth at the end of 2009, distributed in 78 countries (Lund et al., 2011), while Goldstein et al. (2011) estimated direct use at 60 GWth at the end of 2009. Figure 21 shows the direct use of geothermal energy in EU-27.

Direct use (ranging from 60 to 120°C) by type and relative estimates as given by Lund et al. (2016) were space heating (16%), greenhouse heating (3.5%), aquaculture pond heating (1.3%), agricultural drying (0.4%), industrial uses (1.6%), bathing and swimming (18%), cooling/snow melting (0.2%), and others (0.2%). GSHP contributed to 59% (78 GWh) of the global installed geothermal heating capacity in 2019 and is the fastest growing of all forms of geothermal direct use since 1995 (Rybach 2005; Blum et al., 2010; Thorsteinsson and Tester, 2010; Lund et al. 2011; Schimschar et al. 2011; Ogola et al., 2012). Although, most of the installations occur in North America, Europe, and China, the number of countries with installation increased from 33 in 2005, to 43 in 2010, to 48 in 2015, and 54 in 2020. The equivalent number of installed 12 kW units (typical of US and Western European homes) is about 6.5 million (Lund and Toth, 2021).

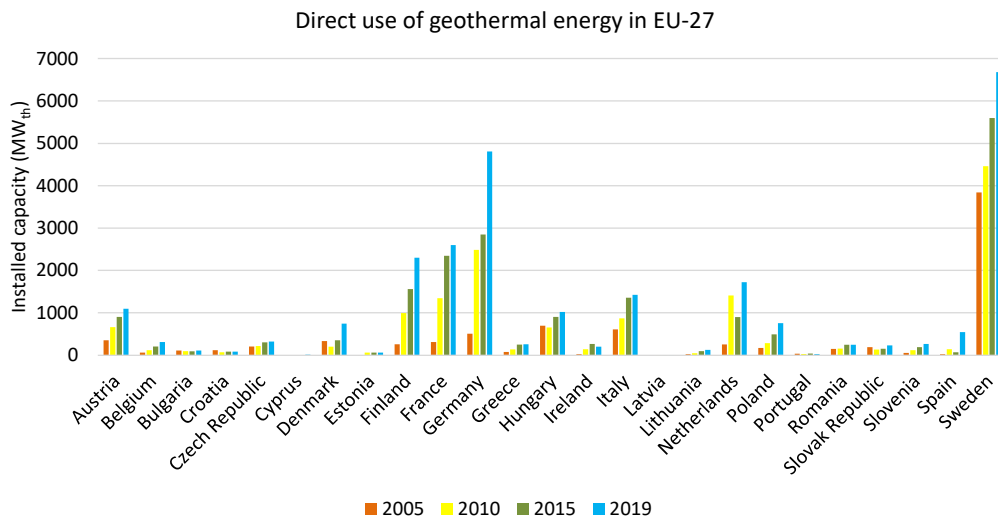


Figure 21: Direct use of geothermal energy in EU-27. Source: (Lund et al. 2005; Lund et al. 2011; Lund and Boyd, 2016; Lund and Toth, 2021; Lund et al., 2022)

To estimate HFC consumption in the GSHP sector in the GAINS model we have taken information about the GSHP installed capacity from Lund et al. (2005), EurObserv'ER (2009), EHPA (2010), Lund et al. (2011), Bayer et al. (2012), Lund and Boyd (2016), Lund and Toth (2021), and Lund et al. (2022). For projections, it is assumed that the annual growth in GSHPs using HFCs follows the growth in energy consumption for ambient heat (including final energy consumption and transformation input in district heating plants) (PRIMES, 2023). Based on available technical information, the current fluid/refrigerant used in GSHP is most likely HFC-410A (IPCC/TEAP, 2005; Johnson, 2011). An average refrigerant charge of 0.22 kg HFC per kW installed capacity (Schwartz et al., 2011) is used to estimate the HFC consumption in the GSHP sector. An assumption is made that roughly 90% of HFC consumption in the heat pump sector will occur in small and medium-sized units, with the remaining 10% being linked to large units. Annual leakage from small and medium size equipment is assumed at 4 percent per year and large units is assumed at 6 percent per year (Birchby et al., 2022). Emissions can be controlled through good practice options and switching to alternative substances. In GAINS,

the primary alternatives for HFC-410A in small and medium-sized units are HFC-32 for the short term and HC-290 and HFO-1234ze for the long term. For large units, the key alternatives to HFC-410A are HFC-32 in the short term and HFO-1234ze(E) in the long term.

5.2.6 Other HFC emission sources

GAINS includes two additional HFC emission sources: fire extinguishers and solvents. Emissions from fire extinguishers are derived from the HFC consumption in fire extinguishers per unit GDP as reported for some EU countries to UNFCCC (2022) for years 2005, 2010, 2015, and 2020. We adopt reported values when available and derive a default factor per GDP for countries not reporting consumption from this source. Emissions from solvents are only included for those countries reporting emissions from this source to UNFCCC (2022) for years 2005, 2010, 2015, and 2020. For projections, emissions from both sources are assumed to grow proportional to GDP. Control options identified for these sources are good practice during scrapping and switching to alternative HFCs with low GWP. PFCs have been banned in fire protection systems since 2007. From 2016, HFC-23 are banned in new fire protection systems (EC 517/2014).

5.3 PFC emission sources

5.3.1 Primary aluminium production

Primary aluminium production has been identified as a major emission source of the two PFCs tetrafluoromethane (CF₄) (with GWP₁₀₀ = 6,630) and hexafluoroethane (C₂F₆) (with GWP₁₀₀ = 11,100 times that of CO₂). During normal operating conditions, an electrolytic cell used to produce aluminium does not generate measurable amounts of PFC. PFC is only produced during brief upset conditions known as "anode effects". These conditions occur when the level of aluminium oxide drops too low and the electrolytic bath itself begins to undergo electrolysis. Since the aluminium oxide level in the electrolytic bath cannot be directly measured, surrogates such as cell electrical resistance or voltage are most often used in modern facilities to ensure that the aluminium in the electrolytic bath is maintained at the correct level.

For EU-27, the GAINS model uses the production volumes of primary aluminium as the activity driver for calculating emissions from this source. Primary aluminium production data for historical years (2005, 2010, 2015 and 2020) and projections are taken from the PRIMES (E3modelling, 2023) baseline projection for the EU. Four different types of activities are distinguished based on the technology used; point-feeder prebake (PFPB), side-worked prebake (SWPB), vertical stud söderberg (VSS), and center-worked prebake (CWPB) technology. Shares of different primary aluminium production technologies were adopted from the aluminium industry website (<https://international-aluminium.org/>) and from national communications to the UNFCCC (2022). The latter source is also used for final verification of emissions. Emission factors depend on the production technology and on a number of site-specific conditions and are taken from Harnisch and Hendricks (2000).

Conversion of SWPB, VSS or CWPB technology to PFPB technology removes over 90 percent of PFC emissions, while retrofitting of the three technologies would remove about a quarter of

emissions (Harnisch and Hendricks 2000). Data on mitigation costs is taken from the same source. As emissions from the primary aluminium production is regulated under the EU-ETS system, control options with marginal costs falling below the expected ETS carbon price in the PRIMES energy scenario are assumed adopted in the GAINS non-CO₂ baseline scenario. This means that with the natural turn-over of capital, all EU member states will have phased-in PFPB technology by 2020.

The development of inert anodes is sometimes promoted as a promising mitigation option, which could eliminate emissions of PFCs from the electrolysis process (Bernstein et al., 2007). In the Energy Technology Perspective (ETP) 2010 by the International Energy Agency (IEA/OECD, 2010), deployment of inert anode technologies is expected to start in 2015-2020 with full commercialization by 2030. If realized, inert anode technology would have significant energy, cost, productivity, and environmental benefits for the aluminium industry worldwide (Inert Anode Roadmap, 1998; RUSAL, 2010). The technology is expected to eliminate PFC emissions from primary aluminium production altogether. However, the commercial aspects of inert anodes have not yet been proven (Kvande and Drabløs, 2014). Despite promising initial results, the technology still needs further development before it can be introduced as a viable alternative to PFPB technology.

Figure 22 shows PFC emissions from primary aluminium production in EU-27 as estimated by the GAINS model and in comparison, with emissions reported to UNFCCC for years 2005, 2010, 2015, and 2020. While the recent version of the GAINS estimates uses IPCC/AR5 GWP₁₀₀ values however, for the comparison with UNFCCC (2022) we have converted GAINS emission estimates for PFC emissions (in kt CO₂eq) from primary aluminium (Al) production into IPCC/AR4 GWP₁₀₀ values.

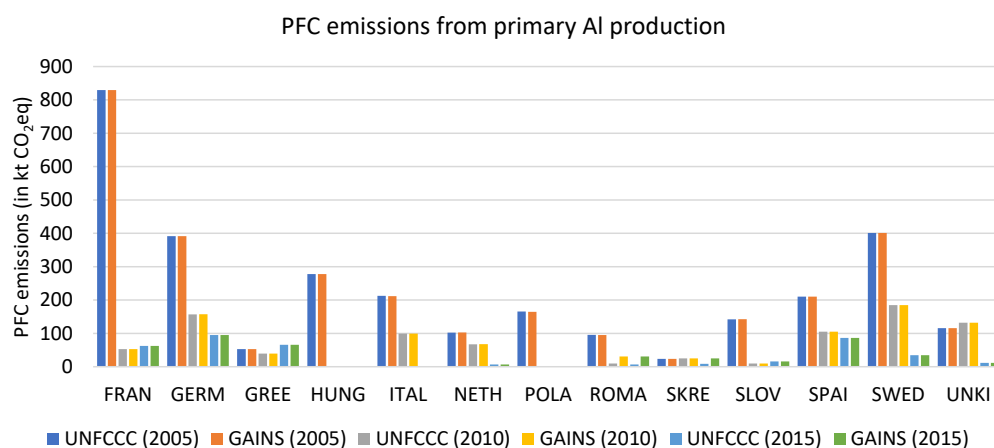


Figure 22: PFC emissions (in kt CO₂eq) from primary aluminium (Al) production in the GAINS model and as reported to UNFCCC (2022) for years 2005, 2010, 2015 and 2020.

5.3.2 Semiconductor industry

The semiconductor industry uses HFC-23, CF₄, C₂F₆, octafluoropropane (C₃F₈), carbon tetrafluoride (c-C₄F₈), sulphur hexafluoride (SF₆) and nitrogen trifluoride (NF₃) in two production processes: plasma etching thin films (etch) and plasma cleaning chemical vapour

deposition (CVD) tool chambers (IPCC, 2000a). Both the PFCs (GWP₁₀₀=6630) and NF₃ are potent greenhouse gases (GWP₁₀₀=16100). PFCs have been regulated under the Kyoto Protocol, while NF₃ is added to the ‘basket’ of six greenhouse gases (covered by the KP in the first commitment period) with effect from 2013 and the commencement of the second commitment period of the protocol. The semiconductor industry has been switching from PFCs to NF₃ as part of a voluntary agreement to reduce PFCs. The commitment has been to reduce PFC emissions to ten percent below the 1995 baseline level by 2010 (ESIA 2006; WSC 2008). In 2008 the industry was close to reaching this target (WSC 2008). Under well managed conditions, a switch from PFC to NF₃ reduces the net global warming effect because about 98 percent of NF₃ is destroyed by industry in the process (UNFCCC 2012). With a release of about 60 percent of the PFCs used in the industry, the switch to NF₃ contributes to a net reduction in greenhouse gas emissions by about 85 percent.

As PFC is only used by a few companies in a country and because the amount of PFC used allows deriving production volumes, data on the use is often confidential. The activity variable used in GAINS for this sector is the volume of PFC emissions as reported by member states to UNFCCC (2022). We use the reported emissions for the years 2005, 2010, 2015 and 2020 while future projections follow growth in value added for manufacturing industry.

The European semiconductor manufacturers have been part of the voluntary commitment to reduce PFC emissions from this source (ESIA, 2006). We assume that the reduction attained by the industry in 2005 will continue into the future. This corresponds to an application of control to 86 percent of the production from 2010 onwards. Costs for switching to NF₃ use were taken from Harnisch and Hendriks (2000) and Tohka (2005).

Figure 23 shows the GAINS model estimates of PFC emissions from semiconductor industry in EU member states. For the comparison with UNFCCC (2022) we have converted GAINS emissions estimates for PFC emissions from semiconductor industry into IPCC/AR4 GWP₁₀₀ values.

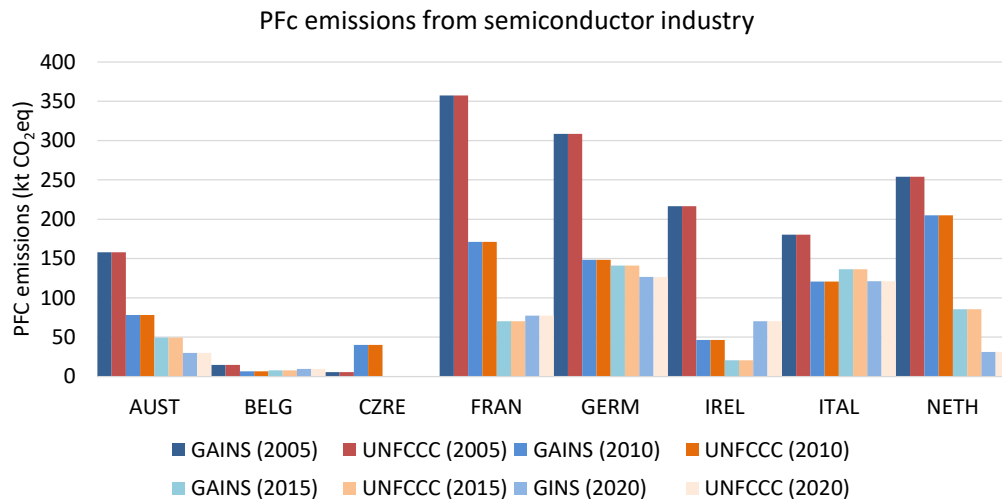


Figure 23: PFC emissions (in kt CO₂eq) from semiconductor industry in the GAINS model and as reported to UNFCCC (2022) for years 2005, 2010, 2015 and 2020.

5.4 SF₆ emission sources

Sulphur hexafluoride (SF₆) emissions are released from high- and mid-voltage switches, magnesium production and casting and a variety of other applications e.g., soundproof windows or sports equipment. SF₆ has a very high global warming potential of 23,500 times that of CO₂ over a 100-year time horizon (IPCC, 2013).

5.4.1 High and mid voltage switches

SF₆ is used as an electrical insulator in the transmission and distribution equipment of electric systems. Most of the SF₆ is stored in gas-insulated switchgears for high and mid-voltage electric networks. Emissions of SF₆ depend on the age of the gas insulated switchgear (GIS) since older models leak more than newer ones, as well as on the size of the transmission network and on recycling practises of the old equipment. The GAINS model uses the reported emissions for the years 2005, 2010, 2015 and 2020 while future projections follow electricity consumption as activity variable for this sector.

In recent years, several alternatives to SF₆ in both mid-voltage and high-voltage electrical switchgear were developed. While the market introduction in the mid-voltage segment is more advanced and alternatives are widely available, this is not yet the case for high-voltage applications so that more time is needed for this market segment (Gschrey et al., 2022). As a result, we have integrated novel substitutes for SF₆ in both high- and mid-voltage electrical switchgear within the GAINS model including AIR with a GWP₁₀₀ of zero, NOVEC-4710 with a GWP₁₀₀ of 2100 and NOVEC-5110 with a GWP₁₀₀ of 1 (Gschrey et al., 2022; Owens et al., 2021). In addition, emissions can be reduced through the adoption of recycling practices of used SF₆ switchgears. The EU F-gas Regulation requires end-of-life recollection and recycling from 2010 onwards. Full compliance with this regulation is assumed in GAINS to apply in all EU countries. Figure 24 shows GAINS emission estimates for this sector in comparison to emissions reported to UNFCCC (2022) for years 2005, 2010, 2015 and 2020. For the comparison with UNFCCC (2022) we have converted GAINS SF₆ emission estimates from high and mid voltage electrical switches into IPCC/AR5 GWP₁₀₀ values.

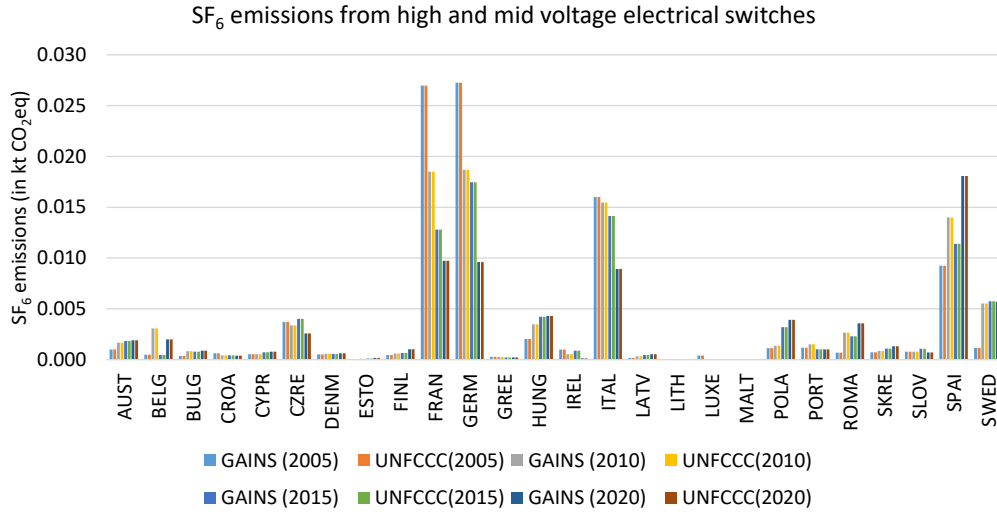


Figure 24: Historical SF₆ emissions from high and mid voltage electrical switches in the GAINS model and as reported to UNFCCC (2022).

5.4.2 Magnesium production and casting

Casting and production of primary and secondary magnesium are well known sources of atmospheric emissions of SF₆ and HFC-134a. The gases are used as shielding gas in magnesium foundries to protect the molten magnesium from re-oxidizing whilst it is running to best casting ingots (IPCC, 2000). GAINS use the reported SF₆ and HFC-134a emissions (UNFCCC, 2022) for the years 2005, 2010, 2015 and 2020 while future projections follow growth in value added for manufacturing industry. The EU’s 2006 regulation only restricted use of SF₆ in die casting operations. This is reflected in the baseline. For the use of HFC-134a, no current control is assumed in these processes. The bans on the use of SF₆ in the recycling of magnesium die casting alloys are new to the 2014 regulation (DEFRA, 2014). SF₆ emissions in magnesium production and casting can be substituted using sulphur dioxide (SO₂) or recently available sustainable cover gas NOVEC-612 with a GWP₁₀₀ of 1 as alternative gas.

5.4.3 Soundproof windows

Some European countries used significant amounts of SF₆ in soundproof windows. From 2006, the F-gas Regulation (EC 842/2006) bans the use of SF₆ in soundproof windows. Soundproof windows have a relatively long life-time and it is therefore expected that the stock of SF₆ found in such windows in 2005 will be successively phased-out over a period of 25 years. The available stock of SF₆ in soundproof windows in 2005 in EU countries is estimated at 288 t SF₆ in Austria, 75 t SF₆ in Belgium, 86 t SF₆ in Denmark, 1764 t SF₆ in Germany, 1.78 t SF₆ in Slovenia, and 11.1 t SF₆ in Sweden. These estimates were verified in national communications between IIASA and country experts as part of review processes of baseline non-CO₂ GHGs organized by the European Commission in 2009 and 2012. With an assumed leakage/refill rate of 1 percent per year for windows still in use and a linear phase-out of emissions, annual emissions from this source until 2030 (when phase-out is completed) are estimated as:

$$E_t^{SF_6} = \frac{Stock_{2005}}{25} + Stock_t * 0.01, \quad (42)$$

where the first term represents the end-of-life emissions from soundproof windows scrapped in year t and the latter term represents the emission leakage from windows still in use.

No further mitigation options beyond the ban included in the F-gas Regulation are considered necessary to control emissions from soundproof windows.

5.4.4 Other SF₆ sources

SF₆ has been used in tyres, sports equipment manufacturers in tennis balls and sport shoes. Activity data for these other sources of SF₆ emissions are taken from emissions reported by countries to the UNFCCC (2022). From 2006, the EU F-gas Regulation (EC 842/2006) bans the use of SF₆ in sports equipment and tyres. GAINS assumes that all EU countries adhere fully to this ban.

5.5 Costs of F-gas mitigation options

Costs of replacing HFCs with alternative cooling agents or through the use of alternative technological processes have recently been updated in the GAINS model as part of work to produce global mitigation scenarios for HFCs. The principal source of information for HFC mitigation costs used here is Schwartz et al. (2011) and Birchby et al., (2022). Assumptions and references for mitigation costs for PFCs and SF₆ can be found in the Supplement of Purohit and Höglund-Isaksson (2017) and Höglund-Isaksson et al., (2017b).

5.6 Comparison to AnaFgas model

As a quality control of the GAINS model results, comparisons were made to the results of the AnaFgas model, which is a bottom-up model independently developed by the Öko-Institut e.V. in Germany for estimation and projections of F-gas emissions in Europe (Birchby et al., 2022; Gschrey et al., 2022). Figure 25 illustrates sector-specific F-gas emissions within the EU27 in the GAINS and AnaFgas models. A contributing factor to the disparity between the two models' emissions data is the use of different global warming potentials (GWPs) over a 100-year timeframe: the GAINS model uses IPCC/AR5 GWPs, while the AnaFgas model uses IPCC/AR4 GWPs. As an illustration, when using IPCC/AR4 GWPs, the estimated weighted GWP for HFCs use in the commercial refrigeration sector in the EU27 is 2601, whereas it is 2525 when using IPCC/AR5 GWPs. Similarly, in the aerosol sector, the GWP of HFC-134a is 1430 using IPCC/AR4 and 1300 using IPCC/AR5.

The AnaFgas model team has access to industry data, e.g., on European aerosol production, including exports, while GAINS does not have access to this type of data but rely on publicly available data free of charge. The GAINS model therefore resorts to use the country-and sector-specific information on HFCs consumption reported to UNFCCC (2022). This disparity in the treatment of exports could potentially be an explanation for the discrepancies in aerosols emissions between the two models. AnaFgas anticipates the adoption of low-GWP refrigerant alternatives in the foam sector before the bans are enforced, resulting in lower emissions for 2020 compared to the GAINS model, which relies on HFC consumption data reported by member states to the UNFCCC. The decreasing HFC consumption reported by several member states confirms the shift to alternatives pre-ban. Within the heat pump sector, the AnaFgas model presumes a higher number of heat pumps in 2020 than what is indicated by other models or sources. In GAINS, we lack access to alternative data sources regarding country-specific

installed heat pump capacity, and rely on the data provided by Lund et al. (2022), Lund and Toth (2021), Lund and Boyd (2016), Lund et al. (2011), and Lund et al. (2005). In general, the AnaFgas model has access to and make use of more industry data (including inventories of small, medium, and large equipment) than GAINS, which relies heavily on the reported HFC consumption data.

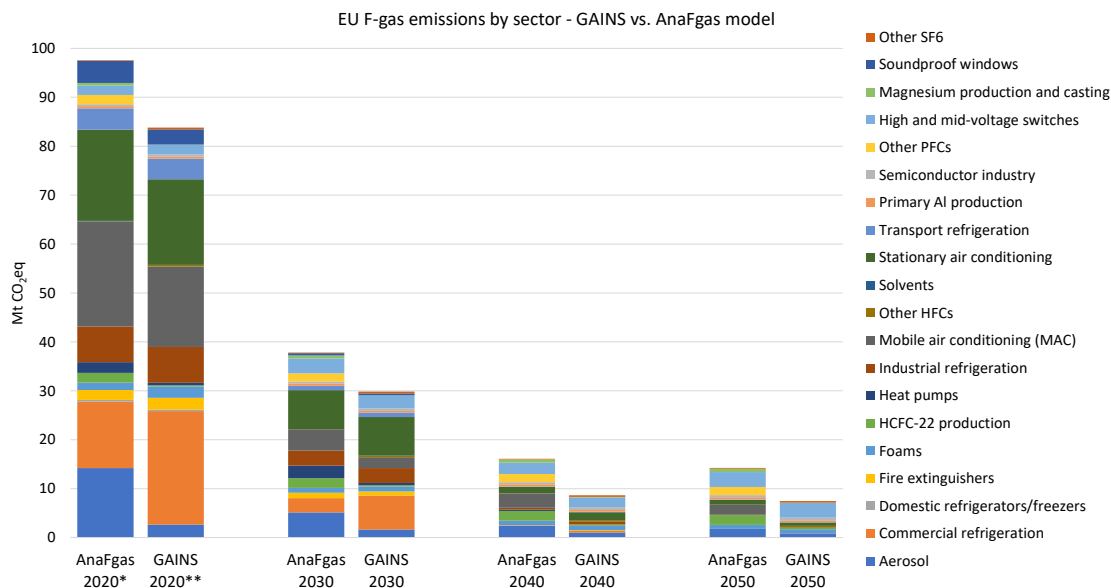


Figure 25: EU27 sector-specific F-gas emissions in Mt CO₂eq, comparing GAINS model results (employing IPCC AR5 global warming potentials) to the AnaFgas model results (employing IPCC AR4 global warming potentials).

6 Comparison of GAINS bottom-up emission estimates to UNFCCC inventory

6.1 Uncertainty in GAINS and national inventory non-CO₂ GHG emissions

There are several sources of uncertainty in emission inventories, however, the highest uncertainty is likely to be found in the choice of emission factors. For non-CO₂ GHG gases these are often linked to specific local conditions at the time and place of release, which makes it hard when converting individual measurements to representative annual average emission factors needed for the up-scaling of emissions in national inventories. E.g., the CH₄ formation from decomposition of organic waste material in landfills and from release of wastewater to water bodies depends to a high degree on climatic factors such as precipitation and temperature. This sensitivity of non-CO₂ emissions to local conditions is in contrast to energy sector CO₂ emission inventories, where emissions can often be linked directly to the carbon content of the combusted fuel. Uncertainty and methodological inconsistencies in non-CO₂ emission inventories carry over to future projections and mitigation potentials, which use the inventories as starting point for driving future emissions. Employing a consistent methodology in

inventories for CH₄ and N₂O is therefore important to ensure “fairness” between countries when assessing the relative ability of countries to contribute to future mitigation potentials.

A significant reduction in the uncertainty would be possible if there were technology that could detect and continuously monitor these emissions. E.g., the development of satellite detection technologies for CH₄ is rapid and promising, with the TROPOMI satellite instrument launched in 2018, however, it can only detect and monitor the very largest CH₄ emission events, which corresponds to about 3% of global CH₄ emissions (Schuit et al., 2023). In the absence of sufficiently powerful detection technology, the way forward when generating national emission inventories has been to agree on a common methodology, i.e., the IPCC guidelines published in 2006 (IPCC, 2006) and refined in 2019 (IPCC, 2019). The GAINS model follows as closely as possible the IPCC guidelines. However, these allow for a high degree of flexibility in methodological assumptions to accommodate the relatively large spread in quality and availability of country-specific data. This leads inevitably to discrepancies between GAINS and national emission inventories reported to the UNFCCC.

To gain some sense of the uncertainty present in both GAINS and the inventories, we make comparisons between the methodologically relatively consistent⁵ GAINS estimates and those reported to the UNFCCC as of April 2022, as well as to the most recent reporting as of August 2023. The former is the submission cut-off date used in all preparations of input data in the EUCLIMIT6 scenarios. A comparison for the years 2005, 2010, 2015 and 2020 is presented in Table 30 by country, gas and UNFCCC submission version. Presented are the discrepancies between GAINS and UNFCCC emissions after having calibrated for differences in the solid waste sector emissions. The reason for excluding these differences is that they can primarily be attributed to assumptions about decay times for landfilled organic waste, and with GAINS and national estimates typically converging in the years 2020 to 2030 (see Section 3.4.1).

As shown in Table 30, despite reasonably good agreement at the EU27 level, there are some significant discrepancies at the country and gas level. This is particularly the case for F-gases and can mainly be traced back to countries using different assumptions for F-gas leakage rates for the same sector and technology, while in the GAINS model the same leakage rates are assumed across all EU member states.

For N₂O emissions from agricultural soils, the GAINS model uses Tier 1 emission factors from the IPCC 2006 guidelines consistently across all countries. Some member states (e.g., Germany, Netherlands, Ireland) have already adopted the updated methodology from the 2019 refinement of the 2006 IPCC guidelines. This includes updated Tier 1 emission factors and also suggests a disaggregation of emission factors by climate region. Typically the refined 2019 methodology produces lower estimates of N₂O from soils than the methodology from the 2006 guidelines. For these countries, the GAINS estimates tend to be higher for this source, which is evident in Table 30.

⁵ Note that this is not to say that GAINS estimates are less uncertain and come closer to reality than the national inventories. It only states that the GAINS estimates are methodologically more consistent when comparing across countries.

Table 30: Deviation of GAINS EUCLIMIT6 from UNFCCC versions from April 2022 and August 2023, respectively.

Country	Gas	UNFCCC Common Reporting Format (version April 2022) in kt CO ₂ e _q (GWP ₁₀₀ from IPCC AR5)				UNFCCC Common Reporting Format (version August 2023) in kt CO ₂ e _q (GWP ₁₀₀ from IPCC AR5)				GAINS-POTEnCIA Baseline scenario in kt CO ₂ e _q (after calibration of waste sector CH ₄ to UNFCCC v2022)				GAINS-POTEnCIA Baseline scenario in kt CO ₂ e _q (after calibration of waste sector CH ₄ to UNFCCC v2023)				% divergence of GAINS scenario from UNFCCC v2022				% divergence of GAINS scenario from UNFCCC v2023			
		2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Austria	CH ₄	8526	7849	7116	6518	8514	7836	7103	6503	8622	7900	7123	6540	8608	7886	7109	6526	1%	1%	0%	0%	1%	1%	0%	0%
	N ₂ O	3207	3013	3161	3111	3188	2994	3142	3089	3561	3459	3548	3459	3561	3459	3548	3459	11%	15%	12%	11%	12%	16%	13%	12%
	F-gases	1210	1407	1906	1786	1254	1496	1942	1732	1690	2068	2397	2401	1690	2068	2397	2401	40%	47%	26%	34%	35%	38%	23%	39%
	sum non-CO ₂	12944	12270	12184	11415	12956	12326	12187	11324	13873	13427	13069	12400	13859	13413	13054	12386	7%	9%	7%	9%	7%	9%	7%	9%
Belgium	CH ₄	9630	9130	8501	7951	9630	9123	8487	7972	9499	8909	8224	7809	9499	8909	8224	7809	-1%	-2%	-3%	-2%	-1%	-2%	-3%	-2%
	N ₂ O	7545	6695	5328	4785	7545	6696	5328	4787	7955	7421	6040	5843	7955	7421	6040	5843	5%	11%	13%	22%	5%	11%	13%	22%
	F-gases	2739	3301	4219	3486	2521	3111	3933	3297	1615	2411	2747	2457	1615	2411	2747	2457	-41%	-27%	-35%	-30%	-36%	-22%	-30%	-25%
	sum non-CO ₂	19914	19126	18048	16222	19697	18931	17748	16056	19069	18741	17011	16109	19069	18741	17011	16109	-4%	-2%	-6%	-1%	-3%	-1%	-4%	0%
Bulgaria	CH ₄	7931	7585	7439	6422	7932	7586	7440	6407	8037	7476	7391	6463	8037	7476	7391	6463	1%	-1%	-1%	1%	1%	-1%	-1%	1%
	N ₂ O	3671	3564	4159	4233	3660	3554	4148	4234	3626	3688	4265	4195	3626	3688	4265	4195	-1%	3%	3%	-1%	-1%	4%	3%	-1%
	F-gases	195	663	2672	1704	166	415	694	790	535	393	495	472	535	393	495	472	174%	-41%	-81%	-72%	222%	-5%	-29%	-40%
	sum non-CO ₂	11797	11812	14270	12360	11758	11555	12282	11431	12198	11557	12152	11730	12198	11557	12152	11116	3%	-2%	-15%	-10%	4%	0%	-1%	-3%
Croatia	CH ₄	4088	4335	4186	3957	4156	4420	4266	4002	3589	3764	3695	3561	3603	3781	3711	3594	-12%	-13%	-12%	-10%	-13%	-14%	-13%	-10%
	N ₂ O	2186	2161	1579	1473	2177	2155	1567	1450	2162	2099	1635	1467	2162	2099	1635	1467	-1%	-3%	4%	0%	-1%	-3%	4%	1%
	F-gases	187	595	1007	1690	189	568	948	1575	390	819	845	1096	390	819	845	1096	108%	38%	-16%	-35%	106%	44%	-11%	-30%
	sum non-CO ₂	6461	7091	6772	7120	6522	7143	6781	7027	6141	6682	6175	6124	6155	6698	6192	6157	-5%	-6%	-9%	-14%	-6%	-6%	-9%	-12%
Cyprus	CH ₄	940	964	966	1084	960	974	957	1065	938	1010	1035	1086	922	991	1012	1053	0%	5%	7%	0%	-4%	2%	6%	-1%
	N ₂ O	249	244	205	229	171	169	151	173	265	274	245	253	265	274	245	253	6%	12%	19%	10%	55%	62%	62%	47%
	F-gases	122	214	262	358	122	199	247	336	111	179	246	273	111	179	246	273	-9%	-16%	-6%	-24%	-9%	-10%	0%	-19%
	sum non-CO ₂	1311	1422	1433	1671	1253	1342	1355	1573	1313	1463	1526	1612	1297	1444	1503	1579	0%	3%	6%	-4%	4%	8%	11%	0%
Czech Rep.	CH ₄	16282	15658	15007	12901	16532	15710	14938	13098	15944	14884	14366	11933	15944	14884	14366	11933	-2%	-5%	-4%	-8%	-4%	-5%	-4%	-9%
	N ₂ O	5598	4756	5457	4738	5236	4399	5151	4472	5212	4557	4863	4770	5212	4557	4863	4770	-7%	-4%	-11%	1%	0%	4%	-6%	7%
	F-gases	1465	2656	3547	4020	1361	2482	3312	3735	906	2016	2616	2763	906	2016	2616	2763	-38%	-24%	-26%	-31%	-33%	-19%	-21%	-26%
	sum non-CO ₂	23345	23070	24011	21660	23129	22591	23401	21306	22062	21457	21845	19466	22062	21457	21845	19466	-5%	-7%	-9%	-10%	-5%	-5%	-7%	-9%
Denmark	CH ₄	8978	8611	8075	8024	9352	8962	8451	8559	8848	8534	8171	8033	8560	8273	7978	7877	-1%	-1%	1%	0%	-8%	-8%	-6%	-8%
	N ₂ O	5324	5055	5097	5172	5361	5172	5204	5388	5568	5534	5610	5649	5568	5534	5610	5649	5%	9%	10%	9%	4%	7%	8%	5%
	F-gases	946	870	518	482	889	816	450	317	1170	1201	1010	772	1170	1201	1010	772	24%	38%	95%	60%	32%	47%	124%	143%
	sum non-CO ₂	15249	14536	13691	13679	15602	14950	14105	14265	15587	15269	14790	14454	15298	15008	14597	14299	2%	5%	8%	6%	-2%	0%	3%	0%
Estonia	CH ₄	1388	1404	1227	1227	1312	1298	1151	1145	1341	1357	1205	1216	1341	1357	1205	1216	-3%	-3%	-2%	-1%	2%	4%	5%	6%
	N ₂ O	598	664	772	827	602	665	778	841	747	819	902	897	747	819	902	897	25%	23%	17%	8%	24%	23%	16%	7%
	F-gases	135	176	223	185	128	171	216	180	133	177	201	184	133	177	201	184	-1%	0%	-10%	-1%	4%	4%	-7%	2%
	sum non-CO ₂	2121	2244	2223	2238	2043	2134	2146	2165	2222	2353	2308	2297	2222	2353	2308	2297	5%	5%	4%	3%	9%	10%	8%	6%
Finland	CH ₄	6253	5992	5440	4930	6258	5993	5470	4938	6379	5976	5433	4872	6379	5976	5434	4872	2%	0%	0%	-1%	2%	0%	-1%	-1%
	N ₂ O	5367	4254	4226	4199	5250	4136	4137	4156	5584	4590	4657	4263	5584	4590	4657	4263	4%	8%	10%	2%	6%	11%	13%	3%
	F-gases	1162	1366	1241	978	1127	1323	1194	905	1056	1520	1668	1429	1056	1520	1668	1429	-9%	11%	34%	46%	-6%	15%	40%	58%
	sum non-CO ₂	12782	11612	10907	10107	12635	11452	10801	9999	13018	12086	11759	10565	13018	12086	11759	10565	2%	4%	8%	5%	3%	6%	9%	6%
France	CH ₄	71741	69541	65317	61738	75397	73731	66819	63774	70549	70024	65582	61223	70018	69569	63693	60468	-2%	1%	0%	-1%	-7%	-6%	-5%	-5%
	N ₂ O	41308	36118	35600	32397	34969	28971	28759	26049	42005	37822	38278	36010	42005	37822	38278	36010	2%	5%	8%	11%	20%	31%	33%	38%
	F-gases	14665	17604	18106	12366	13883	16951	17443	11753	11801	14479	13751	10196	11801	14479	13751	10196	-20%	-18%	-24%	-18%	-15%	-15%	-21%	-13%
	sum non-CO ₂	127714	123264	119023	106500	124250	119653	113021	101576	124355	122325	117610	107429	123824	121869	115722	106675	-3%	-1%	-1%	1%	0%	2%	2%	5%

Cont.Table 30: Deviation of GAINS EUCLIMIT6 from UNFCCC versions from April 2022 and August 2023, respectively.

Country	Gas	UNFCCC Common Reporting Format (version April 2022) in kt CO2eq (GWP ₁₀₀ from IPCC AR5)				UNFCCC Common Reporting Format (version August 2023) in kt CO2eq (GWP ₁₀₀ from IPCC AR5)				GAINS-POTEnCIA Baseline scenario in kt CO2eq (after calibration of waste sector CH4 to UNFCCC v2022)				GAINS-POTEnCIA Baseline scenario in kt CO2eq (after calibration of waste sector CH4 to UNFCCC v2023)				% divergence of GAINS scenario from UNFCCC v2022				% divergence of GAINS scenario from UNFCCC v2023					
		2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010
Germany	CH ₄	76945	65116	62302	54897	72574	60100	55895	47051	81232	62775	57596	49672	76255	57674	52785	45061	6%	-4%	-8%	-10%	5%	-4%	-6%	-4%		
	N ₂ O	33367	27426	28149	25061	33367	27449	28155	24922	42644	35394	36662	32380	42644	35394	36662	32380	28%	29%	30%	29%	28%	29%	30%	30%		
	F-gases	10897	11183	11857	9140	10192	10549	11165	8586	11869	14038	15558	13034	11869	14038	15558	13034	9%	26%	31%	43%	16%	33%	39%	52%		
	sum non-CO₂	121209	103725	102308	89099	116132	98098	95216	80560	135745	112208	109817	95085	130768	107107	105006	90474	12%	8%	7%	7%	13%	9%	10%	12%		
Greece	CH ₄	12776	12412	11363	10847	12799	12432	11379	10959	13378	13286	11911	10943	13378	13286	11911	10946	5%	7%	5%	1%	5%	7%	5%	0%		
	N ₂ O	5284	4866	3759	3792	5468	5035	3904	3931	4934	4581	3720	3347	4934	4581	3720	3347	-7%	-6%	-1%	-12%	-10%	-9%	-5%	-15%		
	F-gases	5170	4597	6119	5271	4586	4333	5750	4950	4350	4114	5670	4426	4350	4114	5670	4426	-16%	-11%	-7%	-16%	-5%	-5%	-1%	-11%		
	sum non-CO₂	23230	21875	21241	19910	22853	21800	21032	19840	22662	21981	21301	18716	22662	21981	21301	18720	-2%	0%	0%	-6%	-1%	1%	1%	-6%		
Hungary	CH ₄	10870	9961	9390	9206	10470	9781	9451	9207	10383	9678	9431	9149	10383	9678	9431	9141	-4%	-3%	0%	-1%	-1%	-1%	0%	-1%		
	N ₂ O	4987	3303	4015	4458	4992	3309	4022	4462	5958	4262	5044	5421	5958	4262	5044	5421	19%	29%	26%	22%	19%	29%	26%	22%		
	F-gases	1034	1253	1825	2192	1000	1263	1889	1850	870	936	1226	1357	870	936	1226	1357	-16%	-25%	-33%	-38%	-13%	-26%	-35%	-27%		
	sum non-CO₂	16891	14517	15230	15856	16462	14352	15362	15519	17212	14875	15701	15927	17212	14875	15701	15919	2%	2%	3%	0%	5%	4%	2%	3%		
Ireland	CH ₄	15724	14085	15742	16700	16332	14535	16233	17287	16601	14859	16443	17487	16601	14859	16443	17477	6%	5%	4%	5%	2%	2%	1%	1%		
	N ₂ O	6139	5736	5757	6108	5900	5583	5575	5926	7947	7661	7794	8037	7947	7661	7794	8037	29%	34%	35%	32%	35%	37%	40%	36%		
	F-gases	1073	1095	1185	764	1017	1059	1135	688	1153	1529	1359	1581	1153	1529	1359	1581	7%	40%	15%	107%	13%	44%	20%	130%		
	sum non-CO₂	22936	20916	22684	23572	23249	21177	22943	23901	25701	24049	25595	27104	25701	24049	25595	27095	12%	15%	13%	15%	11%	14%	12%	13%		
Italy	CH ₄	55109	53022	49406	47914	54703	52690	49316	47513	58125	55186	49298	47912	58123	55185	49296	47908	5%	4%	0%	0%	6%	5%	0%	1%		
	N ₂ O	26038	18080	16777	17315	26048	18090	16788	17346	24210	16031	15560	14952	24210	16031	15560	14952	-7%	-11%	-7%	-14%	-7%	-11%	-7%	-14%		
	F-gases	9584	13601	17116	16438	10502	15726	17183	16556	13084	18696	19486	19062	13084	18696	19486	19062	37%	37%	14%	16%	25%	19%	13%	15%		
	sum non-CO₂	90732	84702	83299	81666	91252	86506	83286	81415	95419	89913	84344	81925	95417	89912	84342	81921	5%	6%	1%	0%	5%	4%	1%	1%		
Latvia	CH ₄	2095	2023	1985	1924	2092	2003	1968	1898	1964	1937	1862	1831	1960	1922	1842	1796	-6%	-4%	-6%	-5%	-6%	-4%	-6%	-5%		
	N ₂ O	1012	1085	1248	1310	1013	1087	1260	1336	1348	1451	1619	1655	1348	1451	1619	1655	33%	34%	30%	26%	33%	34%	28%	24%		
	F-gases	105	214	255	249	101	206	243	237	133	308	292	210	133	308	292	210	27%	44%	15%	-16%	32%	50%	20%	-11%		
	sum non-CO₂	3212	3322	3488	3484	3205	3295	3471	3471	3445	3696	3773	3696	3441	3681	3754	3661	7%	11%	8%	6%	7%	12%	8%	5%		
Lithuania	CH ₄	4352	4038	3776	3207	4391	4093	3862	3322	4198	3851	3573	3064	4198	3859	3604	3094	-4%	-5%	-5%	-4%	-4%	-6%	-7%	-7%		
	N ₂ O	4109	2611	2705	2799	4098	2593	2681	2794	4155	2766	2821	2718	4155	2766	2821	2718	1%	6%	4%	-3%	1%	7%	5%	-3%		
	F-gases	89	256	566	508	86	247	551	502	151	252	378	330	151	252	378	330	69%	-2%	-33%	-35%	74%	2%	-31%	-34%		
	sum non-CO₂	8550	6905	7047	6515	8575	6933	7094	6617	8503	6868	6771	6113	8504	6877	6803	6143	-1%	-1%	-4%	-6%	-1%	-1%	-4%	-7%		
Luxembourg	CH ₄	646	659	644	650	652	673	657	668	655	666	645	641	659	673	653	649	1%	1%	0%	-1%	1%	0%	-1%	-3%		
	N ₂ O	264	283	284	287	220	233	235	239	277	279	287	289	277	279	287	289	5%	-1%	1%	1%	26%	20%	22%	21%		
	F-gases	40	54	67	56	42	56	71	55	46	84	93	88	46	84	93	88	13%	57%	39%	57%	9%	49%	32%	59%		
	sum non-CO₂	950	995	995	993	914	961	963	962	978	1030	1025	1018	982	1036	1033	1027	3%	3%	3%	3%	7%	8%	7%	7%		
Malta	CH ₄	246	165	192	217	245	166	193	233	256	183	225	262	258	183	225	275	4%	11%	17%	21%	5%	10%	17%	18%		
	N ₂ O	68	58	49	49	59	57	51	57	74	87	84	101	74	87	84	101	9%	49%	71%	105%	26%	52%	65%	79%		
	F-gases	38	141	231	272	35	135	220	225	25	102	148	134	25	102	148	134	-35%	-28%	-36%	-51%	-29%	-24%	-33%	-41%		
	sum non-CO₂	352	365	472	539	339	358	464	514	355	372	456	496	357	372	457	510	1%	2%	-3%	-8%	5%	4%	-1%	-1%		
Netherlands	CH ₄	22148	21682	20322	19004	22142	21681	20293	18974	21286	19680	19013	17028	21286	19680	19013	17153	-4%	-9%	-6%	-10%	-4%	-9%	-6%	-10%		
	N ₂ O	12328	7247	7406	6896	12883	7811	7971	7459	14711	9820	10487	9978	14711	9820	10487	9978	19%	35%	42%	45%	14%	26%	32%	34%		
	F-gases	1740	2443	1922	1219	1625	2278	1835	1122	3753	4388	3276	3040	3753	4388	3276	3040	116%	80%	70%	149%	131%	93%	79%	171%		
	sum non-CO₂	36215	31372	29650	27119	36650	31770	30099	27555	39751	33887	32776	30046	39751	33887	32776	30171	10%	8%	11%	11%	8%	7%	9%	9%		

Cont.Table 30: Deviation of GAINS EUCLIMIT6 from UNFCCC versions from April 2022 and August 2023, respectively.

Country	Gas	UNFCCC Common Reporting Format (version April 2022) in kt CO ₂ e _q (GWP ₁₀₀ from IPCC AR5)				UNFCCC Common Reporting Format (version August 2023) in kt CO ₂ e _q (GWP ₁₀₀ from IPCC AR5)				GAINS-POTEnCIA Baseline scenario in kt CO ₂ e _q (after calibration of waste sector CH ₄ to UNFCCC v2022)				GAINS-POTEnCIA Baseline scenario in kt CO ₂ e _q (after calibration of waste sector CH ₄ to UNFCCC v2023)				% divergence of GAINS scenario from UNFCCC v2022				% divergence of GAINS scenario from UNFCCC v2023			
		2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Poland	CH ₄	59178	56293	54387	49679	51777	47759	45941	43188	53615	49110	48353	41331	47738	41106	40229	34280	-9%	-13%	-11%	-17%	-8%	-14%	-12%	-21%
	N ₂ O	22183	19624	19086	20309	22206	19601	19062	20470	22998	20639	19828	20467	22998	20639	19828	20467	4%	5%	4%	1%	4%	5%	4%	0%
	F-gases	3983	5620	5595	5231	3933	5616	5567	5125	3697	6359	8111	7856	3697	6359	8111	7856	-7%	13%	45%	50%	-6%	13%	45%	53%
	sum non-CO ₂	85344	81537	79067	75219	77916	72976	70601	68783	80309	76108	76292	69654	74433	68104	68168	62603	-6%	-7%	-4%	-7%	-4%	-7%	-3%	-9%
Portugal	CH ₄	12200	11255	10279	10043	12396	11442	10438	10235	14327	12648	12068	12137	14578	12831	12220	12300	17%	12%	17%	21%	18%	12%	17%	20%
	N ₂ O	3440	3180	2885	2940	3443	3194	2906	2965	3527	3172	3132	3052	3527	3172	3132	3052	3%	0%	9%	4%	2%	-1%	8%	3%
	F-gases	1058	2065	2819	3358	988	1924	2608	3110	951	1729	2321	2323	951	1729	2321	2323	-10%	-16%	-18%	-31%	-4%	-10%	-11%	-25%
	sum non-CO ₂	16698	16500	15983	16341	16827	16560	15951	16311	18804	17549	17522	17512	19055	17732	17673	17675	13%	6%	10%	7%	13%	7%	11%	8%
Romania	CH ₄	36393	29244	27420	25489	36857	29799	28062	26341	31486	26483	25695	24015	31486	26483	25696	24018	-13%	-9%	-6%	-6%	-15%	-11%	-8%	-9%
	N ₂ O	12166	9726	9504	9717	12185	9814	9579	9756	11517	9318	8916	8751	11517	9318	8916	8751	-5%	-4%	-6%	-10%	-5%	-5%	-7%	-10%
	F-gases	470	1011	1672	2313	434	907	1387	1851	905	1004	1535	1615	905	1004	1535	1615	93%	-1%	-8%	-30%	108%	11%	11%	-13%
	sum non-CO ₂	49029	39982	38595	37518	49476	40521	39028	37947	43909	36805	36146	34381	43909	36805	36147	34384	-10%	-8%	-6%	-8%	-11%	-9%	-7%	-9%
Slovakia	CH ₄	4864	4377	3941	3653	4865	4380	3981	3700	5003	4593	4164	3932	5004	4597	4204	3979	3%	5%	6%	8%	3%	5%	6%	8%
	N ₂ O	2695	2375	1702	1729	2687	2366	1690	1722	2841	2362	1934	1961	2841	2362	1934	1961	5%	-1%	14%	13%	6%	0%	14%	14%
	F-gases	317	622	743	684	299	592	712	652	356	545	553	500	356	545	553	500	12%	-12%	-26%	-27%	19%	-8%	-22%	-23%
	sum non-CO ₂	7875	7374	6386	6067	7851	7338	6383	6074	8200	7500	6652	6393	8201	7503	6692	6440	4%	2%	4%	5%	4%	2%	5%	6%
Slovenia	CH ₄	2753	2430	2256	2121	2753	2431	2258	2131	2781	2527	2414	2292	2781	2527	2414	2292	1%	4%	7%	8%	1%	4%	7%	8%
	N ₂ O	682	648	666	686	681	648	665	685	716	685	672	658	716	685	672	658	5%	6%	1%	-4%	5%	6%	1%	-4%
	F-gases	287	267	359	305	258	241	326	286	251	207	289	288	251	207	289	288	-13%	-23%	-19%	-5%	-3%	-14%	-11%	1%
	sum non-CO ₂	3722	3346	3282	3111	3692	3320	3250	3103	3749	3419	3375	3237	3748	3419	3375	3237	1%	2%	3%	4%	2%	3%	4%	4%
Spain	CH ₄	45815	44139	42805	42267	45439	43790	42288	41467	42618	42481	42294	41608	42637	42482	42295	41537	-7%	-4%	-1%	-2%	-6%	-3%	0%	0%
	N ₂ O	17090	15742	15612	16215	13422	12011	11605	12031	16280	15859	16580	16143	16280	15859	16580	16143	-5%	1%	6%	0%	21%	32%	43%	34%
	F-gases	11918	16527	9255	5200	11341	15672	8735	4883	7725	9374	6104	3902	7725	9374	6104	3902	-35%	-43%	-34%	-25%	-32%	-40%	-30%	-20%
	sum non-CO ₂	74824	76408	67672	63682	70202	71473	62628	58381	66623	67714	64977	61652	66643	67715	64978	61581	-11%	-11%	-4%	-3%	-5%	-5%	4%	5%
Sweden	CH ₄	6863	5837	5061	4603	6864	5833	5058	4589	7125	6113	5293	4789	7184	6199	5368	4862	4%	5%	5%	4%	5%	6%	6%	6%
	N ₂ O	4416	4294	4122	4105	4235	4124	3935	3953	4574	4512	4453	4426	4574	4512	4453	4426	4%	5%	8%	8%	8%	9%	13%	12%
	F-gases	1517	1322	1157	1004	1410	1233	1090	947	2173	2097	1929	2068	2173	2097	1929	2068	43%	59%	67%	106%	54%	70%	77%	118%
	sum non-CO ₂	12795	11453	10340	9713	12509	11190	10084	9489	13872	12723	11674	11283	13931	12809	11749	11356	8%	11%	13%	16%	11%	14%	17%	20%
EU-27	CH ₄	504735	467809	444545	417172	497394	459220	432355	406225	498779	455889	432500	400827	487421	442325	417753	388565	-1%	-3%	-3%	-4%	-2%	-4%	-3%	-4%
	N ₂ O	231320	192809	189311	184940	221066	181915	178449	174693	245397	209140	209636	201143	245397	209140	209636	201143	6%	8%	11%	9%	11%	15%	17%	15%
	F-gases	72149	91124	96443	81261	69490	89570	90876	76245	70898	91025	94304	83856	70898	91025	94304	83856	-2%	0%	-2%	3%	2%	2%	4%	10%
	sum non-CO ₂	808204	751742	730299	683373	787949	730705	701680	657163	815074	756054	736440	685826	803716	742490	721693	673563	1%	1%	1%	0%	2%	2%	3%	2%
United Kingdom	CH ₄	95634	69955	57146	52371	95711	70128	57334	52266	101450	72836	58886	54105	101501	72886	58925	54083	6%	4%	3%	3%	6%	4%	3%	3%
	N ₂ O	21456	18848	18097	17161	21730	19314	18749	17438	26458	23808	23423	21814	26458	23808	23423	21814	23%	26%	29%	27%	22%	23%	25%	25%
	F-gases	9587	12352	14326	12369	9043	11760	13607	11677	10262	12848	13624	12164	10262	12848	13624	12164	7%	4%	-5%	-2%	13%	9%	0%	4%
	sum non-CO ₂	126678	101155	89569	81901	126484	101202	89689	81380	138170	109492	95932	88082	138220	109542	95972	88061	9%	8%	7%	8%	9%	8%	7%	8%

6.2 Calibration to emissions reported to the UNFCCC

EU member states report on an annual basis their emissions of non-CO₂ GHGs to the European Environment Agency (EEA), which cross-checks, reviews and, if necessary, requests revisions of the national inventory, before these are submitted jointly by the EEA to the UNFCCC. When developing climate policy proposals, the European Commission starts from the national emission inventories that have been vetted and approved by the EEA. With GAINS using a consistent methodology across member states, non-CO₂ GHG emissions will differ from the reported. For this reason it is necessary to introduce a calibration procedure where the differences between GAINS and reported inventories are monitored and reported as part of the GAINS results.

The calibration procedure is performed such that the differences in CH₄ and N₂O emission estimates, respectively, at the major sector level (agriculture, energy, waste, other) are derived for each year 2005, 2010, 2015 and 2020. The differences found for the year 2020 are then propagated into future years, but now scaled proportionately to the future development in the respective sector level emissions. An exception is made for the calibration factor in future years for CH₄ emissions from solid waste, where the difference in GAINS model estimates and national reported emissions is largely referred to the variability in national assumptions on the length of the time-lag between deposition of organic waste to landfills and the release of emissions after the waste has decomposed (see Section 3.4.1). Some countries seem to make more optimistic assumptions than GAINS about the waste decay rate and how fast measures implemented to fulfil the 1999 amendment of the Landfill Directive have an impact on future emissions. From 2025 onwards, GAINS and national emission estimates for solid waste appear to converge (as illustrated in Figures 5 and 6). The CH₄ calibration factor for solid waste is therefore set to zero for all future years in all countries.

Another complication is that countries update their inventory submissions to the UNFCCC at least once a year. As updates often include methodological changes, emission estimates will change for all historical years to maintain methodological consistency throughout the entire time series from the UNFCCC baseyear in 1990 to the last reported year. For the modelling of non-CO₂ GHGs in GAINS, several source sectors use input data from the UNFCCC Common Reporting Format (CRF) tables submission as of April 2022, e.g., F-gas consumption in different sectors by F-gas species, data on waste and wastewater treatment pathways, implied CH₄ emission factors for livestock, and simulation of current control levels for gas distribution networks. The conversion of this information into GAINS is a time-consuming process in several steps, which cannot be done on a too frequent basis. Between the April 2022 and August 2023 submissions, several countries made methodological changes to their inventories. To account for these without making a full reiteration of the GAINS run, which would not be possible due to time constraints, calibration of GAINS emission estimates was also performed to the national emission inventories reported to the UNFCCC as of August 2023.

F-gases have not been calibrated to the National reporting to the UNFCCC, due to less complete reporting for some of the EU member states. Instead, the modelling and key assumptions used in GAINS have been cross-checked with the modelling of the AnaFgas model (by Öko-institut) as described in Section 5.6.

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