Attributing and Verifying European and National Greenhouse Gas and Aerosol Emissions and Reconciliation with Statistical Bottom-up Estimates

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Specification of Target Quantities for the Evaluation of the Capabilities of Future Observing Networks

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Attributing and Verifying European and National Greenhouse Gas and Aerosol Emissions and Reconciliation with Statistical Bottom-up Estimates (AVENGERS)

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1 Executive Summary

The AVENGERS project acts with the overall objective to reconcile between top-down methods based on atmospheric observations and existing national bottom-up emission inventories based on statistics and reporting from industry and other activities. The project evaluates potential contributions of top-down capacities to current emission monitoring. This work analyses the current emission situation in Europe, together with the existing reporting schemes and corresponding policies, in order to increase the impact the AVENGERS project and top-down monitoring capacities can achieve. It provides a baseline for those monitoring applications and formulates potentials and requirements for future developments of top-down capacities, to be become applicable for compliance reporting and compliance monitoring. A particular focus is on the GHG methane (CH_4) due to recently adopted mitigation policies and a rapid evolution of a potential monitoring infrastructure. First similar considerations for the GHGs carbon dioxide (CO_2) and nitrous oxide (N_2O) are summarized at the end of this document.

The analysis reveals that capacities for top-down methane emission detection have the opportunity to study individual strong emission sources in Europe from different sectors. They can provide intra-annual and spatially-attributed insight into emission processes in addition to existing annual reporting frameworks. Target-specific monitoring allows to reach the highest monitoring standards for competent authorities and operators. A reliable detection limit for methane emissions down to 10 kg/h should optimally be reached by monitoring tools in order to make them applicable for target specific emission surveillance in Europe with relevance for the current reporting frameworks, for example to detect occurring emissions and allow to monitor temporal differences in the emissions in Europe.

Top-down methods ideally could be used to construct emission factors according to the existing UNFCCC reporting framework, to contribute to existing inventories directly. Monitoring capacities need to provide results in structured and user-oriented manner, in order to be usable for end-users such as competent authorities for emission reporting. Besides direct contributions to inventories, top-down capabilities have the potential to allow for diverse complementary applications such as to inform current and future policies, provide public information and support emission reduction measures. Furthermore, top-down methods provide the opportunity to identify and attribute unconstrained emissions to their source, analyse emissions along global production chains and study targets beyond reporting frameworks (e.g. in the context of cattle farming).

2 Context and Scope of this Document

Evolving detection capabilities for greenhouse gas emissions provide the opportunity to improve the transparency about emissions into the atmosphere: In the last few years, diverse detection capacities have demonstrated their ability to measure GHG emissions, in particular methane, under favourable conditions like strong enough emission rates and favourable wind conditions [see e.g. 1, 2, 3, 4]. Spaceborne, airborne and ground-based measurement capacities have proven to be able to measure greenhouse gas concentrations in the atmosphere, while inverse atmospheric transport models and emission plume propagation models have been used to allocate emissions to their source and calculate its emission rates [see e.g. 4, 5, 6].

With the Global Methane Pledge, launched at the 26th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), more than 150 parties (i.e. mostly countries) have committed themselves to reduce the global methane emissions by at least 30 percent until 2030 compared to 2020 [7]. A central component of efforts to cut emissions and corresponding policy frameworks are existing national bottom-up emission inventories. They are currently based on activity data from industry and others activities, like fuel consumption or detailed information reported under different contexts such as the European Union's Emission Trading System (ETS). Parties report their compiled emission situation and procedures how the emissions were constrained annually in detailed national inventory reports (NIR) [see e.g. 8]. In this context, the AVENGERS project acts with the overall objective to evaluate potential contributions of top-down capacities to current inventories, to improve and support bottom-up emission reports and reconcile with top-down results based on atmospheric observations [9].

In order to increase the impact the AVENGERS project and top-down capacities can achieve, this work analyses the existing emission reporting schemes, the current emission situation in Europe and corresponding policies. In particular, the key emitting sources in Europe, which are compiled by inventory compilers such as competent authorities taking part in the AVENGERS project, are evaluated to guide the application of top-down methods and formulate requirements for developing capacities with regard to inventories and policies, such as the recently adopted EU methane policy for the energy sector.

This document focuses on the emission situation of methane in Europe, due to the rapidly evolving methane emission detection capacities [see e.g. 1, 3, 4, 10], including aggregated national emissions, individual point sources and respective policies. At the end of this document, similar considerations are made in support of evolving CO_2 and N_2O monitoring capacities.

3 Bottom-Up Inventories as a Baseline for Top-Down Approaches

In December 2015, at the 21th UNFCCC's Conference of the Parties, the Paris Agreement was adopted [11]. Each party that signed the agreement creates an annual overview of greenhouse gas emissions in the country and submits it to the UNFCCC in the form of written documents and data tables [reporting requirements: 12, data access: 13]. Competent authorities, such as the Umweltbundesamt (German Environment Agency) in Germany, ISPRA (Italian Institute for Environmental Protection and Research) in Italy or RIVM (National Institute for Public Health and the Environment) in Netherlands, act as national entities in charge of emission reporting (including for example data collection, estimation, quality assurance and compilation). National entities can also commission parts in the emission reporting process to partners, such as for the emissions by Land Use, Land-Use Change and Forestry in Sweden the SLU (Swedish University of Agricultural Science) or for preparation of emissions and reporting in Cyprus the Cyprus Institute [see 8]. The entities produce comprehensive bottom-up emission inventories and submit them to the UNFCCC in the form of annual reporting tables for the period from 1990 to the latest year for submission (two years before the present). In addition, they produce and submit corresponding annual National Inventory Reports (NIRs) about their methodical procedures and the national emission situation. The entities build, for example, domestic reporting cycles, foster research and discussions with companies, associations and other agencies, as well as research by universities or private research institutes, and implement the reporting guidelines defined in the UNFCCC framework.

In the past, parties have been reporting under the UNFCCC's Kyoto Protocol [14], where they have been separated into Annex-I and Non-Annex-I parties, based on their industrialisation and economy. With the Paris Agreement's reporting guidelines entering into action in 2024, all parties will follow the same yearly reporting cycle. In the European Union, national inventories are also annually submitted to the EU, which has also ratified the UNFCCC agreements and the Paris Agreement's objectives are joint objectives for both the EU and its Member States individually [15].

These national inventories allow for comprehensive insights into the bottom-up compiled emitting sources and are used in this document to sketch a baseline for target selection and objectives of top-down approaches. In the following, the compiled methane emissions in Europe are sorted by their sector based on the UNFCCC reporting guidelines sector definition and presented in Figure 1.

In Figure 1, pie charts depict the emissions assigned to each individual country, where the area of the pie represents each country's emission total relative to the other countries' emission total. Likewise, the sectoral wedges represent the sector's share of the national total emissions. The wedge's area represents the absolute amount of emissions matching in size relative to the general pie areas.

- The UNFCCC classification divides source types into categories, with the sectors describing the upper-level classification, composed of subcategories. As an example, the category “2. Industrial Processes and Product Use” includes the category “2.B Chemical Industry”, again including the category “2.B.1 Ammonia Production”. In this document, the upper-level classifications are called sectors. Their full denotations based on the UNFCCC scheme are abbreviated for visualisation.

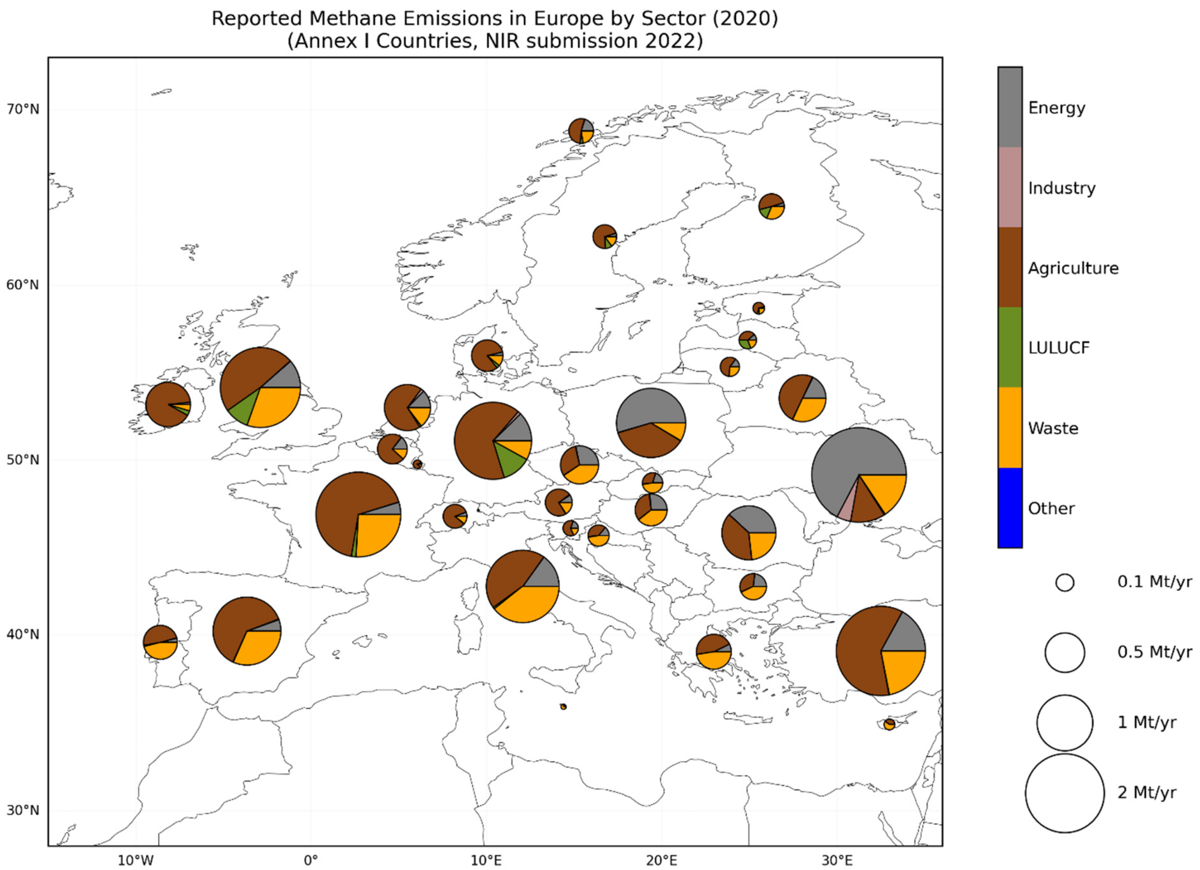

Figure 1: *Reported aggregated methane emissions in Europe for the UNFCCC Annex I countries in 2020, based on their 2022-submission of National Inventory Reports to the UNFCCC. Emissions for each country are illustrated as pie charts showing the individual sectors contributing to the national emission budget. The pie areas adequately represent the total national methane emission rates relative to each other. Emissions are allocated to the respective national centroid with deviations for France, Croatia, Netherlands and Türkiye for visualisation purposes. Full sector denotations are abbreviated for visualisation purposes as well.*

In Figure 1, multiple aspects become apparent. First, few sectors contribute the majority to the European methane emission budget. Contributions come from the energy sector, where methane is emitted, for example, via leakages along the extraction and use of fossil fuels. In many countries, methane emissions from the waste sector make up a substantial part of the emission budget, typically caused by the decomposition of organic components in waste on landfills or in the treatment and discharge of wastewater. The agricultural sector contributes the largest sectoral share of methane emissions, mainly caused by enteric fermentation in cattle farming and manure management. Depending on the country, industrial emissions and the emissions from LULUCF (Land Use, Land-Use Change, and Forestry) sector can contribute a minor share to the country's emission budget, whereas other emission sources hardly contribute.

The individual sectors differ in the nature of their underlying emission procedures and origins. On the one hand, particularly the energy, industry and waste sectors host individual facilities such as mines, industrial plants, landfills, and wastewater treatment plants. In theory, their emissions can often be assigned to individual installations having a high magnitude of emissions, which are released by a localised and permanently installed facility. On the other hand, for example in agriculture and LULUCF sectors, emissions are typically caused by many smaller entities, low in emission rate per entity but large in numbers such as in cattle farming, or produced area-wide over extended areas such as wetlands. Thus, a variety of possibilities for applying top-down methods along with bottom-up approaches is discussed below.

One of these top-down methods is atmospheric inversion modelling which aims to constrain emission fluxes from spatially-resolved grids to detect emissions from defined areas. Atmospheric inversion modelling is used in multiple work packages of AVENGERS. In general, its valuable contributions to existing bottom-up inventories are for example verification of total emission fluxes, regional attribution of emissions or source attribution via sectoral classification. A different general method is to directly monitor emission sources in sectors where single strong emitters are releasing methane emission rates within detection limits, to make individual releases transparent and attribute the released amount to its particular origin. For a more precise assessment, the workflows of inventory reporting are sketched briefly in the following.

National inventories are primarily built on activity data and emission factors such that they are able to constrain nation-wide emission situations beyond describing emissions of single emitting entities, describing national emissions for example by sector or gas. Emission factors are parameters that describe what amount of material, such as methane, is released per amount of activity causing the emission. The activity should be a determinable quantity in the process of the release, such as the number of methane-producing animals. In this example, the emission factor could be the average emission rate of an individual animal. Even though this is a simple example, it is difficult to consider all parameters such as impacts of different food supplies, animal size and more. A more complex case would be leakage rates along the production and exploitation of gas or oil. In principle, methane leaks can exist everywhere, from leakage at the initial drilling location over leaks along the pipeline networks up to leakage rates during incomplete combustion processes at the gas consumer. These examples illustrate the differences and complexities of emission processes impacting the inventory compilation.

Different methods for inventory calculations are categorised into Tier levels. The most basic form of inventory calculations implements international default values for the emission factors, such as from the IPCC guidelines, which are then multiplied with national activity rates (Tier 1 method) [16]. More elaborate approaches use nationally determined values for emission factors (Tier 2 methods). Tier 3 methods are the most comprehensive approach to constrain the emission situation, considering individual target emissions. However, since the emission-causing scenarios widely differ between sectors, the Tier levels and their standards widely depend on the individual category (i.e. sectors and sub-sector classifications). As an example, emission processes in the waste sector include decomposition and their Tier 1 emission calculations can incorporate a decay function.

Inventory compilers create a complete overview of every emitting classification, hence each source type that contributes emissions to the national emission budget. Therefore, focusing on constraining emission factors has a major benefit beyond the detection of emission rates. They can be compared, transferred and projected between sources, spatially and temporally, and inventory compilers can compare them with existing emission factors of other studies, bottom-up or top-down and between nations or regions.

Finally, as a summary and general overview, general conceptual requirements and opportunities for top-down methods are listed below.

Potential direct improvement and verification of current inventories:

- Construction of emission factors for individual source types, in particular according to the UNFCCC classification.
- Verification of national, subnational and sectoral emission budgets and emission reduction trends and identification of potentials for future improvement in the bottom-up inventories.
- Uncertainty assessment of emission situations in support of current uncertainty representation in the bottom-up reporting framework, assuming information gain from a top-down method.

Complementary approaches to current reporting schemes for future reporting, policy advice, public information and direct support of mitigation measures:

- Regional attribution of emission budgets beyond national aggregation.
- Analysis of intra-annual emission trends complementary to yearly reporting schemes.
- Identification of emission sources and leakages in support and guidance of emission mitigation measures.
- Improving insights and understanding of production processes of complex emissions, which are not driven or difficult to be determined by individual activities (i.e. which depend on many parameters).

4 Methane Emitting Targets Accessible for Detection Capacities

In this chapter, the composition of individual sites that contribute to the European methane emission is analysed, particularly with respect to existing top-down emission detection capabilities and the context of the AVENGERS project. Besides the aggregated emissions in the UNFCCC reports, individual facilities in the European Union that release pollutants beyond a certain amount have to report their emission to the competent authorities. Their reporting scheme is based on the EU's regulation for the European Pollutant Release and Transfer Register (E-PRTR) [Regulation: 17]. This regulation covers a large range of pollutants released into air, water and ground. For methane emissions into air, the threshold for facilities to report is 100 tonnes per year. Those reports are typically built on estimates, calculations or measurements from the operator or their contractors. They are collected by the respective national competent authorities, implementing the reporting scheme on a national level [e.g. 16], where the E-PRTR links to the national PRTRs of the Member States [Summary: 19, Data Access: 20]. In Germany, for example, the national PRTR information is compiled by the Umweltbundesamt and published via a national online portal, to also inform the public about activities in Germany [21]. Switzerland and the United Kingdom collect pollutant registers similar to the Member States. In the future, a revision of the E-PRTR and the European Industrial Emission Directive (IED) is expected to incorporate registers of Switzerland, United Kingdom, Iceland, Liechtenstein, Norway and Serbia into a common European register (details on the regulations are part of Chapter 8) [22].

Evolving spaceborne remote sensing missions have demonstrated methane emission detection and can currently reach detection limits of down to 100 kg/h [e.g. 1, 23, 24]. Therefore, as a first step, the emission targets in Europe with rates above 100 kg/h are analysed. Note that inventory emission rates typically operate with yearly emission rates due to year-long reporting cycles (see Chapter 3), while observational emission rates prefer hourly or shorter time scales due to the nature of measurement time scales. Hence, to analyse the potential for detecting methane emitting targets in Europe, Figure 2 depicts all individual facilities which reported an emission rate above 1 kt/yr within the E-PRTR framework. The threshold of 1 kt/yr is selected because it responds to an emission rate of 114 kg/h, which equals roughly 100 kg/h if constantly distributed over the year.

- In the following, emissions that can directly be attributed to an individual location or installation based on top-down approaches are called emissions from point sources, such as emissions which are released on-site at a facility. Those sources are referred to as targets in the context of discussing monitoring capacities in this document.

Figure 2 displays every emitting facility above the threshold, where the relative emission rate is represented by the circle area. The colour scheme assigns every facility to its corresponding sector. The sectors do not conform with the UNFCCC classification in Chapter 3, since the E-PRTR reporting scheme is separate from the UNFCCC reporting scheme and it covers only sources with emission rates exceeding a predefined threshold per facility. A further comparison between both reporting schemes is part of Chapter 5. The year 2019 is selected to illustrate emitting facilities in Europe, including the United Kingdom which is only covered until 2019 and intendedly again from 2027 (see Chapter 8).

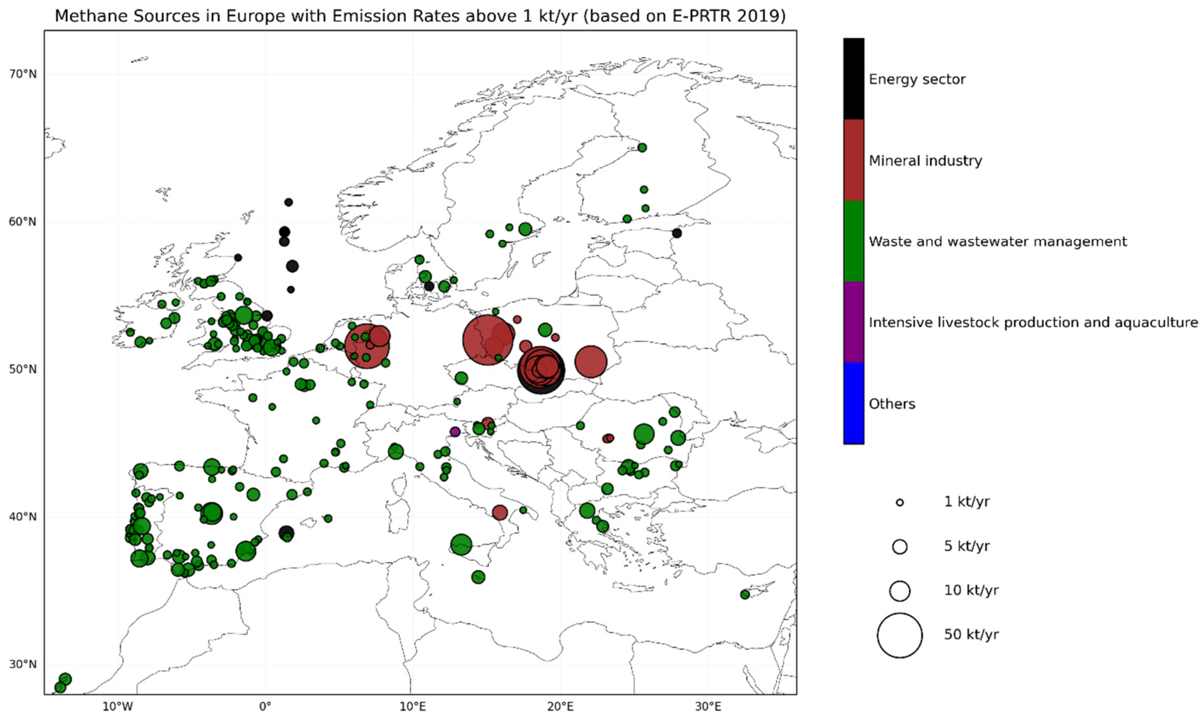

Figure 2: *Methane emitting sources in Europe in 2019 with an emission rate above 1 kt/yr, corresponding to roughly 100 kg/h if continuously distributed over the year, based on the E-PRTR reporting framework status December 2023. For each emitting source, its emissions are indicated by a circle at the location of the site. The colour scheme represents the corresponding source type based on the E-PRTR sector classification and the total circle area describes the site-specific emission rate. Source types which are not explicitly named are included in the "Others" category. The year 2019 is selected to include the source in the United Kingdom, which is only covered until 2019 and intendedly again from 2027 onwards (see Chapter 8).*

Several aspects are apparent in Figure 2. First, the sector classification clearly divides the emitting facilities shown. The strongest emission rates occur in the mineral industry in a few regions in Europe. Within the sector of mineral industry, in particular underground mining activities are included. More specifically, those sites comprise ventilation shafts from hard coal mining activities. In most countries, the majority of sites with emission rates above the discussed detection limit are from the waste and wastewater treatment sector, typically landfills. A few European sites belong to the energy sector, generally thermal power stations and oil and gas production sites. Second, in most countries, several emitters have bottom-up emission rates above the selected limit. A few super emitters with emission rates above 10 kt/yr, i.e. about 1000 kg/h, are located in single European countries.

➢ For visualisation, the blue category Others contains all source types which barely have any sites emitting at such rates. This includes for example sites from the production of animal and vegetable products or from the chemical industry.

To study the impact of improved detection capabilities and consider different detection capacities (spaceborne, airborne and ground-based approaches), Figure 3 shows the emission situation in Europe considering sources which have an emission rate above 0.1 kt/yr, i.e. about 10 kg/h if continuously distributed over the year. In general, there are many more sites with mid-range emission rates between 10 kg/h and 100 kg/h in Europe than in the range above 100 kg/h. (For a more quantitative analysis see Chapter 7). Based on the bottom-up reporting, mostly landfills and partly urban wastewater treatment plants are sites that emit methane in this mid-range and are potential top-down targets. Further, additional thermal power plants and installations for pig farming lie in that range.

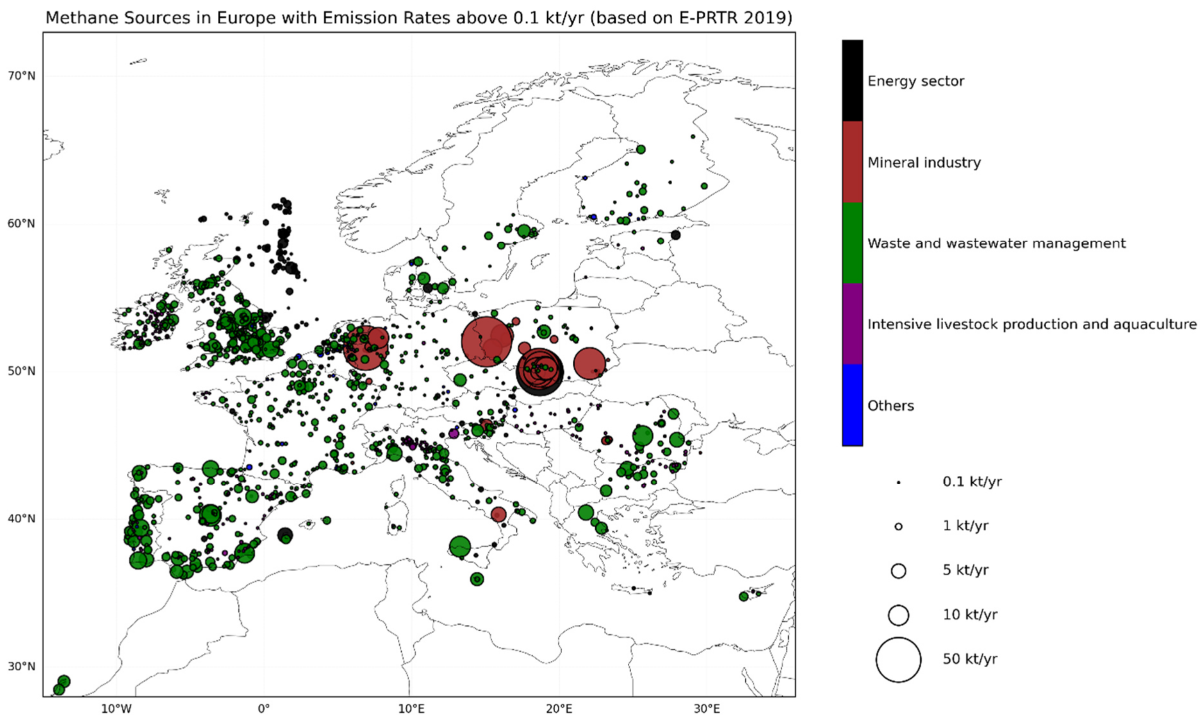

Figure 3: *Methane emitting sources in Europe in 2019 with an emission rate above 0.1 kt/yr, corresponding to roughly 10 kg/h if continuously distributed over the year, based on the E-PRTR reporting framework status December 2023. For each emitting source, its emissions are indicated by a circle at the location of the site. The colour scheme represents the corresponding source type based on the E-PRTR sector classification and the total circle area describes the site-specific emission rate. Source types which are not explicitly named are included in the "Others" category. The year 2019 is selected to include the sources in the United Kingdom, which is only covered until 2019 and intendedly again from 2027 onwards (see Chapter 8).*

➢ For convenience, sites with methane emission rates above 100 kg/h are called hotspot emitters in the following. Sites with methane emission rates between 10 kg/h and 100 kg/h are called mid-range emitters.

One major difference to the aggregated national emission situation in Chapter 3 is the lack of agricultural sites for cattle farming in the target overview. Poultry and pig farming facilities report methane emission rates when they exceed both the emission reporting threshold and a production capacity (i.e. amount of poultry places). Specifically cattle farming is excluded from the E-PRTR regulation's reporting obligations. In contrast to this, the agricultural sector contributes the largest share of methane emissions in several European countries, with cattle farming as the most essential part. Therefore, top-down approaches can especially contribute to understanding and constraining emissions from agriculture, being a complementary database to the E-PRTR reporting framework.

5 Impact of Hotspot and Mid-Range Methane Emitters on the European Emission Situation

To set the discussed CH_4 emissions of individual targets into context with the individual national methane emissions, Figure 4 compares the nationally aggregated E-PRTR emissions with the national emission total based on the UNFCCC report for the matching year. The ratio between the overall sum of emissions from all E-PRTR sources per country divided by the national total per country is shown in percentage.

First of all, the hotspot and mid-range emitters share makes up a few percent of the national total for the individual countries. For most countries, the percentage is single-digit while for few countries it makes up to more than 20% of the total emissions. In reference to the previous chapters, countries typically reach higher shares if many strong emitting facilities are reported, like coal mining shafts in the mineral industry or landfills in the waste sector. For many countries, the share slightly decreases over time, illustrated by the reporting years 2009 and 2019 in Figures 4 and 5; however, they typically remain of similar magnitude.

Secondly, the E-PRTR hotspot and mid-range targets do not reach a majority of the nation's emission budgets, but only fractions, depending on the country. However, with the E-PRTR regulation, the requirement was formulated to cover the emission situation with the E-PRTR, setting the reporting thresholds accordingly to cover 90% of the releases per emitting compartment [25].

As described in the previous chapter, the schemes of the target-specific E-PRTR reporting and the integrated national emission situation reporting within the UNFCCC framework differ. Specifically, they have access to different sources of information. To illustrate this with an example, the aggregated emissions of a category can build on statistics from an association while the target specific rates are calculated by the individual facility operator in charge. Most importantly, the E-PRTR only covers emitting sources down to the emission threshold. Therefore, both emission assessments can in principle deviate from each other.

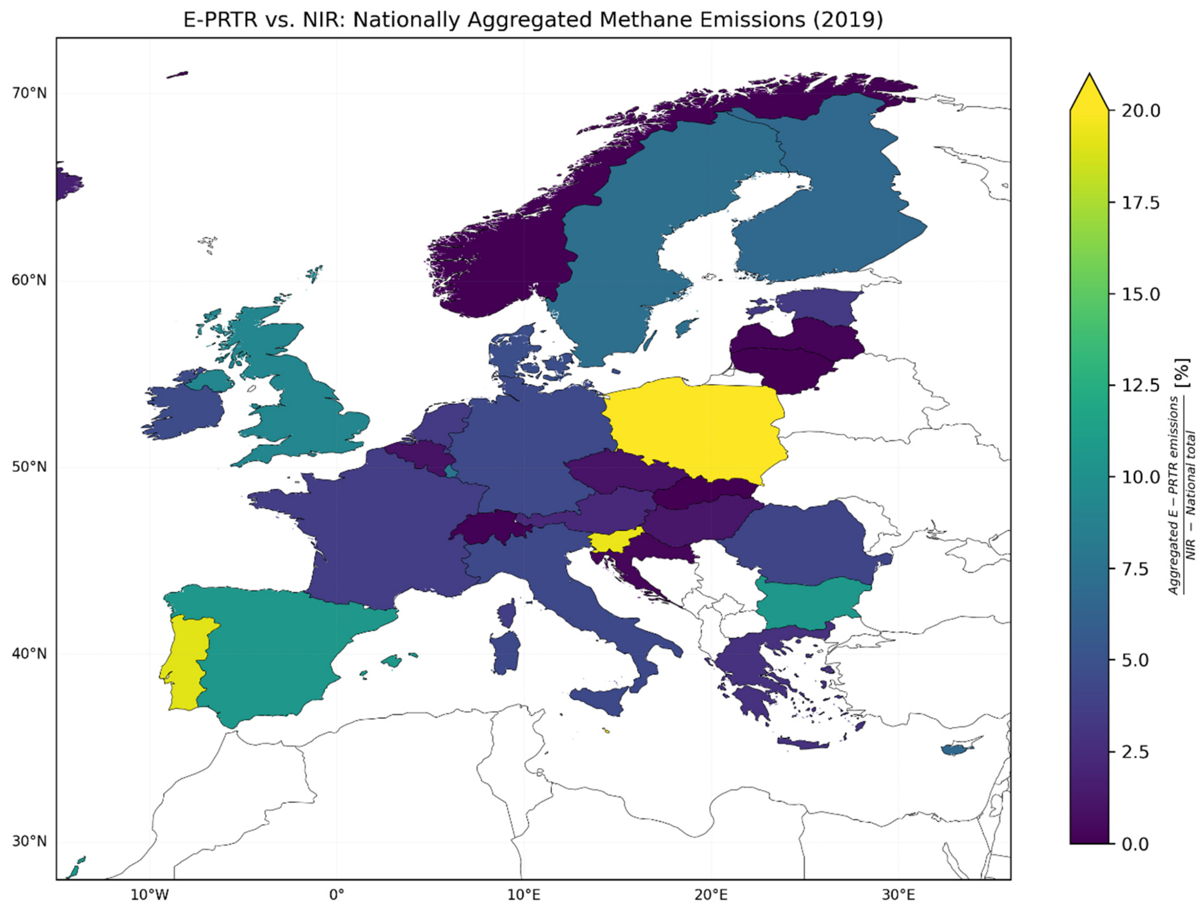

Figure 4: *Contributions of individual methane emitting sites with an emission rate above 0.1 kt/yr, covered by the E-PRTR framework status December 2023, to the individual nation's total methane emission budget, based on the UNFCCC National Inventory Reports submitted in 2022. The ratio of the aggregated emissions by country are shown in percentage for the year 2019, the year selected in accordance to Figure 2 and 3.*

One important aspect is that cattle farming is excluded from the E-PRTR reporting obligations, while the aggregated UNFCCC emissions aim to cover the total integrated national emissions. The share of the hotspot and mid-range targets strongly increases in most countries, if the agricultural sector's emissions are equally excluded from both point sources and national total. This is because the agricultural sector's emissions are significantly composed of cattle farming emissions and agriculture often contributes a majority to the national total emission budget.

Even if the monitoring of individual targets covers only shares of the total national emission or an individual sector, those targets can be used to make predictions for the general emission situation by constructing emission factors, in the case that they are good representatives. Then, those emission factors can be incorporated in the UNFCCC inventory emission reporting scheme. Therefore, with the capability to monitor individual facilities, top-down approaches provide the opportunity to study emission scenarios in well-detectable circumstances, constructing case studies for individual sectors, and additionally need to evaluate their representativity.

Furthermore, top-down approaches in general allow to perform in-country analyses and target-monitoring capacities perform site-specific analyses, given the case that detected emissions can spatially or otherwise be attributed to their individual source. Therefore, derived results have the potential to meet standards of the highest quality, in particular of UNFCCC Tier 2 and Tier 3 levels and thereby improve inventory parameters.

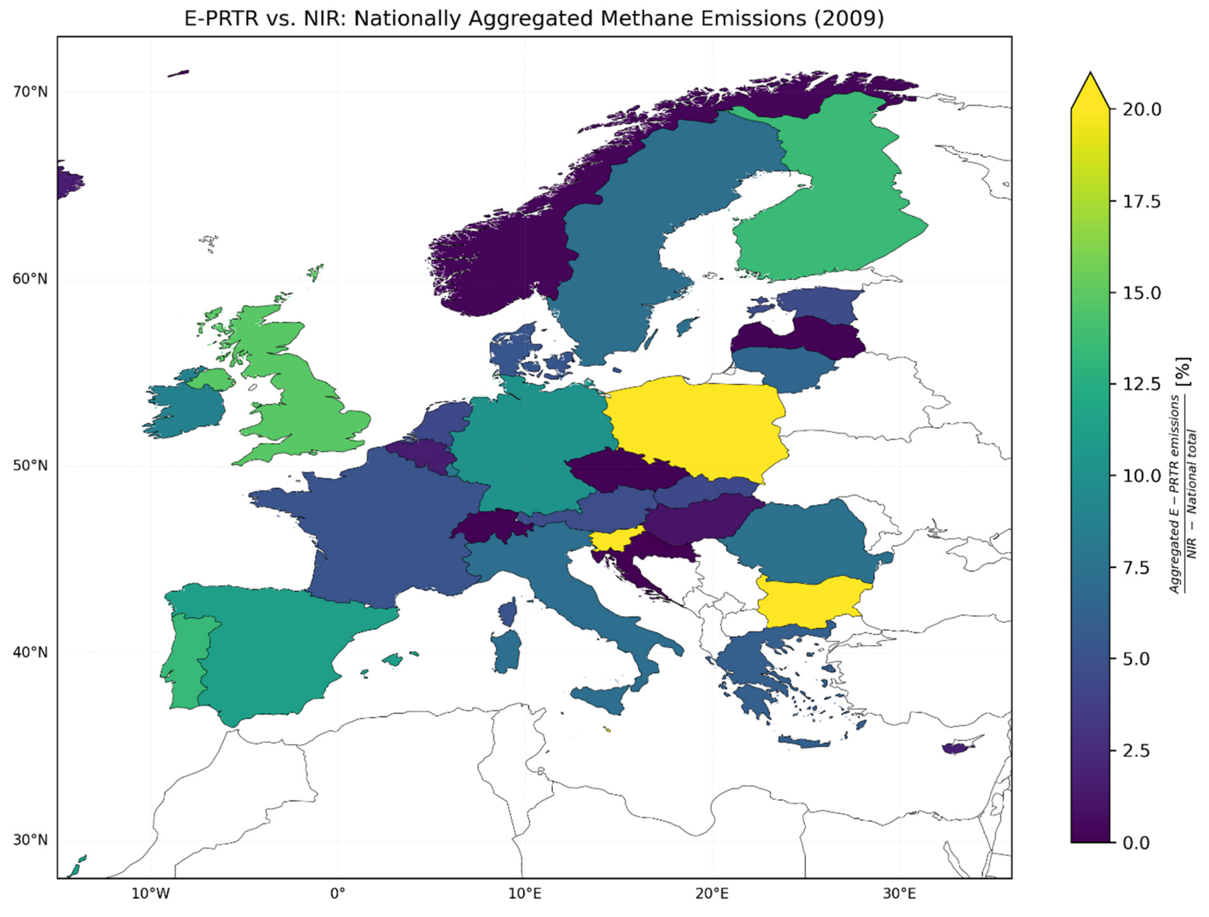

Figure 5: *Contributions of individual methane emitting sites with an emission rate above 0.1 kt/yr, covered by the E-PRTR framework status December 2023, to the individual nation's total methane emission budget, based on the UNFCCC National Inventory Reports submitted in 2022. In addition to Figure 4, the ratio of the aggregated emissions by country are shown in percentage for the year 2009, to illustrate existing variation over a ten-year period.*

6 Constructing Emission Factors and Activity Rates for Inventory Compilation

As illustrated in the previous chapters, the framework of emission factors and activity rates is central in the UNFCCC reporting. Therefore, inventory compilers need top-down capacities that are able to construct emission factors. To support top-down capacities in their construction, some essential guidelines are summarized here as an orientation on how inventories can profit most from top-down results:

1. An emission factor needs to be constructed and made available in a citable manner such that an inventory compiler can implement it in the reports and refer to the source of the emission factor.
2. The activity quantity, to which an emission factor refers, should be an accessible parameter. It should be publicly available or at least obtainable from an institution or association.
3. Inventory compilers need to produce a continuous time series of emission rates, for example to examine national emission mitigation efforts over time. Therefore, the activity quantities are needed not only for a single year but for multiple years, ideally starting with the first reporting year 1990. If the emission factors are derived from a limited time period, the activities should still be available for longer time periods.
4. With every UNFCCC submission, emissions for the previous years are included in the report and revised where applicable. However, inventory compilers need to avoid hard methodical breaks in the construction of emission time series. When a methodical change takes place but covers only a limited time period, a calibration is needed to ensure that time series are consistent, using products which were accessible for earlier time periods. For example, an inventory compiler can implement results from a new spaceborne product that is only accessible from the launch of the mission on through a comparison and calibration with an already existing product.
5. To be applicable for end-users such as inventory compilers, results from top-down monitoring need to be provided in a user-oriented manner. This includes e.g. well-structured and uncomplicated access to results, comprehensive interactive dashboards, consistently reported and validated emission rates, emission factors and uncertainties, as well as long term continuity and maintenance of the respective capacities. In particular, general user requirements have been formulated in the AVENGERS deliverable D1.1.

In general, the IPCC Guidelines for National Greenhouse Gas Inventories provide details about the construction of emission factors for individual source types together with descriptions of the methodical Tier levels for the individual source types [16]. Therefore, it is a valuable information source also for top-down capacities about how emission factors in different sectors are typically constructed and how results from top-down methods can fit in for the individual sector and study case.

7 Coverage of Methane Sources for Improving Detection Limits

Within this chapter, the coverage of emission sources in Europe with improving detection limits is analysed quantitatively. To give a quantitative overview of the discussed methane emitting targets in Europe, all methane emitting sites which report to the E-PRTR in 2019 were selected and are presented in Figure 6. In the logarithmic histogram, the numbers of methane emitting sources per respective emission rate are displayed in green. Additionally, in blue the cumulative distribution illustrates how much of the E-PRTR's total emissions is covered with an upper threshold of a specific emission rate.

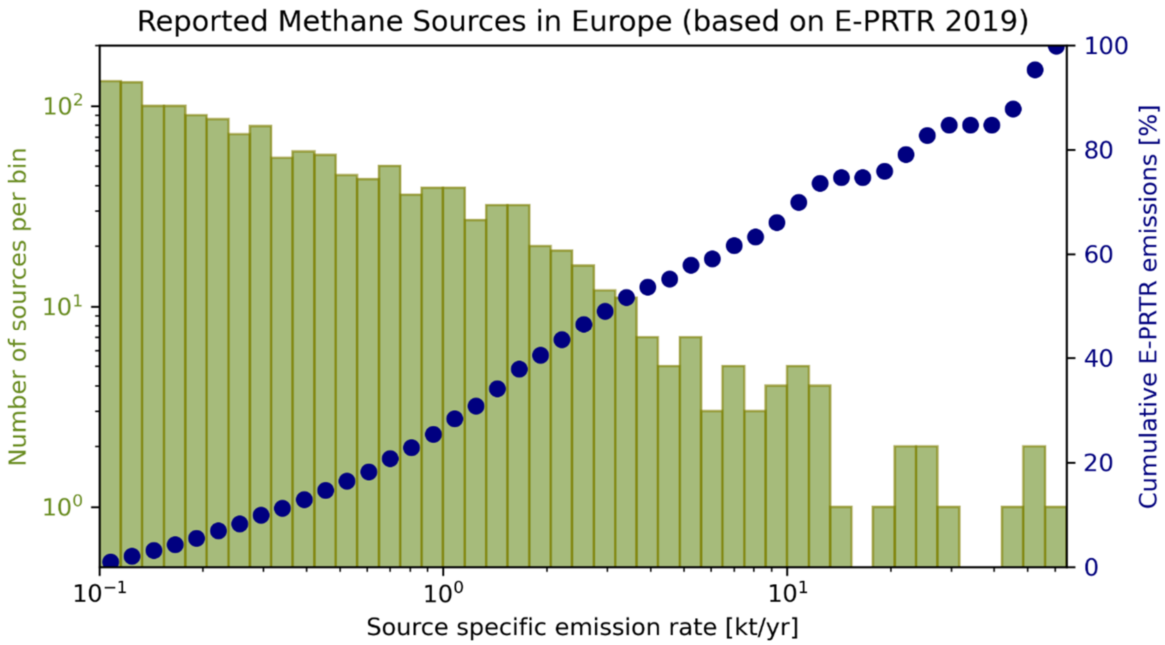

Figure 6: *Quantitative assessment of methane emitting sources in Europe in 2019, based on the E-PRTR framework status December 2023: The green histogram shows the total number of methane releasing sources at different source-specific emission rates is shown. The share of the sum of emissions for a specific upper emission threshold with respect to the total E-PRTR emissions is shown in blue as cumulative distribution.*

Figure 6 shows that top-down capacities which observe facilities with emission rates of more than 10 kt/yr, i.e. about 1000 kg/h if constantly distributed over the year, can only be used to study few individual sites. However, those European super emitters contribute one third of the total E-PRTR methane emissions in the selected year. With detection capacities for emission rates of 1 kt/yr, i.e. about 100 kg/h, several hundred hotspot facilities in Europe can be studied, covering the second third of the E-PRTR total emissions. Top-down capacities with detection limits of 0.1 kt/yr, i.e. about 10 kg/h, reach the same level as the reporting threshold for the bottom-up target register, potentially allow to detect emissions from every facility reporting to the E-PRTR framework. In total, such capacities can study more than one thousand individual facilities, in the case that their spatial resolution allows for detected emissions to be separated or otherwise attributed to its source. With even further improving detection limits, monitoring capacities would advance to the detection of additional emitting sites beyond the bottom-up target register, thereby creating the opportunity to review compliance with the threshold and the overall target-specific emission situation.

For a quantitative assessment of targets with respect to their source type, Figure 7 shows the cumulative E-PRTR emissions for a selected upper emission threshold, differentiating the sectors by different colour.

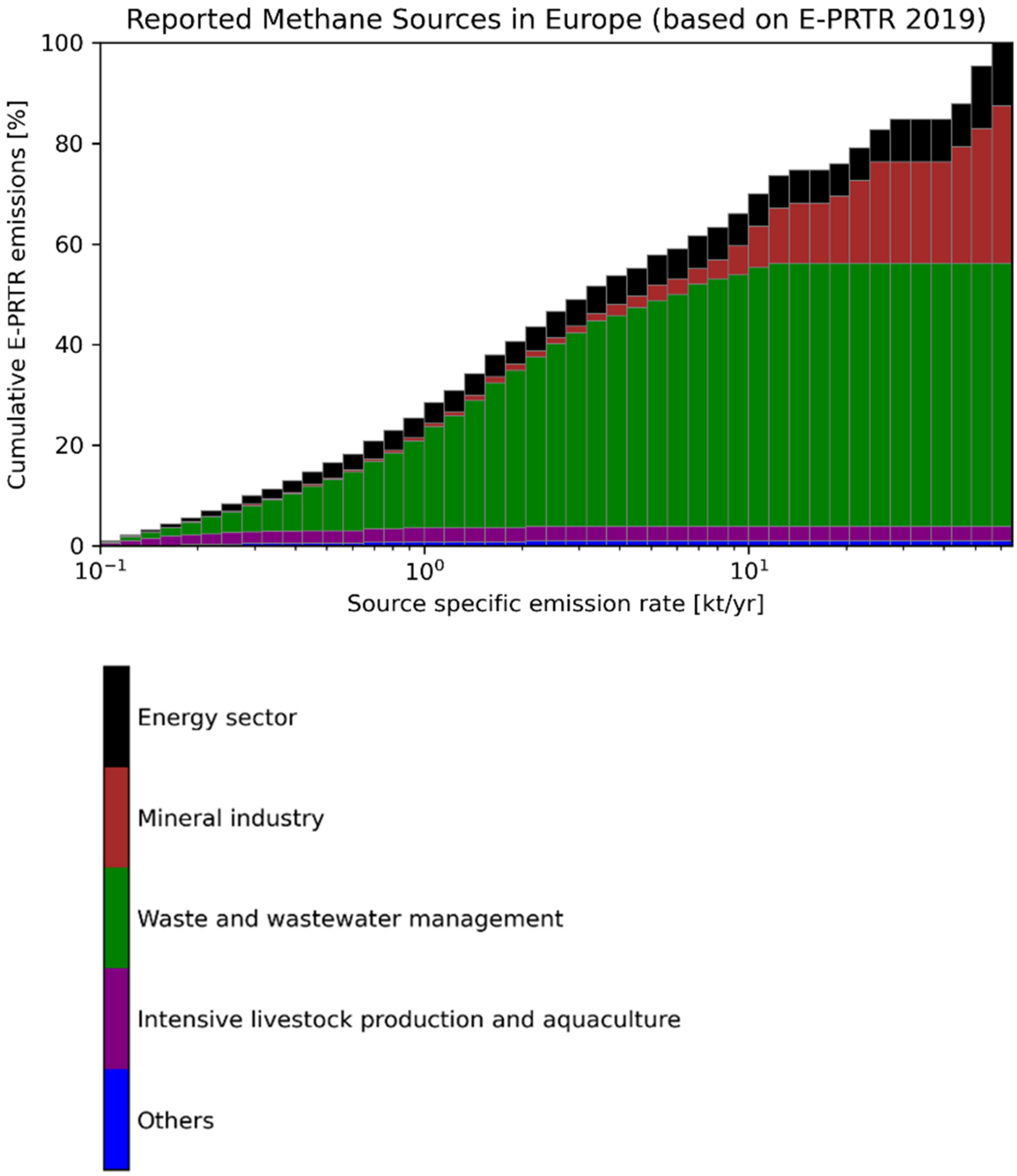

Figure 7: *Contributions by sector-specific emitters with different emission rates to the E-PRTR emission budget: As a cumulative and stacked histogram, Figure 7 shows which sectors contribute to the E-PRTR emission budget at which emission rates. The sectors are labelled by colour. Each bar represents a selected upper threshold for the source-specific emission rate.*

Firstly, the histogram shows that facility emissions from the energy sector occur over all different sizes of emission rates, including emissions from hotspot, mid-range and near-to-reporting-threshold emitters. Secondly, site-specific emissions in the mineral industry are mainly composed of emissions by hotspot emitters of 1000 t/yr and higher, namely from the already discussed emitters in hard coal mining. Thirdly, in particular the waste sector and its landfills release their major amount of emissions in mid-range emission scenarios, as well as partly in the lower range of emission strengths per facility. Last, intensive livestock production and aquaculture, as well as facilities of other categories only contribute emissions to the E-PRTR budget near to the reporting threshold.

Note that the bottom-up E-PRTR inventory relies on the emissions reported by the respective operators. Also, the use of the PRTR data varies among the EU Member States. In this work it has been selected to function as a baseline for observations. The observations themselves have the opportunity to review and study the emission situation and analyse targets that are not already covered by the E-PRTR reporting scheme. This allows top-down capacities to act as a complementary source to the E-PRTR framework, where only facilities with emission rates above 100 t/yr are reported and in particular cattle farming excluded from reporting obligations (see Chapter 8).

8 Assessing Top-Down Methods with Regard to Current and Future Policies

8.1 Monitoring Capacities in the Current EU Methane Policy for the Energy Sector

In November 2023, the European Council and the European Parliament reached an agreement on a new regulation on the reduction of methane emissions with a focus on the energy sector [26]. Entering into force in August 2024, the regulation specifies how the EU plans to reduce methane emissions in oil, gas, and coal activities and particularly emphasises the role of monitoring capacities [Policy: 27, Summary: 28].

- The regulation formulates rules in the context of leak detection and repair (LDAR). It covers for example frequencies and standards how operators have to analyse and verify their emissions. In addition, it formulates standards on how an operator has to react to leak detection and, in particular, how fast leakages have to be closed.
- The regulation links to the framework of the Oil and Gas Methane Partnership 2.0 (OGMP 2.0). OGMP 2.0 is a preceding voluntary initiative for operators to monitor and report their emissions in a standardised manner [29]. The United Nations Environmental Program (UNEP) and the Climate and Clean Air Coalition (CCAC) initially created the OGMP in 2014.

- Referencing the OGMP classification, the regulation structures monitoring attempts with five different reporting levels for methane emissions [29]. On starting levels, operators estimate their own emission rates by applying generic emission factors considering to their activity. On higher levels, an operate performs direct measurements for leakage detection either themselves or, for example, by commissioning contractors. The gold standard is achieved by reconciliation of bottom-up estimates with top-down verification, where in general the implementation of top-down methods for emission detection comply with the highest standards.
- In addition, the regulation declares the requirement and objective to focus on methane emissions produced along the global production chains. Since the European Union massively depends on the import of fossil fuels [27], global emission monitoring is required to analyse the methane emission impact of production chains in Europe's supply, also for the methane emissions that are not emitted in Europe. The regulation formulates a critical demand for global emission detection in support of reduction measures not only in Europe. This particularly applies to super-emitters.
- The regulation refers to developing methodologies and demands cooperation and consideration of the competent authorities and verifiers in forming monitoring capacities, such as in the framework of UNEP's International Methane Emissions Observatory (IMEO) program.

Many national and subnational jurisdictions have adopted policies for reducing methane emissions, in Europe and globally [30]. However, regulators are only starting to consider remote emission detection capacities and the versatility of implementing top-down capacities is yet to be evaluated. Clear demands of target-emission surveillance have been formulated for the accessibility of methane data in multiple sectors, especially for subnational and local advocates and for developing countries, as described in [30].

8.2 Future Facility-Level Emission Reporting and Policies in Europe

In Europe, the regulation and reporting schemes for facility-level emissions recently experienced a major revision to guide large industry towards the EU's climate and pollutant objectives. In August 2024 the European Union's Industrial and Livestock Rearing Emissions Directive (IED 2.0) entered into force, revising the previous Industrial Emission Directive (IED) which authorises and controls the release of pollution of industrial activities [Policy: 31, Summary: 32]. Closely connected is the Industrial Emissions Portal Regulation (IEPR) which entered into force in May 2024 and has revised the E-PRTR regulation and its reporting system [Policy: 33, Summaries: 22, 34]. The new reporting scheme will replace the E-PRTR system, with 2027 as the first reporting year and the first reporting obligation by the EU Member in 2028.

- With the revision, both policies are now more closely connected and aligned. The IEPR becomes the central streamlined access point for environmental data of industrial emissions regulated by the IED framework.
- The new emission databases are intended to increase the transparency of emitting sources, with permission to publicly review installation-specific emission reporting, in addition to factory-assigned emissions. The regulations formulate requirements, minimum standards and demands for measurement, reporting and verification (MRV).
- As a development, landfills are now included in the IED framework. Large combustion plants (LCPs), landfills, intensive livestock farms for pigs and poultry and other industrial installations will consistently be addressed in both the IED and the IEPR, with both frameworks coupled.
- Key objectives are to control emission reduction, promote the most effective emission reduction measures, and strengthen and broaden public information and participation.
- The Industrial Emissions Portal is expected to implement pollutant information and registers of the European Union's Member States as well as of Switzerland, United Kingdom, Iceland, Liechtenstein, Norway and Serbia.

As before, cattle farming is essentially excluded from the revised versions of the policies, although the European Commission plans to submit a report on livestock emissions in 2026 [32].

9 Requirements for CO_2 and N_2O Detection Capacities

9.1 National Emission Situation for CO_2 and N_2O

To reflect on monitoring potentials for carbon dioxide and nitrous oxide, the emission situation for those two greenhouse gases is analysed in the following. The analysis is based on the UNFCCC-reported national inventories, similar to analyses for methane. Figure 8 shows the CO_2 emission situation in Europe aggregated by nation, based on the UNFCCC reporting classification, with the colour code representing individual sectors. National sectors which in total have a negative emission balance (which means an uptake of CO_2) are shown as zero emissions. Thereby, especially emissions from the LULUCF sector are balanced by the uptake of CO_2 in the sector, where the uptake is caused by photosynthesis processes and positive emissions for example by changes in forest stocks.

Figure 8 shows that in Europe each country's energy sector almost completely causes the positive national CO_2 emissions. Only the industry sector slightly contributes to the national CO_2 emission budgets, and, in some countries, the LULUCF sector has a positive total. Consequently, a sectoral differentiation and focus based on the UNFCCC upper-level classification similar to methane is less suitable for CO_2. A separation on the sub-category level is necessary to analyse for example the LULUCF sector and its composition of emission sources and sinks in the individual countries. Especially, emitters in the energy sector are potential targets for top-down monitoring capacities. More specifically, the emissions from the energy sector are typically caused by fuel combustion in electricity generation, heat production and transport, as well as in manufacturing industries. Those emissions which are specifically part of the industry sector classification are for example caused in cement, ammonia, iron and steel production.

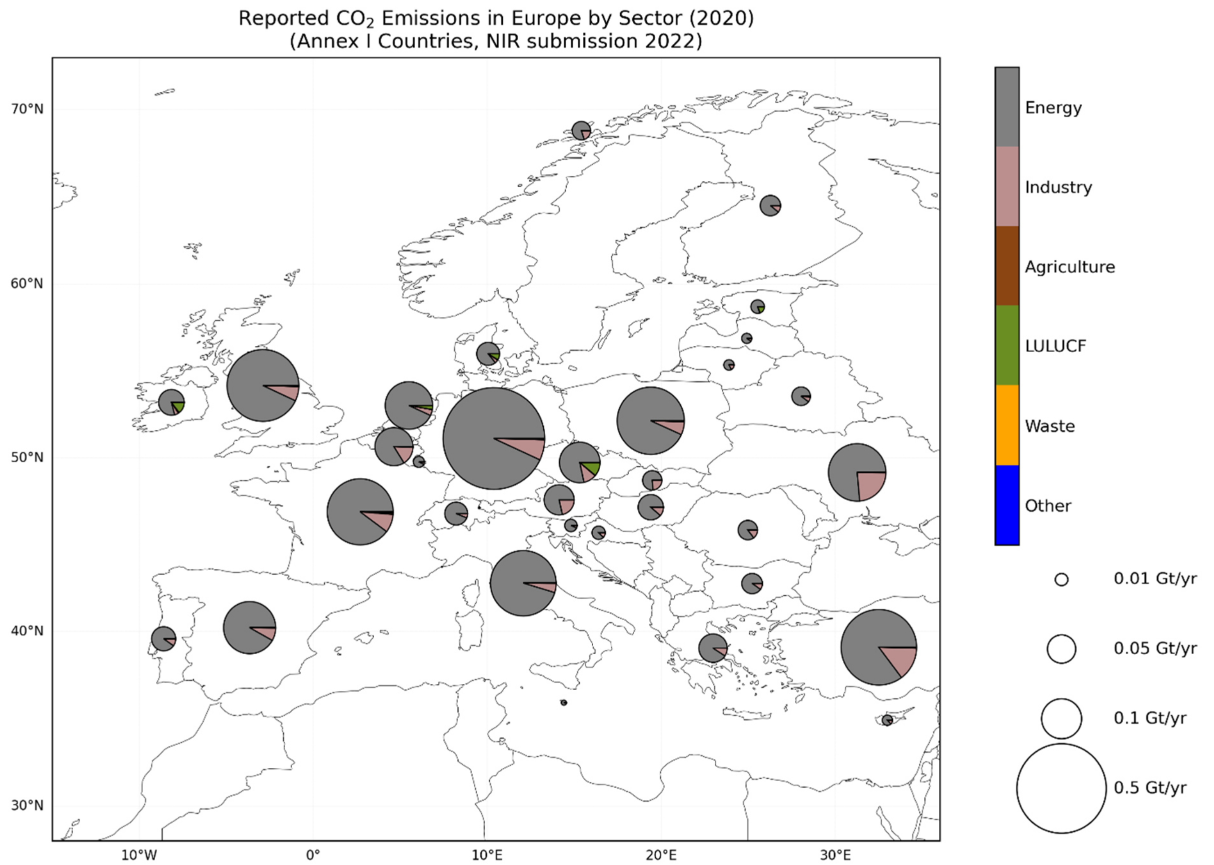

Figure 8: *Reported aggregated carbon dioxide emissions in Europe for the UNFCCC Annex I countries in 2020, based on their 2022-submission of National Inventory Reports to the UNFCCC. Emissions for each country are illustrated as pie charts showing the individual sectors contributing to the national emission budget. The pie areas represent the total national carbon dioxide emission rates relative to each other. Emissions are allocated to the respective national centroid with deviations for France, Croatia, Netherlands and Türkiye for visualisation purposes. Full sector denotations are abbreviated for visualisation purposes as well. National sectors, which in total have a negative emission balance, are shown as zero emissions. Especially, the LULUCF sector in multiple countries has a negative balance due to the uptake of CO_2 in the sector.*

Similar to the case of CO_2, Figure 9 shows the emission situation of N_2O in Europe. The majority of emissions is caused by processes in the agricultural sector in all countries, with minor contributions from the other sectors, depending on the individual country. N_2O emissions in the agricultural sector are regularly produced by manure management, fertiliser application and direct emissions from soils. In the chemical industry, specifically the production of acids contributes to the N_2O emissions.

To elaborate on the targets which contribute to the emission budgets of CO_2 and N_2O and to sketch the potentials for applying target-monitoring methods, the target-specific emission scenarios for CO_2 and N_2O in Europe are analysed in Section 9.2.

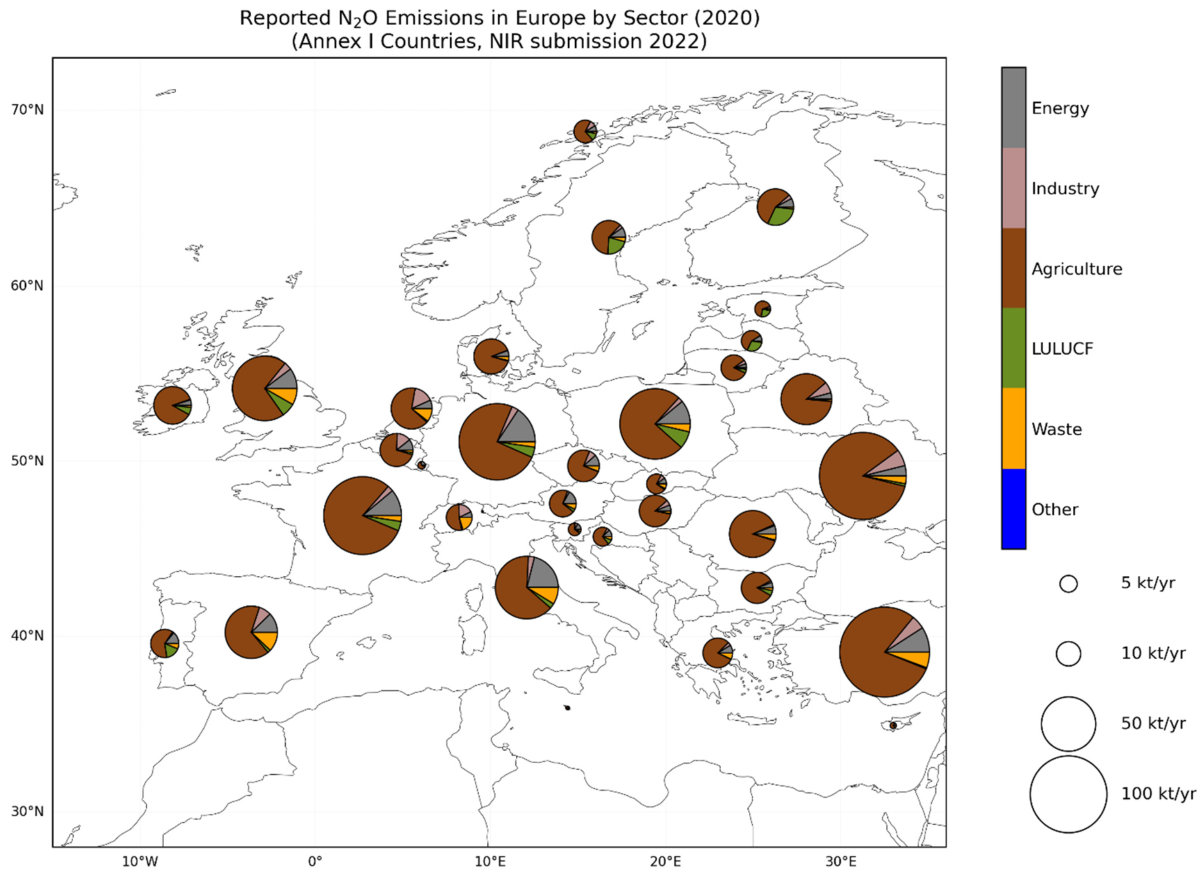

Figure 9: *Reported aggregated nitrous oxide emissions in Europe for the UNFCCC Annex I countries in 2020, based on their 2022-submission of National Inventory Reports to the UNFCCC. Emissions for each country are illustrated as pie charts showing the individual sectors contributing to the national emission budget. The pie areas represent the total national nitrous oxide emission rates relative to each other. Emissions are allocated to the respective national centroid with deviations for France, Croatia, Netherlands and Türkiye for visualisation purposes. Full sector denotations are abbreviated for visualisation purposes as well.*

9.2 Conditions for Targeting CO_2 and N_2O Emitters

In the literature, discussions of detection capacities for monitoring CO_2 emitting targets have already been started [e.g. 35]. CO_2 monitoring capacities have demonstrated their ability for target-specific emission detection of exceptionally strong emitters, for example for CO_2 emissions of power plants down to a few hundred tons per hour [36]. To discuss the potentials for applying top-down methods in CO_2 emission surveillance, the general scenario of CO_2 emitting targets in Europe is analysed in the following. For this, all sites which report CO_2 emissions in the E-PRTR framework are shown in Figure 10 for the year 2019.

First, Figure 10 shows that multiple emitters exist in Europe with emission rates in the order of 10 Mt/yr, i.e. about 1000 t/h if continuously distributed over the year, which can already be studied with monitoring capacities of such detection limits. Among those facilities are several power plants and other facilities, for example from the production of metals. Second, if detection limits improve towards 1 Mt/h, i.e. about 100 t/h, monitoring capacities have the opportunity to study several hundred targets distributed throughout European countries.

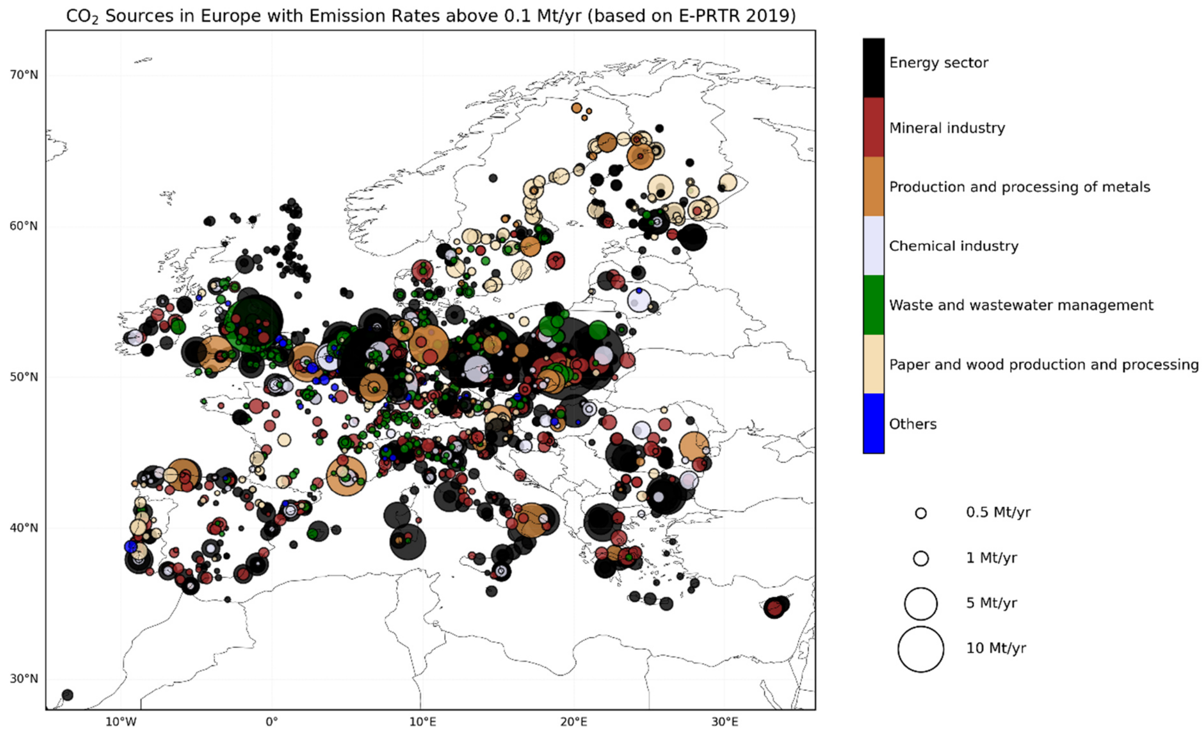

Figure 10: *Carbon dioxide emitting sources in Europe in 2019 with an emission rate above 0.1 Mt/yr, corresponding to roughly 10 t/h if continuously distributed over the year, based on the E-PRTR reporting framework status December 2023. For each emitting source, the emission rate is described by a circle at the location of the site, the colour scheme representing the corresponding source type based on the E-PRTR sector classification and the total circle area describing the site-specific emission rate. Source types which are not explicitly named are included in the "Others" category. The year 2019 is selected to include sources in the United Kingdom, which is only covered until 2019 and intendedly again from 2027 onwards (see Chapter 8). For CO_2 emissions the rate of 10 Mt/yr per facility is the reporting threshold under the E-PRTR regulation.*

In Figure 10, a threshold for site-specific CO_2 emissions of 0.1 Mt/yr is selected, i.e. about 10 t/h. This represents the reporting threshold for CO_2 emissions within the E-PRTR framework. Therefore, reliable CO_2 monitoring capacities for the detection emissions as low as 10 t/h would allow to review and verify the CO_2 emissions of sources covered by the E-PRTR and could be used to support CO_2 emission reporting or review reporting compliance. More than 2000 sites report an emission rate above the threshold and would be accessible for such capacities.

CO_2 emitting facilities in the energy sector or in energy intensive production are part of the European Union's Emission Trading System [see e.g. 37]. Therefore, when CO_2 detection capacities evolve, the ETS framework could become a potential beneficiary - and indirectly the emission reporting in general, whereas the national reporting is connected with the ETS as indicated in Chapter 2.

As for N_2O, Figure 11 illustrates the situation of target-emitters for the year 2019.

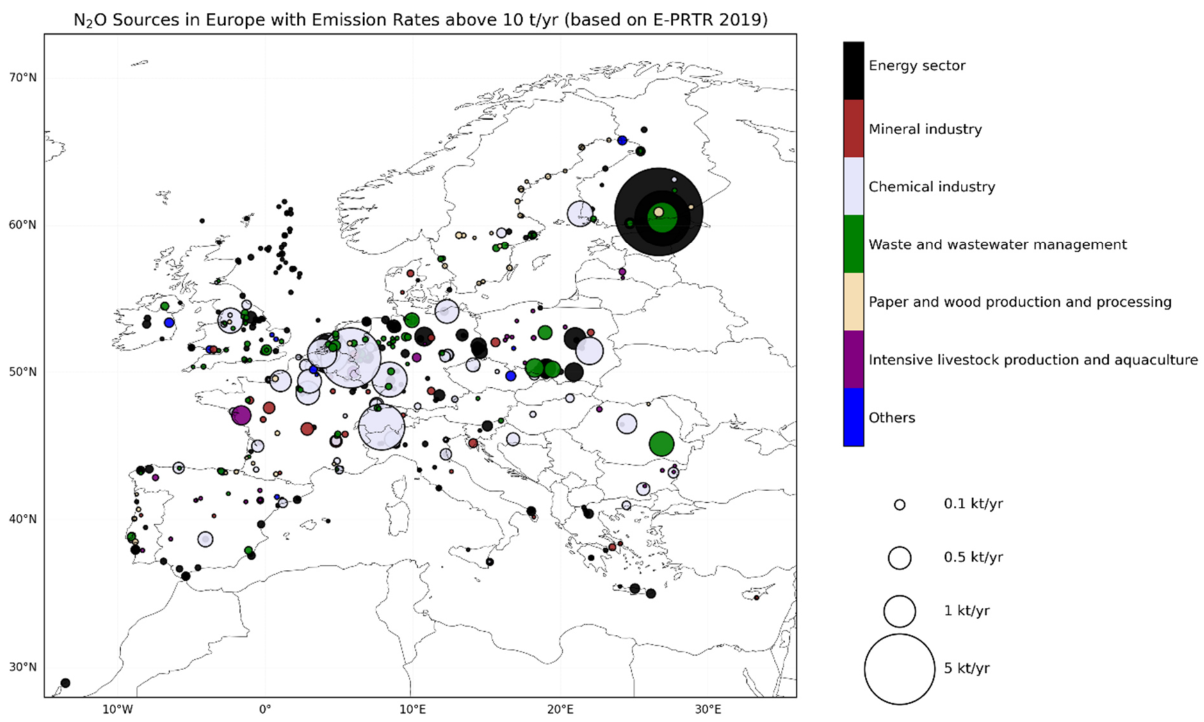

Figure 11: *Nitrous oxide emitting sources in Europe in 2019 with an emission rate above 10 t/yr, corresponding to roughly 10 t/h if continuously distributed over the year, based on the E-PRTR reporting framework status December 2023. For each emitting source, the emission rate is described by a circle at the location of the site, the colour scheme representing the corresponding source type based on the E-PRTR sector classification and the total circle area describing the site-specific emission rate. Source types which are not explicitly named are included in the "Others" category. The year 2019 is selected to include sources in the United Kingdom, which is only covered until 2019 and intendedly again from 2027 onwards (see Chapter 8). For N_2O emissions the rate of 10 t/yr per facility is the reporting threshold under the E-PRTR regulation.*

Firstly, Europe's highest reported emission rate of N_2O-emitting sites reaches about 8 kt/yr, i.e. about 800 kg/h if continuously distributed over the year. Secondly, sites from the industrial production of organic chemicals, inorganic chemicals, or fertilisers are among the stronger emitting sources, as well as combustion installations in the energy sectors and individual landfills. However, as discussed in Section 9.2, many N_2O emissions are caused in the agricultural sector, for example, in the application of fertiliser to soils. Hence, those emissions are released more area-wide than in a target-specific installation scenario.

In Figure 11, an emission threshold of 10 t/yr is selected, i.e. about 1 kg/h if continuously distributed over the year. This rate represents the threshold for reporting N_2O emissions in the E-PRTR framework. Monitoring capacities with such detection limits could allow to study emissions of the N_2O-emitting facilities covered within the E-PRTR framework and to independently verify emissions which are monitored and reported by operators, in particular providing site-integrated emissions complementary to e.g. measurement procedures on site.

10 Summary and Discussion

The key results from this work are briefly summarised and discussed in the following:

(1) **Insights into reporting schemes:** This work provides a baseline for potential applications of top-down methods in order to increase the impact of the AVENGERS project and of top-down capacities in general on emission inventories and emission mitigation measures. In summary, competent authorities compile current bottom-up emission inventories of aggregated type (i.e. reported to the UNFCCC) and target specific type (i.e. framework of the E-PRTR). The reporting frameworks, emission situations and target potentials are sketched in this document and used to analyse potentials for AVENGERS and top-down capacities, which are listed in the following.

(2) **Direct improvements of inventories:** The current reporting schemes implement emission factors and activity rates in addition to constraining emission fluxes. In order for top-down capacities to directly validate and improve existing inventories, they need to follow comparable standards and need consistency with the existing reporting frameworks. Consequently, inventory compilers need top-down capacities which construct emission factors for individual source types, in particular following the UNFCCC classification, in addition to emission rates and related uncertainties.

(3) **Complementary monitoring in support of emission reduction measures:** Top-down methods provide the opportunity to support current inventories with diverse complementary information. This includes measurements of intra-annual emission trends, direct identification of occuring leakages, target-specific monitoring of

integrated facility emissions and sub-national source attribution of detected emissions in general. By extending the current bottom-up based emission reporting with additional complementary information, they can support policy advice, provide public information, and directly facilitate emission mitigation measures. In addition, top-down method allow to study and analyse emissions along global production chains, as required e.g. by the new EU methane policy for the energy sector.

(4) Top-down monitoring complies with standards: For emission monitoring following the UNFCCC reporting guidlines and the new EU regulation on methane emissions in the energy sector, target-specific emission monitoring complies with the highest standards for emission monitoring.

(5) Observing methane emitting targets in Europe: Strong methane emitting targets in Europe are located commonly in the waste and wastewater treatment sector, mineral industry, and energy sector. Reliable monitoring capacities for detection limits down to 10 kg/h are needed to be able to measure emitting targets that reach the current E-PRTR emission reporting threshold. This limit should optimally be reached by monitoring tools in order to makes those capacities applicable for target-specific emission surveillance in Europe with relevance for the current reporting frameworks, compliance reporting and compliance monitoring.

(6) Methane emitting targets in the context of national emissions: Hotspot and mid-range methane emitters of down to 10 kg/h emission rate in the E-PRTR target register contribute several percent to the European methane emission budget, with strong country to country variation. However, the register misses some emitting sources such as cattle farming or area emissions from agriculture. Emission detection of individual sites is most useful for emission inventories if emission detection capabilities are used to construct emission factors and analyse their representativity for sources of similar type, in addition to analysing emission rates. Using emission detection for emissions of few selected sites to construct emission factors, allows using those sites to infer results for sources of similar type, given that they are representative.

(7) Requirements for carbon dioxide emission monitoring: The vast majority of national CO_2 emission budgets in Europe is caused by energy production processes. Multiple facilites report CO_2 emission rates above 1000 t/h, if their emissions are continuously distributed over the year. Future detection capacities for emission rates between 1000 t/h and 100 t/h would allow to study several hundred facilities in Europe of different source type, e.g. for independent verification of emission monitoring and reporting by operators or site-integrated emissions complementary to measurement procedures on site. To fully cover the bottom-up reported CO_2 emitting targets in the E-PRTR framework, reliable detection capacities for emission rates of 10 t/h would be needed.

(8) **Requirements for nitrous oxide emission monitoring:** The strongest N_2O emitters in Europe have emission rates of up to several hundred kg/h. N_2O emissions are for example caused by emitters in the agricultural sector and by chemical productions. To fully cover the bottom-up reported N_2O emitting targets, reliable detection capacities for emission rates of 1 kg/h would be needed.

In the current bottom-up reporting frameworks, emission rates are reported as annual rates. To compare facility emissions with detection limits from monitoring capacities, the annual rates are here converted to hourly rates respectively through uniform distribution. However, for different emission processes it is reasonable to assume that temporal variation of the emissions is of relevance. Therefore, the discussed detection requirements are benchmarks. Assessing temporal variation of emission (e.g. inter-annually, weekly, daily or even hourly differences) are of major interest for understanding emission processes and top-down capacities are an opportunity to analyse them.

This document mainly focuses on the emission situation of individual years for conceptual specification and evaluation of targets in Europe. As indicated in Chapter 5, the total methane emissions reported within the E-PRTR framework slightly decrease with time. In general, top-down capacities provide the opportunity to support and review concrete emission reduction measures of individual emitting facilities with temporal resolution. The first step to generally support those evolving detection capacities is the analysis in this document, providing conceptual insights into the situation of GHG emissions, targets and policy frameworks. As a next step, this document could be continued and expanded by e.g. additional temporal analyses of the emission situation, to work towards the goal to reduce greenhouse gas emissions.

List of Abbreviations

Abbreviation	Full Designation
AVENGERS	Attributing and Verifying European and National Greenhouse Gas and Aerosol Emissions and Reconciliation with Statistical Bottom-up Estimates
CH_4	Methane
CO_2	Carbon Dioxide
E-PRTR	European Pollutant Release and Transfer Register
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gas
IED	Industrial Emissions Directive
IEPR	Industrial Emissions Portal Regulation
IMEO	International Methane Emissions Observatory
IPCC	Intergovernmental Panel on Climate Change
ISPRA	Italian Institute for Environmental Protection and Research
LCP	Large Combustion Plant
LDAR	Leak Detection and Repair
LULUCF	Land-Use, Land-Use Change and Forestry
MRV	Measurement, Reporting and Verification
N_2O	Nitrous Oxide
NIR	National Inventory Report
OGMP 2.0	The Oil & Gas Methane Partnership 2.0

RIVM	National Institute for Public Health and the Environment (Netherlands)
SLU	Swedish University of Agricultural Science
UBA	Umweltbundesamt (German Environment Agency)
UNFCCC	United Nations Framework Convention on Climate Change

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