First Progress on Targets Report

DELIVERABLE 5.8

Author(s): Wilfried Winiwarter, Glen Peters, Rona Thompson

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Summary

Top-down assessments of greenhouse gas emissions through inverse modelling supports national greenhouse gas inventories (NGHGIs) and can help evaluate their accuracy. From the first year of the project, top-down products from EYE-CLIMA are not yet available, hence inversion results from previous projects have been used to determine the potential of inversions for supporting NGHGIs and to guide the further development of the inversion methodology in EYE-CLIMA. Results from RECCAP-2 demonstrate a continuous decrease in the emissions of CO_2, CH_4 and N_2O over Europe in decadal trends from the 1990s to the 2010s. NGHGIs show similar trends, though the combination of individual national information indicates lower CH_4 emissions and less pronounced early trends of emission reductions, while the more recent trends appear stronger. Nationally determined targets will require a further increase in mitigation rates to achieve the aims set for 2030, which seems possible with adequately high policy ambition. A focus on more recent data, on finer resolution that also allows for comparing inventories and inversions on the national scale, and the analysis of interannual variations towards identifying source patterns will further increase the relevance of EYE-CLIMA results for policy evaluations.

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Abbreviations / Acronyms

BU	Bottom-Up
CH_4	Methane (greenhouse gas)
CO_2	Carbon dioxide (greenhouse gas)
COP	Conference of Parties
EU	European Union
ETS	Emission Trading System
F_{direct}	Direct anthropogenic fluxes (of CO_2)
GCP	Global Carbon Project
GHG	Greenhouse Gas
GPP	Gross Primary Production
IMEO	International Methane Emissions Observatory
IPCC	Intergovernmental Panel on Climate Change
N_2O	Nitrous oxide (greenhouse gas)
NDC	Nationally Determined Contribution
NGHGI	National Greenhouse Gas Inventory
RECCAP-2	Regional Carbon Cycle Assessment Program – phase 2
Re_{terr}	Terrestrial respiration
TD	Top-Down
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
VERIFY	Observation-based system for monitoring and verification of greenhouse gases – project funded under the Horizon 2020 programme

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1. Introduction

The EYE-CLIMA project demonstrates how atmospheric measurements can be used to estimate fluxes of various greenhouse gases (GHGs) to the atmosphere. Based on standardized measurements and infrastructures, such as networks of tall tower sampling stations or satellites, fluxes can be estimated using atmospheric transport models and a method generally known as inverse modelling. EYE-CLIMA aims to develop the inverse modelling method from its current use as scientific tool into a routine method that can be used to robustly estimate national GHG emissions, and their uncertainties, and improve national greenhouse gas inventories (NGHGIs).

Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are obliged to provide information about anthropogenic fluxes of greenhouse gases occurring on their territory. Obligations are stricter and require annual reporting for industrialized countries as listed in Annex 1 of the UNFCCC (also called Annex-1 countries). The reporting procedures are outlined by the Intergovernmental Panel on Climate Change (IPCC, 2006; IPCC, 2019), but the reporting also has to follow the rules set out at the UNFCCC conferences of parties (COPs). One of the principles of the IPCC (2006) guidance is to maximize Accuracy, Completeness, Consistency, and Comparability. Based on such principles, it is no surprise that also inventory verification ranks high in the demands set out for national GHG inventories. While such verification first refers to quality checks and audits on the procedural aspects to calculate inventories, also reviews by external experts (delegated by UNFCCC) are standard practice. Based on these experts' advice, national inventory agencies are required to update and improve their inventories. While the use of independent data (such as measurements) in principle is already envisaged by IPCC (2006), this has not been implemented into standard practice.

With countries developing their own national emission targets (nationally determined contribution, NDC, as required by the Paris Agreement under the UNFCCC), observation of national emissions has been converted into the observation of achievement of national targets. Target setting and target monitoring obviously relates to the national inventories. Benchmarking of achievement, therefore, requires the use of inventories, which are officially adopted obligations of a country. All efforts are needed to make sure these obligations indeed reflect the real fluxes, hence requiring verification. Progress towards targets of emission reductions thus needs to be measured against the results of national inventories.

2. The need for emission inventories

Emission inventories are standard regulatory tools to quantify the fluxes of GHGs as well as of air pollutants into the atmosphere. Their methodology to quantify emissions often consist of complex algorithms that have been developed over many years, and detailed methodological guidance exists (IPCC, 2006, 2019), which also allows for the accommodation of very specific circumstances or even the results of emission measurements. Still, for most sources the core approach, expressed in simplified form, may be referred to as an extrapolation. A given indicative quantity of an economic activity (e.g., energy consumption) is multiplied with an often constant factor describing the emission rate of a given substance (e.g. Carbon Dioxide, CO_2). Such "emission factors" are derived from measurements, ideally these measurements describe typical operating conditions and are representative for the activity in question. Emission processes, however, can be quite variable, and statistical data to describe activities may be sparse, inadequate, or otherwise compromised, which added complexity can only partially compensate. Furthermore, measured emission factors may be sparse, and a complete coverage of all emissions not feasible when there are unknown sources.

Emission inventories have been criticized for being based on such limited knowledge and, therefore, not being robust. This is why validation and verification are important. In particular, the use of independent

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approaches and by independent investigators, would help verify NGHGIs and lend confidence and credibility to the process of monitoring progress towards emission reduction targets. One such independent approach is the use of atmospheric observations in inverse modelling. Atmospheric observations are made routinely from national and international networks of observing stations, as well as from satellites. The measurements reveal what is actually in the atmosphere, and is the integrated signal from possibly many individual sources. This approach is termed Top-down (TD). On the other hand, approaches combining information from individual sources, such as used in inventories, are called Bottom-up (BU). The comparison of TD versus BU approaches has been a rapidly expanding area of research in recent years.

TD assessment has improved greatly over the last years (see e.g. for ammonia, Van Damme et al., 2021; or for local air pollutants and CO_2, Lamprecht et al., 2021). With the introduction of additional measurements, the accuracy of inverse modelling will further improve and with a sufficiently dense observation network it may also be able to detect previously unknown emission sources. The coverage and accuracy of the atmospheric observations also strongly determines the sensitivity of the inversion to detect changes in emissions, such as whether they can identify emission reductions due to implementing mitigation measures, and whether given reduction targets are met. Emission inventories, in contrast, can be applied in a scenario mode in which they assess beforehand the impact on the emission estimates given different mitigation measures. The combination of TD (inverse modelling) and BU (emission inventories) provide information that is essential for monitoring the effectiveness of past and current emissions mitigation policies and for planning further action to reduce emissions of climate changing substances. This combination recognizes the strengths and weaknesses of both approaches, and it is one aim of EYE-CLIMA to find how to best use TD and BU methods for supporting NGHGIs and policy decisions.

There is one further important difference between TD and BU (i.e., inventories) approaches, and that is in who mostly uses them and the implications this has. Inventories are prepared by an inventory agency on behalf of a national authority. Provided an inventory follows certain quality standards using appropriate guidance for harmonization and validation (e.g., as outlined by IPCC, 2006), it allows its producer or commissioner (e.g., a national authority or a national government) to take responsibility for these emissions. Taking responsibility for emissions means also taking the responsibility for the steps needed leading to emission abatement. On the other hand, TD methods are generally used by the research community and by non-governmental organisations (e.g. UNEP's IMEO), and although they do not have the authority to address the emissions, they can inform national authorities of these, they can publicize the emissions and, in case of discrepancies observed, call for inventory improvements.

3. Information content of combined Top-down and Bottom-up approaches

EYE-CLIMA is currently preparing TD emission estimates based on new prior information and improved methods. However, as of present, there are no TD results available from the project (the project started in January 2023). Instead, EYE-CLIMA has contributed to the synthesis of inversion results obtained from other projects in the framework of RECCAP2 (Regional Carbon Cycle Assessment Program, led by the Global Carbon Project). This report is based on this synthesis and indicates how validation of NGHGIs should be pursued in the course of EYE-CLIMA.

For comparing NGHGIs with set targets, we use here the most current comparison of TD versus BU emissions for Europe prepared in RECCAP2 (Lauerwald et al., 2024, paper submitted), which uses results from the VERIFY project. Lauerwald et al. analyse European emissions (covering almost all countries of Europe, except Russia and Turkey) and trends on a decadal scale, using decadal averages (1990-1999, 2000-2009 and 2010-2019). This creates three datasets each covering ten years.

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For the CO_2 budget, these authors use multiple sources of BU and TD estimates to establish the most plausible developments for Europe, for which they find considerable emission reductions of around 16% over the whole time span presented (i.e., from the mean of the first to the mean of the last 10-year period, representing a total difference of 20 years). They differentiate the land budget and the direct anthropogenic CO_2 fluxes (F_{direct}) from energy, industry, waste, and agriculture. The land budget of CO_2, representing an overall sink, is governed by the not quite compensating fluxes of gross primary production (GPP) and terrestrial respiration (Re_{terr}) (i.e. the total of autotrophic and heterotrophic respiration). The only consistent representation available for the whole time span turns out to be derived from the FLUXCOM ERA5 dataset (Jung et al., 2020), based on upscaled flux measurements. In contrast, F_{direct} has been derived from a combination of BU datasets. In terms of decadal change (difference between the means of two subsequent 10-year periods), there was a slight reduction in F_{direct} from the first to the second period (5%), while there was a distinct reduction from the second to the third period (19%, of the original total CO_2 emission). The increased reduction in F_{direct} from the second to the third period, however, was countered by a reduction in GPP and, especially, an increase in Re_{terr}, which when combined counter-balanced about 40% of the reduction in F_{direct}.

Similar evaluations have been provided by Lauerwald et al. (2024) for methane (CH_4) and nitrous oxide (N_2O). Over the time span of two decades (from the 1990s to the 2010s average), European CH_4 emissions have been reduced by about 25%. From the first to the second period, this is a result of reductions in the combined sectors of energy, industry and waste as well as that of agriculture. For the second to the third period (2000s average to 2010s average), energy/industry/waste continue to decrease at a similar pace, while reductions in agricultural emissions become much slower, less than a third of the reductions seen in the between the first and second period. For N_2O, more than 22% of original emissions have been abated between the 1990's and the 2010's. The strongest reductions are seen in industrial emissions, amounting to about two thirds of the total reduction between the first and second period, and about 90% of the total reduction between second and third period. Sectoral results for both CH_4 and N_2O derive from BU datasets, which have been validated using TD methods (regional TD CH_4 emissions tend to be on the high end of the BU results, while regional TD N_2O emissions agree well with BU data).

In their assessment, Lauerwald et al. (2024) estimate the confidence of fluxes to express uncertainty ("moderate level", ±50%, for land-based CO_2 sources/sinks as well as most CH_4 and N_2O emissions, lower uncertainty for energy-related CO_2 emissions, but much higher uncertainty for industrial N_2O) based on discrepancies between their input sources, but they provide no uncertainty information for trends. Generally, many uncertainties will cancel out for trends, reducing trend uncertainty.

Lauerwald et al. (2024) provide additional information on the spatial distribution of the emissions, yet only for the most recent decade. The spatial resolution of the regional inversions is at 0.5°, while the BU data have different and mostly finer resolution (Lauerwald et al., 2024). Spatial information is only available for the final decade (2010's), nevertheless also averaged trend information has been derived for this period. While anthropogenic CO_2 fluxes use BU inventory information, results for land-based CO_2 and for CH_4 and N_2O are shown as derived from regional inversions.

Land-based CO_2 fluxes show large sinks in the northern parts of Europe, and also in northern France and Germany. These sinks have increased for northern France and Germany, as well as Poland or Belarus, whereas sinks have decreased over Scandinavia. Some areas that are current sources (i.e. release carbon) show a trend towards becoming a sink, such as in Northeast Spain, Southwest Germany and Ukraine.

Results from CH_4 inversions show that emissions have decreased widely, except for Germany and especially the Netherlands where an increase is seen. Also, N_2O emissions decreased over large parts

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of Europe, here including specifically Germany, but increased over Belgium, the Netherlands and the UK.

4. Evaluating reduction targets

The GHG fluxes as derived from a combination of BU and TD methods (Lauerwald et al., 2024) may be used to compare against national reports and national targets of GHG emissions. Under the United Nations Framework Convention on Climate Change (UNFCCC), countries are obliged to annually report their national emissions (following a BU inventory-approach). Here we select data for the European Union (EU), which reports separately in addition to all member countries individually, for Norway, Switzerland and the United Kingdom (UK) as the countries specifically addressed in EYE-CLIMA, as submitted in 2023 (currently the latest available submission). We also evaluate against reduction targets – here obtained from the NDCs according to the Paris Agreement. The EU prepared joint NDCs, allowing for effort sharing across member countries. The promised reductions (NDCs) between 1990 and 2030 (40 years) are 55% for the EU and for Norway, 68% for the UK, and 50% for Switzerland (see Appendices 1 and 2 of this document).

Figure 1 allows the comparison, by greenhouse gas, of the results compiled by Lauerwald et al. (2024) to those provided by the national inventories. Differences in approaches have not been resolved, instead these differences guide to improvements needed for EYE-CLIMA inversions. Discrepancies in absolute numbers can be attributed, at least in part, to the different domains investigated – this is Europe without Russia and Turkey for the decadal averages, while the annual data include the EU plus Norway, Switzerland and the UK only. A decadal average may avoid weather peculiarities, but also misses out on particular economic instances that become visible in the annual pattern such as the 2008 economic crisis or the Covid pandemic in 2020, in both cases resulting in emission dips followed by a quick rebound. Moreover, a lack of sectoral information renders it challenging to provide detailed guidance of inventory improvement. Here further information (e.g., annual cycles of specific emission sources) may further guide comparisons.

Nevertheless, Figure 1 is able to display the general trends, specific for the three GHGs investigated. The decadal averages show reductions of 16% for CO_2, 25% for CH_4 and 22% for N_2O, respectively, over the whole time span, representing a difference of 20 years. Annual data allow for a much more refined differentiation, indicating lower reductions of CO_2 emissions in the first period (representing the difference between first and second decadal average), but higher reductions in the second time step (from the second to the third decadal average). For both CH_4 and N_2O, trends of annual emission data seem smoother and better reflect also the decadal averages.

Extrapolation to meet the 2030 emission targets requires more stringent emission reduction rates than have been seen in the past (with a slope about twice as steep), but recent trends lend credibility that achievement of the target is possible in principle. TD results of these recent trends have not been made available yet.

In a comparison of all reported greenhouse gases, Figure 2 shows that the higher emissions for CO_2 reported by the national inventories and the lower results for CH_4 and N_2O emissions largely even out. F-gas emissions, which also have been included in the national (annual) data but have not been evaluated by Lauerwald et al. (2024) are too small to make a difference. NDC targets have been proposed on the total emissions only, so benchmarking also needs to be done on this level. While data demonstrate a clear decrease of overall emissions, the current trend seems insufficient to achieve the 2030 targets. This indicates the need to further increase policy ambitions aiming to double the decrease rates seen in the recent decade.

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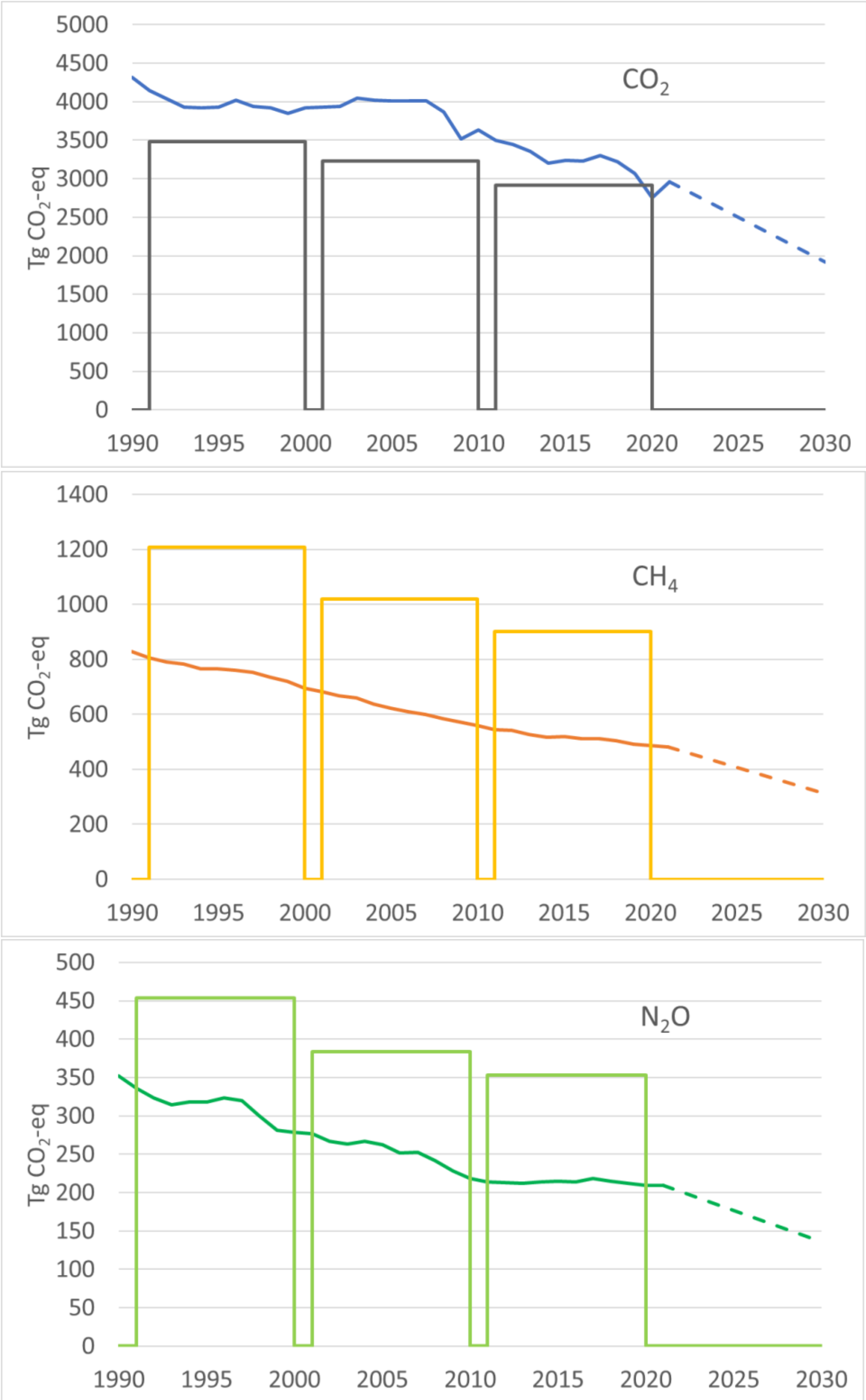

Fig. 1: Comparison of decadal averages from TD-BU intercomparison (Lauerwald et al., 2024) with annual values of national GHG inventories (2023 submissions for EU, Norway, Switzerland, UK) extrapolated to 2030 assuming NDC reduction targets, all in CO_2-eq emissions on a 100-year time horizon as defined by the respective sources. Differences in underlying data remain and are described in the text (specifically, decadal averages cover Europe without Russia and Turkey, while annual time series reflect the EU plus UK, Switzerland, and Norway).

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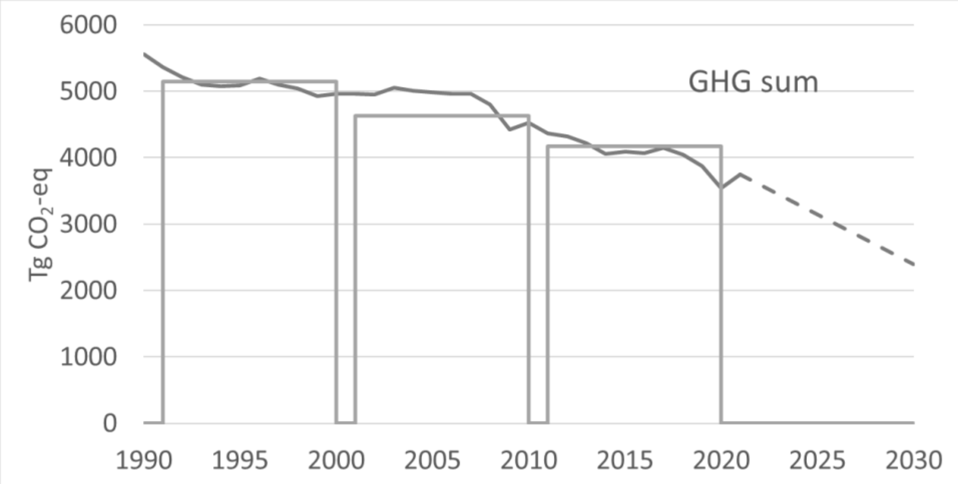

Fig. 2: Comparison of total GHG emissions using the same underlying data as in Fig. 1. Decadal averages are taken from TD-BU intercomparison (Lauerwald et al., 2024), while annual values refer to the national GHG inventories (2023 submissions for EU, Norway, Switzerland, UK) and are extrapolated to 2030 assuming NDC reduction targets. Emissions are summed up according to their CO_2-eq on a 100-year time horizon as defined by the respective sources. Emissions of F-gases are included in the national inventories but contribute a minor share only (70 – 120 Tg CO_2-eq).

5. Prospects of EYE-CLIMA work: inverse models and expectations of future achievements

The evaluation of existing TD-BU combined assessments provides guidance for future analyses in EYE-CLIMA. This refers specifically to setting priorities in evaluations, so that TD results complement BU inventories to the greatest extent possible.

- Policy guidance needs to be up-to-date: While year-to-year comparisons between TD and BU results may remain challenging (BU method may not be able to sufficiently reflect weather anomalies that atmospheric measurements used in TD approaches might capture), at least obtaining results with minimal lag would be useful to capture trends as early as possible. The delay of BU inventories (typically submitted to UNFCCC about 16 months after the end of any given year) should allow sufficient time for TD results to be also provided (e.g., for verification).
- Higher spatial resolution of TD emission estimates in EYE-CLIMA (0.2° compared to 0.5° in RECCAP-2) should help to better distinguish emissions deriving from either side of a country border, when aiming to provide results on a country level. While initially TD estimates allow to address large countries and entities that are geographically very distinct only, the higher spatial resolution may more generally support differentiation of emissions between countries and thus also approach country levels. Analyzing TD versus BU data on country levels should also provide guidance to national inventory agencies regarding improving their respective inventories.
- Little focus has been given yet to periodic sub-annual variations. Such variations may help to distinguish source sectors, another relevant factor for identifying discrepancies between TD and GHG inventories.

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Appendix 1: Nationally determined targets of countries relevant for EYE-CLIMA under the Paris Agreement

European Union (submitted 10/19/2023)

"The EU and its Member States, acting jointly, are committed to a legally binding target of a domestic reduction of net greenhouse gas emissions by at least 55% compared to 1990 by 2030."

United Kingdom (submitted 09/22/2022)

"In its NDC the UK commits to reducing economy-wide greenhouse gas emissions by at least 68% by 2030 compared to 1990 levels."

Switzerland (submitted 12/17/2021)

Switzerland commits to reduce greenhouse gas emissions by at least 50% by 2030 compared to 1990 levels, corresponds to an average reduction of at least minus 35 percent over the period 2021-2030. Switzerland also states an indicative goal to reduce greenhouse gas emissions to net-zero emissions by 2050 and a 25 percent increase of the domestic share of emission reductions. Switzerland's NDC comprises a mitigation target only.

Norway (submitted 11/03/2022)

"Norway is committed to a target by at least 55 per cent reduction in greenhouse gas emission compared to 1990 levels."

(target year is 2030)

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Appendix 2: Effort Sharing Directive of the European Union

For the first time, all EU countries are required to reduce their greenhouse gas emissions between 10% and 50%. The national targets vary according to each country's gross domestic product per capita and cost-effectiveness. In addition, EU countries will have to ensure they do not exceed their annual greenhouse gas emission allocation as of the Emission Trading Scheme of the EU.

	Member State greenhouse gas emission reductions in 2030 in relation to their 2005 levels determined in accordance with Article 4(3)	
EU country	Column 1 (old target)	Column 2 (new target)
Belgium	- 35 %	- 47 %
Bulgaria	- 0 %	- 10 %
Czechia	- 14 %	- 26 %
Denmark	- 39 %	- 50 %
Germany	- 38 %	- 50 %
Estonia	- 13 %	- 24 %
Ireland	- 30 %	- 42 %
Greece	- 16 %	- 22.7 %
Spain	- 26 %	- 37.7 %
France	- 37 %	- 47.5 %
Croatia	- 7 %	- 16.7 %
Italy	- 33 %	- 43.7 %
Cyprus	- 24 %	- 32 %
Latvia	- 6 %	- 17 %
Lithuania	- 9 %	- 21 %
Luxembourg	- 40 %	- 50 %
Hungary	- 7 %	- 18.7 %
Malta	- 19 %	- 19 %
Netherlands	- 36 %	- 48 %
Austria	- 36 %	- 48 %
Poland	- 7 %	- 17.7 %
Portugal	- 17 %	- 28.7 %
Romania	- 2 %	- 12.7 %
Slovenia	- 15 %	- 27 %
Slovakia	- 12 %	- 22.7 %
Finland	- 39 %	- 50 %
Sweden	- 40 %	- 50 %

Source: REGULATION (EU) 2023/857 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

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