



ACHIEVING HIGH-INTEGRITY VOLUNTARY CLIMATE ACTION

D1.4 – IAM Guidance on actor group output and downscaling

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Responsible Author	Mark Roelfsema		PBL





	Mark.roelfsema@pbl.nl
Contributors	Mark Roelfsema (PBL), Stephen Maycock (PBL), Maria-Iro Baka (E3M), Panagiotis Fragkos (E3M), Birka Wicke (RU), Takeshi Kuramochi (NCI), George Xexakis (Holistic) External contributors: Angel Hsu (UNC at Chapel Hill)
Reviewer(s)	Isabel Haase, Lauri Peterson
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EC Summary Requirements

1. Changes with respect to the Description of Action (DoA)

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This report proposes methods to assess the progress and ambition of subnational and non-state actors. It is meant to function as a guideline for integrated assessment models. First, these methods can be used in WP2 and WP4 of the ACHIEVE project. Second, it can be used by all modelers that use integrated assessment models, and it will specifically be included in model protocol of the NEWPATHWAYS (Horizon) project.

3. Short summary of results (<250 words)

Non-state and subnational actors are increasingly significant in addressing the climate crisis. These actors were recognised in the Paris Agreement and are called upon to support actions to reduce emissions. This study aims to provide new approaches to enhance the assessment of non-state actors' collective progress and ambition towards the Paris Agreement goals, as well as to support benchmarking cities, subnational regions, and companies against Paris-aligned pathways. This study gives a global perspective by using integrated assessment models and give a consistent picture at this level considering various scenarios. However, to facilitate the benchmarking of climate actions by diverse actors and help policymakers understand their potential contributions to mitigation, new methodologies for these models are needed. Therefore, the assessments done with these models should include a broader range of actors to give a detailed understanding of the global impact of various levels of non-state and subnational climate action. To achieve this, the actors' commitments could be aggregated for model inputs, model outputs could be downscaled to specific actor groups and geographic locations, and the actors' decisions could be incorporated into the model's decision-making process. Two case studies were conducted to demonstrate the new approaches. The first case study focuses on companies and shows that scaled-up emissions reduction targets in key sectors are projected to decrease global emissions 25% by 2030 compared to the levels projected under current national policies alone. The second case study focuses on cities and shows that downscaled urban emissions from a current policy scenario need to be reduced by 50% to close the gap with a downscaled urban 1.5° C-aligned pathway.

4. Evidence of accomplishment

This report.





5. Disclosure statement on the use of generative artificial intelligence (AI)

[Name of the tool e.g., ChatGPT] was used for editing English language and the added prompts were excluded for ChatGPT learning. The authors critically reviewed the outputs of the tool by checking and adjusting suggestions word for word before integrating them with the authors' own work. All prompts to the AI tool are collected and listed on Zenodo (Roelfsema 2025), and access can be requested from the responsible author.





Preface

In recent years an unprecedented number of voluntary climate commitments have been made by a wide array of non-state and subnational actors. These voluntary climate actions aim to reduce greenhouse gas emissions and build climate resilience and are crucial for lowering risks of exceeding warming limits. However, the full potential of voluntary climate action can only be realised when integrity-related concerns are overcome. ACHIEVE aims to identify opportunities to strengthen and scale up high-integrity voluntary climate action towards achieving net-zero emissions by mid-century. The project will generate transformative and timely scientific insights on the role, effectiveness and integrity of voluntary climate action including carbon credits; assess the integrity and impacts of such action; analyse how policies and regulations, and high-integrity voluntary climate action can strengthen each other; and use scientific findings to support the scaling up of high-integrity voluntary action. This will be achieved through a highly inter- and transdisciplinary consortium that, from the start, actively engages policymakers and other societal stakeholders in co-creating outcomes that respond to end users' needs. ACHIEVE is aligned with the Work Programme of Cluster 5, Destination 1 "Climate sciences and responses for the transformation towards climate neutrality" as the project directly contributes to advancing knowledge and providing solutions for climate change specifically on high integrity voluntary climate action. ACHIEVE will develop transition pathways to climate neutrality that integrate voluntary climate action by cities, regions and companies; it will develop novel social science insights for climate action; contribute to better understanding sustainability co-benefits and trade-offs; and increase transparency and trust in voluntary climate action by strengthening integrity and making scientific results easily accessible for different stakeholder groups.

RU – Stichting Radboud Universiteit	NL	
NCI – New Climate Institute for Climate Policy and Global Sustainability GGMBH	DE	
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Executive Summary

Non-state and subnational actors play an increasingly critical role in addressing climate change. This study aims to develop new approaches to include these actors into integrated assessment models to assess the collective progress and ambition and support benchmarking their targets against Paris aligned pathways. These actors, including cities, subnational regions, and companies, have been explicitly recognized in the Paris Agreement and are called upon to take voluntary actions to support global efforts to reduce emissions. To accomplish their assessment in the context of the climate negotiations, a global perspective is necessary, which is best achieved using Integrated Assessment Models (IAMs). IAMs provide a structured approach to evaluating long-term climate and energy scenarios, ensuring consistency across global and macro-regions. However, current IAM frameworks are often overlooking the contributions of subnational and non-state actors. Therefore, new methodologies must be integrated into these models to account for the role of decentralized climate action.

Three independent methods are described in this study aiming to provide a more detailed understanding of the global impact of various levels of non-state and subnational climate action:

1. **Aggregating non-state actor commitments for model inputs** – This approach involves compiling and aggregating voluntary climate commitments from cities, regions, and companies to integrate them as model input parameters. Two key challenges are to determine the overlap of targeted emissions between actor groups and the additionality of these commitments to national government policies.
2. **Downscaling model outputs to specific actor groups** – Since IAMs typically operate at the national or macro-regional level, they do not provide sufficient detail to evaluate the impact of climate actions at the urban or corporate level. To address this limitation, model outputs can be downscaled to specific actor groups with similar characteristics.
3. **Endogenizing decision-making into IAMs** – A more advanced approach involves modifying IAM decision-making algorithms to explicitly account for the heterogeneity of actors including their choices and behaviour.

Two case studies are presented in this study to demonstrate how global aggregation of company commitments and simple downscaling to global cities could take shape. The first case study focuses on companies and evaluates the potential emissions reductions achievable if reported corporate climate targets were scaled up to all companies globally. Using aggregated corporate commitments from key industrial sectors—including energy, industry, freight transport, and commercial buildings—the study estimates that enhanced corporate climate action could reduce global emissions by 25% by 2030 compared to the levels projected under national policies alone. The second case study examines the role of cities in climate mitigation. It downscales regional emissions trajectories to city-urban areas, assessing how emissions reductions at the city level compare to a Paris-aligned 1.5°C pathway. The findings indicate that global emissions from city-urban areas following current policy trends would need to be reduced by 50% to align with a 1.5°C-compatible pathway.

Although integrated assessment models are well suited to assess groups of subnational and non-state actors, several aspects, including overlap and additionality, reliability of data, complexity in Scope 3 emissions accounting, and data collection would require a more detailed and focused research.





- It is currently assumed that commitments from subnational and non-state actors do not replace actions elsewhere. As these commitments become increasingly regulated, this assumption needs further research.
- Many literature studies scrutinise the data reliability of cities and corporates, and more elaborated tests of self-reported data need to be developed.
- Reported estimates of Scope 3 emissions are uncertain and avoiding double counting is complex. Linking these estimates to input-output models or proceeding to sector specific indicators, such as share of electric vehicles and share of hydrogen steel making could help in overcoming the complexities.
- As there are millions of cities and companies in the world, manual data collection is impossible. However, existing and new artificial intelligence techniques could support this process.

In conclusion, IAMs have significant potential to enhance the assessment of non-state actors' climate actions by integrating their commitments into global climate policy scenarios. While challenges such as data quality and assumptions on overlap persist, advancing these models can provide valuable insights for the UNFCCC climate negotiations, national policy development, sub-national climate strategies, and stakeholder engagement.





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1 Introduction

The role of subnational and non-state actors in implementing climate actions has grown significantly since the adoption of the Paris Agreement. These actors were explicitly encouraged in the Agreement to scale up their efforts and support actions to reduce emissions (UNFCCC 2015b). The term *Climate action* refers to a wide range of activities aimed at addressing climate change undertaken by national governments as well as other actors such as regions, cities, and companies (Tosun 2022). This term is often used in the context of the United Nations Framework Convention on Climate Change (UNFCCC), which increasingly operates as a central coordinator to manage interactions between states, non-state actors (Kuyper et al. 2018).

The involvement of subnational and non-state actors in climate change mitigation is essential, as they are major contributors to and implementors of on-the-ground measures and increasingly pledge voluntary climate mitigation actions to support achieving the Paris goals and the implementation of national climate policies. Beside their support to national implementation, they could catalyse implementation or increase overall ambitions (Hsu et al. 2019; Hultman et al. 2020). The climate actions from these actors are aggregated and showcased under the umbrella of the UNFCCC Global Climate Action Portal (UNFCCC 2024a). These actions are often emissions reduction targets supported by concrete actions such as efficiency improvements in buildings and waste reductions. The actors pledging these actions have increased from 1,000 to 39,000 between 2014 and 2024 (UNFCCC 2024b).

Furthermore, these actors increasingly take action driven beyond voluntary motivations. Companies and investors are now frequently required to implement climate actions, whether through soft law, such as the UN Guiding Principles of Business and Human Rights (UNGP) and the OECD guidelines for multinational enterprises (OECD 2024) or through legislation such as the Emissions Trading System (ETS) (European Commission 2021) or more generally by the EU Corporate Due Diligence Directive (CSDDD) (EU 2024), which will become effective in 2027. Also, depending on whether national governments have adopted climate mandates for subnational governments, cities and regions may face direct and indirect regulations.

Non-state and subnational actors play a unique role in climate action, distinct from national governments. While country-level policies can be subject to political cycles and policy rollbacks—such as recent political developments in the United States, Brazil, and Australia—non-state actors can provide continuity in climate action, helping to maintain progress despite shifting national policies. However, the accountability, credibility and permanence of non-state actor commitments remains a challenge. Recent occurrences of corporate target withdrawals highlight the risk of non-binding pledges, raising concerns about their long-term reliability (Jiang, Kim, and Lu 2025). In addition, issues of integrity, including greenwashing and the effectiveness of voluntary commitments, underscore the need for robust frameworks to track and assess non-state action (UN HLEG 2024; UN HLEG 2022). Greenwashing refers to companies misleading or deceiving society regarding the positive environmental impact of their products or services (Santos et al. 2024). The UN High-level Expert Group (HLEG) emphasises that to ensure the integrity of these actions, mitigation targets should be set for the short-, medium-, and long-term, aligned with investments, and meet criteria for transparency, accountability, equity and justice (UN HLEG 2024; UN HLEG 2022).





Non-state actors include businesses, industries, investors, and civil society organisations, while subnational actors include regions (e.g. provinces and states) and cities (Hsu et al. 2019). The actors pledging these voluntary climate actions are often organised in voluntary cooperative climate initiatives (VCIs) initiated and coordinated by international organisations or sector institutes. However, these actors also pledge individual climate actions. This is an important distinction for the assessment of non-state and subnational actions, and this study focuses on both climate mitigation actions from VCIs and individual actions from cities, regions, and companies, excluding investors.

VCIs bring together diverse groups of actors, often under the coordination of a multilateral organisation (Chan et al. 2022; Widerberg and Pattberg 2015). These initiatives include various ‘alliances’, ‘declarations’, ‘coalitions’, and ‘partnerships’ (Kuramochi et al. 2024). Such initiatives often have defined overarching mitigation targets, sometimes supported by specific commitments from individual actors. The climate initiatives can serve various functions, such as knowledge production, capacity building, and training (Chan et al. 2018, 2022). In this study, we focus on those that implement mitigation actions and have clearly defined (aspirational) goals and targets. The progress and ambition of these initiatives present a mixed picture. While the number of voluntary climate initiatives has grown significantly since 2014, their effectiveness has not improved in this period (Chan et al. 2022) and they are not incorporated in Nationally Determined Contributions (NDCs) (Hsu et al. 2019; Kuramochi et al. 2024). Chan et al. (2022) argue that many initiatives have already addressed the “low-hanging fruit” and that voluntary climate initiatives perform effectively only when supported by strong sectoral organisations with dedicated secretariats, and monitoring arrangements. Still, the aspirational global goals of voluntary climate initiatives are estimated to bring current climate policies closer to a well-below 2 °C or 1.5 °C pathway by 2030, provided their overall targets are globally implemented (Kuramochi et al. 2024; Lui et al. 2021).

Individual cities, regions, and companies pledge mitigation commitments that are typically captured in their climate plans and sustainability reports and are collected by non-profit organisations such as CDP (CDP 2021a, 2021b) or Data-Driven EnviroLab (Hsu et al. 2020). Although much of this data is not publicly available, the Global Climate Action Portal (UNFCCC 2024a) compiles a significant portion. Similar to VCIs, the progress and ambition of individual voluntary climate action gives a mixed picture. Publicly registered individual commitments are estimated to collectively achieve modest additional emissions reductions compared to national policies by 2030 (Kuramochi et al. 2020). Furthermore, Song et al. (2023) highlight that while the number of climate pledges from individual cities and subnational regions is increasing, many fail to implement the necessary actions. Similarly, Boley et al. (2024) report a rapidly growing number of company emissions reduction targets, of which 55% are on track, while 30% have shown increased emissions relative to the base year.

To allow assessment of voluntary climate action, researchers from both the corporate and scientific communities often use sectoral benchmarks to assess the Paris alignment of subnational and non-state actor climate mitigation targets. This is an important but complex task. Even for countries, determining how to equitably share the efforts to meet the Paris goals presents challenges, given the ethical and equity considerations involved (Dooley et al. 2021).





The challenge for non-state actors such as cities, subnational regions, and companies is even more significant, as they often lack explicit jurisdiction or operate across multiple countries (Lecocq and Winkler 2024). Currently, existing standards for companies — such as the Science Based Target Initiative (SBTi) and the Transition Pathway Initiative — operationalise Paris alignment benchmarking methods. However, these methods are not always rooted in the scientific literature (Rekker et al. 2022). Moreover, these methods vary significantly, as some apply uniform criteria to all companies, while others differentiate based on geography, sector, projected growth rate, or baseline emissions intensity (Bjørn et al. 2021). Most fail to specify which greenhouse gases are included (Bjørn et al. 2023). In addition, no benchmarking frameworks exist for cities and subnational regions, and Schwanitz et al. (Schwanitz et al. 2023) suggest balancing scientific rigour with policy practicality, resulting in clear and communicable targets.

The focus of this study is on integrated assessment models (IAMs) which can support the development of Paris-aligned benchmarks for company sectors and groups of cities or subnational regions with similar characteristics. These models integrate the climate and human systems, incorporating representations of multiple economic sectors — such as energy and land use — as well as their interactions and associated greenhouse gas emissions (van Diemen et al. 2022). IAMs often generate quantitative scenario results, producing energy, land use and emissions projections based on exogenous socio-economic assumptions, excerpted narratives, and climate policy goals (Riahi et al. 2017) ([see Section 2](#)). The focus is on process-based IAMs, particularly those with detailed energy system representations, as they provide a globally consistent approach to assessing climate policy by capturing the dynamics within and between regions and sectors. However, these models typically focus on large countries (e.g. USA, China, and India) or macro-regions comprising multiple countries. The 2023 IPCC Scenario Workshop recommends to enhance these macro-region results to subnational regional resolution through activities such as downscaling, which translates the global or macro-region to smaller spatial scales, maintaining the consistency of the original dataset (IPCC 2023; van Vuuren et al. 2010). Downscaling could also be applied to businesses, but this is more challenging due to their operations across multiple locations, often not publicly disclosed.

In conclusion, this study aims to enhance the assessment of non-state actors' collective progress and ambition towards the Paris goals and to support benchmarking groups of cities, subnational regions, and companies against Paris-aligned pathways. To achieve this, we explore how integrated assessment models can incorporate these actors and their climate mitigation actions and propose scenarios to assess progress or benchmark ambition. Given the inherent limitations in the level of detail these models can capture (Keppo et al. 2021), our focus is on modelling groups of actors with similar characteristics. For example, these actor groups can represent specific types of actors within a country, cities of similar sizes (e.g. small, medium, large), or economic sectors in the Global North and South.

We start with outlining the key components of integrated assessment models necessary for incorporating non-state actors. Then we describe three independent methods to support the assessment of subnational and non-state actions by including them in integrated assessment models. The first shows how their climate action targets could be implemented through the aggregation of commitments; the second explains how downscaling to the specifically the urban level could be implemented, and the third sketches ways to endogenize actor decisions. Finally, these methods are demonstrated through two case studies: one assessing the global progress





in company ambition relative to current national climate policies and the other showcasing a simplified downscaling of global emissions to the urban level. These case studies are for illustration purposes, showing what type of results can be expected, but need to be expanded in terms of data and implementation of methods in future research.

The methods outlined in this study will serve as a starting point for the work in the ACHIEVE project. The most appropriate methods will be selected for deliverables 2.5, 4.2, and 4.4. Consequently, not all methods described in this guidance document may be implemented in the ACHIEVE project.





2 Integrated assessment models

Integrated assessment models capture the interactions between the natural and human environment and are used in this study to simulate the progress and ambition of subnational and non-state actors. This is done by developing scenarios and transition pathways that build upon existing policy scenarios representing the global Paris goals, national targets secured in Nationally Determined Contributions and Long-term strategies, and national policies consisting of policy mixes of instruments.

2.1 Characteristics of Integrated Assessment Models

Integrated Assessment Models (IAMs) are advanced modelling tools that integrate knowledge, information, and data from multiple disciplines — primarily economics, energy structures, and environmental science — to explore and analyse the interactions between different interconnected systems such as the human and natural environment (Diemer et al. 2019). IAMs provide a framework for assessing the medium and long-term impacts of policy decisions, technology developments, and societal behaviours. These modelling frameworks are primarily applied to evaluate and assess the impacts of various policies on complex global challenges, such as climate change, energy transitions, and sustainable development.

In recent years, IAMs have been widely used to evaluate a range of climate policies, such as carbon pricing, emissions trading systems, and renewable energy incentives. The results of these models are regularly featured in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) (van Beek et al. 2020) which inform the UNFCCC climate negotiations through an officially established link (UNFCCC 1992). These models help policymakers better understand the complex interactions between economic growth and ambitious climate targets and provide insights for developing optimised transformation strategies to achieve the Paris goals. Moreover, multi-model exercises using IAMs have been conducted to compare cost-optimal global pathways representing well below 2 °C or 1.5 °C pathways with currently implemented domestic policies or economy-wide NDCs (Roelfsema et al. 2020; Vrontisi et al. 2018). In addition, IAMs provide alternative pathways that adhere to the same temperature limits established in the Paris Agreement (Soergel et al. 2024; van Vuuren et al. 2018). They also enable assessments of the coherence of national pathways and help identify potential gaps in national policies relative to NDC targets and 2° C/1.5 °C climate scenarios (van Soest et al. 2017). In addition, IAMs and other climate-economy models have been directly informing the design and development of climate policies, such as the European Union’s climate target for 2040 (EEA 2023), the NDCs of various countries and the National Energy and Climate Plans of the EU Member States. Furthermore, IAMs participate in model ensembles alongside energy system models to provide insights into the interactions between energy systems, climate change and broader economic and land use developments (Dekker et al. 2023; Henke et al. 2024; van der Zwaan et al. 2025), while recently they also focus on assessing sectoral transformations consistent with the Paris goals (van Heerden et al. 2025; Müller-Casseres et al. 2024).

Typically, IAMs optimise aggregated economic costs to achieve global or macro-regional climate goals (Clarke et al. 2014), thereby identifying cost-effective pathways for meeting these targets. The macro-regions in these models consist of multiple countries with similar characteristics or large individual economies. IAMs can be broadly categorised into cost-benefit models, which estimate high-level abatement costs and damages, and process-based mitigation models, which are activity-focused and incorporate a detailed representation of the various sectors and





technologies (Keppo et al. 2021). Process-based models can be further divided into macro-economic models, which represent the dynamics between economic activity and mitigation policy, and models that include physical activity and offer greater sectoral and technological detail (Dekker et al. 2023; Keppo et al. 2021; Roelfsema et al. 2022). Activity-based models use either simulation or optimisation techniques to develop projections. While both aim for cost-effective implementation of climate policy, simulation models (recursive dynamic models) make investment decisions on an annual basis, whereas optimisation models (inter-temporal models) allocate investments over longer periods to achieve specified goals.

IAMs are commonly used to assess the ex-ante impact of climate policy through scenarios that project possible future pathways based on ‘what-if’ assumptions. These scenarios are broadly categorised into explorative and normative scenarios. Explorative scenarios analyse a range of plausible futures by considering current trends, important drivers (e.g. population and GDP), current policies, and uncertainties, while normative scenarios illustrate possible pathways to achieve a certain preferred state (i.e. a specific net-zero emissions target for 2050). The IAM community has developed Shared Socioeconomic Pathways (SSPs), which combine quantitative assessments of future socioeconomic pathways (explorative) with long-term climate policy targets (normative) (Moss et al. 2010; Riahi et al. 2017; van Vuuren and Carter 2014). Normative climate policy scenarios are developed to identify which conditions need to be fulfilled for specific goals to be accomplished (Fortes et al. 2015), such as the global temperature goals or national targets and policies. Typically, these scenarios start from an explorative variant of the SSPs scenarios, which is often the SSP2 scenario, a ‘middle-of-the-road’ scenario that extrapolates current trends (Fricko et al. 2017).

2.2 Climate policy scenarios

This study builds on existing policy scenarios published in the literature. These scenarios project the environmental impact (e.g., change in GHG emissions) of climate policy goals and targets. In this context, goals are seen as long-term and systemic (aspirational) ambitions (Edenhofer et al. 2014), while targets translate these goals to more specific policy objectives implemented through policy instruments (Roelfsema et al. 2022). The policy scenarios encompass current policies, NDCs potentially combined with Long-Term Strategies (LTSSs), and various interpretations of the Paris temperature goals, including cost-effective implementation and assumptions about fair effort-sharing (van den Berg et al. 2019; Dafnomilis et al. 2024; Roelfsema et al. 2020).

The current policies scenario incorporates policies formally adopted by governments through legislation or executive orders (e.g., EU’s target for 55% reduction of GHG emissions compared to 1990 levels by 2030), as well as non-binding targets supported by effective policy instruments (e.g. Brazil Power Purchasing Agreements supporting the realisation of the Ten-Year Energy Expansion Plan) (Roelfsema et al. 2020), assuming similar efforts beyond the policies’ target years. NDCs and LTSSs reflect the climate ambitions of countries under the Paris Agreement, expressed as specific goals that generally include quantified emission reductions targets. NDCs primarily focus on medium-term commitments (a maximum of ten years), whereas LTSSs outline long-term goals to reach net-zero in the second half of this century. Temperature scenarios align with the Paris Agreement’s goals to limit global temperature increases relative to the pre-industrial period to well below 2°C and to pursue efforts to hold it below 1.5°C (UNFCCC 2015a).



**Table 1.** Model implementation of different national climate policy scenarios: current policies, NDCs, LTS, and Paris temperature goals

Scenario	Translation to model input targets	Model implementation
Current policies scenario	- Policy instruments with explicit policy targets are used as is. - For policy instruments without explicit targets, aspirational targets are identified and used if they lead to the instrument's implementation	- Model parameters are adjusted based on the policy instruments, such as sectoral carbon taxes, enforcing installed capacity levels, or modifying efficiency improvements of technologies - This is implemented at the macro-region level, where country-level policy targets, translated into model parameters, are aggregated under the assumption that countries without policies follow a 'no-policy scenario' (e.g. SSP2) - Extrapolation after target year based on continuation of efforts
NDCs/LTS	- Most NDCs include quantifiable targets such as emissions reduction targets, installed renewable energy capacity targets, emissions intensity targets or reforestation targets.	- Emission reduction and capacity targets are directly used as model input targets - Emissions intensity targets are modelled by calibrating sectoral carbon taxes - Reforestation is modelled by maintaining/increasing forests in designated areas. - Country NDCs are aggregated on the macro-regions level, similar to the current policies scenario - Extrapolation after target year based on continuation of efforts
Paris temperature goals	- Interpretations required of temperature limit for model implementation - Probability of keeping temperature increase below a temperature limit (typically with 66% probability) - Time period to which the limit applies (often until 2100 or the	- Cost-effective: optimisation over a horizon until 2100 based on the interpretation of temperature goals using long-term discount rates - Equity-based: the effort-sharing emissions levels are domestically implemented (mostly through carbon pricing?) at the lowest costs - Optimisation is done at the global level, and emissions reduction measures are





	time of net-zero “peak temperature”) - Allowance for temperature overshoot and, if so, by how much - Translation to radiative forcing targets or carbon budgets - Interpretations required for sharing mitigation efforts across regions - Cost optimal: measures are implemented with the lowest climate policy costs - Effort sharing: budgets are allocated based on fair share principles such as equality, responsibility, or capability	implemented where this is most cost-effective (global carbon price) - The equity-based method allocates emissions to macro-regions based on an exogenously given global carbon budget
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The model implementation of these climate policy scenarios involves multiple steps. First, high-impact domestic climate policies are collected based on input from national experts and literature, along with country-level NDCs and LTSs. The goals and targets of these climate policy variants are then translated into model input parameters to replicate their impact on greenhouse gas emissions (Roelfsema et al. 2022); see Table 1. Methods for implementing global temperature targets can be approached in two ways: cost-effective pathways, which optimise the global cost of climate mitigation (Rogelj et al. 2019; van Vuuren et al. 2011), and equity-based pathways, which allocate mitigation efforts based on different effort allocation principles (van den Berg et al. 2019; Dekker et al. 2024). In the first approach, emissions pathways are determined by minimising the global mitigation costs, often using a social discount rate. In the second approach, equity principles are translated into fair effort-sharing formulations to allocate the global carbon budget to specific emission budgets or pathways for macro-regions or individual countries.

2.3 The challenge of incorporating subnational and non-state actors into IAMs

Integrated Assessment Models are well-suited for simultaneously representing voluntary actions alongside national climate policies (Hsu et al. 2019). Incorporating subnational and non-state actors into IAMs can facilitate the development of diverse transition pathways tailored to their specific roles and contributions. These pathways can serve as benchmarks for setting measurable and achievable climate targets for non-state actors, assessing their alignment with national and global commitments, and providing a framework for tracking progress and evaluating the effectiveness of climate initiatives over time. However, the level of detail that can be incorporated





has limitations, and IAMs should be utilised in ways that leverage their strengths while at the same time producing results that are credible and relevant for policymakers and the wider public.

The strength of Integrated Assessment Models lies in their representation of the complex interconnections between the environment and economic, energy, and land use systems, while also capturing the interactions between the global dynamics and specific macro-regional or national contexts. Comparing scenario results under different assumptions can support policy decisions and highlight the potential consequences of different climate actions over time and across sectors.

At the same time, Integrated Assessment Models also face limitations since they often rely on simplified representations of real-life dynamics. The Models' simplified depictions of actual mechanisms lead to a lack of heterogeneity in actor groups, no basic representation of capital markets, and no finance and energy economy feedbacks (Keppo et al. 2021). The accurate depiction of the complex dynamics depends on the provision of credible data, so increasing any type of modelling resolution (spatial, sectoral or temporal) requires additional data which are not always available or reliable. Different levels of governance compared to the national level could inevitably lead to different likelihoods of implementation and effectiveness of non-state climate action. Furthermore, although the finance sector plays a critical role in support of voluntary climate actions (despite recent developments in the US where several banks exit the Net-Zero alliance after Trump's win). Process-based models by default do not include the financial sector, while most macro-economic models do not explicitly include capital flows (Keppo et al. 2021).

Although IAMs can support stakeholders in better understanding the potential impacts of ambitious climate policies on economic growth, there is a lack of diverse stakeholder perspectives in scenario development (van de Ven et al. 2025). To address this issue, there has been an increasing number of participatory methodologies to actively involve stakeholders in the exploration of different futures and scenarios with Integrated Assessment Models (McGookin et al. 2024; Pereira et al. 2021; Salter et al. 2010). Nevertheless, the diversity of stakeholders involved is important, especially since the user base of IAM scenarios is constantly expanding, not only including high-level policymakers and researchers but also companies, cities, investors, industries, and other subnational governments (Weber et al. 2018).

In conclusion, to deploy the strength of IAMs, this study outlines how climate action from voluntary climate initiatives or groups of subnational and non-state actors can be implemented in IAMs, thereby utilising the dynamics of these models within and between sectors and macro-regions. This allows to develop transition pathways including both national policies, subnational and non-state climate actions make long-term projections under alternative scenarios. This way, it is possible to compare IAM pathways with 2 °C and 1.5 °C pathways to compare the ambition and progress of non-state actors with the (model implementation of) Paris goals, use sectoral pathways to benchmark business sectors, and use downscaled urban pathways to benchmark groups of cities and subnational regions with similar characteristics.

The integration of non-state actors into IAMs is described with the IMAGE model (Stehfest et al. 2014) and PROMETHEUS model in mind (Fragkos et al. 2018), see SI for details. However, the approach can also be adapted for use by other models, potentially with a few modifications.



3 Modification of integrated assessment models needed to assess voluntary climate action

This study presents three independent methods for incorporating cities, subnational regions, and companies into integrated assessment models, each serving a distinct function for analysing actor climate actions. These methods build upon existing scenarios that describe current policies, Nationally Determined Contributions, and Paris-aligned pathways. We illustrate the use of the first two methods with straightforward case studies.

3.1 Three independent approaches to include voluntary climate actions

The starting point for modifying IAMs to include voluntary climate actions is the suite of climate policy scenarios described in Section 2. These scenarios illustrate the impacts of implemented climate policy goals and targets on the energy and land-use system and focus on national governments and global agreements. The approaches outlined in this study build upon these scenarios by incorporating the climate actions of subnational and non-state actors. To draw on the strengths and limitations of IAMs, voluntary climate actions are assessed for groups of actors with similar characteristics and assessed on the level of macro-regions or sectors. In this context, three independent methods are proposed for incorporating voluntary climate actions leveraging sector dynamics, long-term scenarios, and aggregate decision-making (see Figure 1).

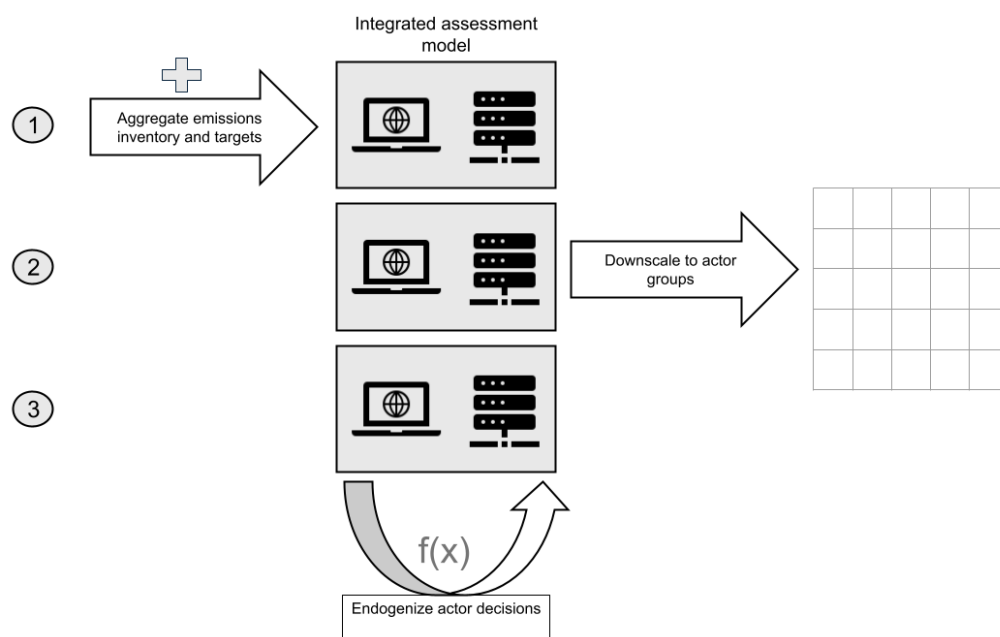


Figure 1. Three independent approaches to include cities, subnational regions, and companies into integrated assessment models that support the assessment of non-state and subnational climate actions

While these methods can be combined, they are designed to be used independently for IAM-based analysis and are categorised as follows:



1. **Aggregation.** Aggregating actors' goals and targets to sectors and macro-regions, accounting for overlap between actors and geographic areas;
2. **Downscaling.** Downscale existing model results to groups of cities, subnational regions, and companies;
3. **Endogenize investment decisions.** Incorporating actor investment decisions for subnational and non-state actors regarding technologies and behaviour in the model.

The first two approaches do not require modifications to the model itself, as they involve adjusting input parameters or processing model outputs. However, the third approach requires extensive model development. The following sections provide a description of each approach. The first two approaches give concrete suggestions for implementation and are illustrated with a case study. The third approach offers suggestions for implementation.

3.2 Aggregation of subnational and non-state actors' climate mitigation targets

The progress and ambition of voluntary climate actions can be assessed for both cooperative climate initiatives and groups of individual non-state actors. Although for both types of action the aim is to replicate the impact of pledged climate action targets on greenhouse gas emissions, each requires a distinct aggregation methodology for incorporating them into IAMs.

Voluntary Cooperative Climate Initiatives

Voluntary Cooperative climate initiatives often set overarching targets for specific thematic areas and aim to achieve these goals globally by expanding their membership. The signatories of these initiatives may include national governments, as well as subnational- and non-state actors. A comprehensive list of current climate initiatives is provided by Chan et al. and initiatives often have websites containing information or those announced around the UNFCCC Conference of Parties (COPs) frequently publish their aims, goals, and targets on COP websites.

The method for incorporating climate actions from voluntary climate initiatives into IAMs is less complex compared to that for individual actors, as these climate initiatives generally put forward global aspirational goals, for which model implementation is relatively straightforward. For instance, the Global Methane Pledge aims to cut methane emissions by 30% below 2020 levels by 2030. The exact implementation of the initiative goals in IAMs depends on the availability of country- and sector-specific information provided. Implementing the goals of such initiatives in the IAMs requires two steps:

1. **Attributing goals to model elements**

Based on the available information from a voluntary climate initiative and the formulation of its global goal, the target associated with the goal is attributed to macro-regions, greenhouse gas emissions, and/or sectors. If no specific information is available on how to attribute the global goal to these model elements, only the global goal itself will be used (e.g. the global methane pledge). In addition, for each macro-region, greenhouse gas and sector (or if these are not available, for the global level), the percentage of signatories in terms of sectoral emissions must be determined based on the last reporting year of





historical emissions available. To calculate the percentage change relative to a baseline in the target year, it is assumed that signatories achieve the target while the non-signatories follow the baseline scenario (e.g. Current Policies).

2. Implementation of goals

The translated goals are implemented by determining the model carbon price, or adjust other model input parameters, in the target year required to achieve the percentage reduction derived in step 1 globally, in the macro-region or sector. Carbon prices between the base year and target year can be interpolated using linear or exponential interpolation techniques.

Some initiatives, such as the Science Based Targets initiative (SBTi), do not set overarching goals, but instead require signatories to establish their own targets in line with the Paris goals. The assessment of such initiatives follows the approach described below for individual actors.

Individual subnational and non-state climate actions

The models can capture the targeted ambition of groups of *individual* actors in three steps. For each step, we provide guidelines on the data and methods that can be used; however, this is not an exhaustive list.

1. Data collection.

Data collection focuses on subnational and non-state actor historical emissions, in each case for the last reporting year, and climate mitigation targets. These datapoints are gathered from various sources. The following are prominent examples of such sources:

- The Global Climate Action Portal allows individual cities, subnational regions, and companies to register their climate commitments (UNFCCC 2024a)
- CDP collects emissions inventories and reduction targets through annual questionnaires sent to companies, though this data is only limitedly available publicly (CDP 2023)
- The Net Zero Tracker compiles emissions from the last reporting year and interim and net-zero targets of 2,000 publicly traded companies as well as cities and subnational regions (Energy and Climate Intelligence Unit et al. 2024).
- Climate TRACE uses satellite data to monitor greenhouse gases for cities and other subnational areas, providing spatial details such as buildings and power plants (Climate Trace 2024).
- The Data EnviroLab collects self-reported GHG inventories and reduction targets for cities and subnational regions from a variety of data platforms, including CDP, which is not publicly available (Hsu et al. 2020).
- The Carbon Monitor dataset provides daily CO₂ emissions from fossil fuels and the production of cement for cities (Huo et al. 2022).

Certain climate initiatives report data from individual subnational and non-state actors, such as the Science Based Targets Initiative (SBTi) and the Global Covenant of Mayors (GCoM). They require their signatories to set individual targets, which are reported on the initiatives' respective websites and could serve as important data sources for the analysis (GCoM 2025b; SBTi 2025).





2. Attribution and aggregation of individual targets.

Collected emissions and mitigation targets are attributed and aggregated to the macro-regions and sectors represented in the IAMs (see Table 2 for sectors). The attribution is not straightforward. For companies, this is because the aggregation level of IAMs lacks the granularity to represent individual companies (see Table 2). For cities, the attribution is more straightforward as the same sector categorisation is often used (see for example GCoM (2025a)), but the challenge is the availability of information about direct emissions sources included in the target—such as power generation—and whether information is available on their locations. Based on the geographical and sectoral attribution, emissions pathways between the last reporting year and target years can be constructed, with assumptions made about post-target-period projections. For companies, only Scope 1 emissions (direct emissions) and Scope 2 emissions (emissions from purchased electricity and heat) are included in the aggregation. Scope 3 emission targets are excluded because Scope 1+2 emissions and targets enable a more direct mapping to IAM sectors. In addition, avoiding double counting for Scope 3 emissions is complex due to overlap across multiple companies in the supply chain. Furthermore, current Scope 3 emission estimates are very uncertain (Gillenwater 2023) and systematically underreported (Li et al. 2024), and methodological approaches to calculate overlap are currently not available.

Although excluded here, scope 3 emissions targets aiming at lowering emissions in the value chain represent an important point of attention in future assessments of voluntary climate action. This is because of their large share in total emissions of many actors (Li et al. 2024). For companies, a possible approach is to include targets which directly impact value chain emissions and focus on targets for specific activities, such as sales of EV cars or steel production based on imported hydrogen. For cities or subnational governments, there are only few sources that directly report Scope 3 or consumption-based emissions (Wiedmann and Allen 2021). In addition, large-scale methods to assess the global carbon footprints of urban areas are limited in temporal resolution since datasets to evaluate embodied carbon flows are frequently proprietary (Moran et al. 2018). The discussion in Section 4 reflects on possible steps in incorporating Scope 3 emissions in future research, including how IAMs could be adapted to include activity-based value chain targets.

The aggregation of Scope 1+2 emissions from cities, subnational regions, and companies requires assessing overlaps between subnational and corporate actor groups regarding emissions coverage, both within and between groups. In addition, it requires making assumptions about the additionality of overlapping targets relative to national targets and other overlapping actor groups (Hsu et al. 2019). Kuramochi et al. (2020) and Lui et al. (2021) already provide methods for accounting for overlap and additionality when analysing individual non-state action and cooperative climate initiatives.

3. Translation and implementation

The aggregated emissions and targets from the previous step are translated into model input parameters and implemented in the model by adjusting model parameters such as sectoral carbon taxes. Due to limited information (at this moment) on specific measures with quantified targets (e.g., share of renewable electricity or reduced emissions intensity in steel production) that cities, subnational regions, and companies employ to meet their commitments, aggregated targets are implemented through increased sectoral carbon taxes. If more detailed information becomes available, it can be similarly aggregated and integrated into the models as is done for national policies (see Section 2.2). Based on these aggregated emissions and targets, scenarios can be developed that project emissions reflecting actor group commitments. In addition, alternative scenarios can be created by scaling up (parts of) these commitments to macro-





regional or global levels, potentially informed by actor characteristics, such as mitigation performance predictions of cities (Hsu and Wang 2022).

Table 2. The attribution of IAM sectors to company sectors, needed for incorporating aggregated targets in models; company sectors are based on classification system from CDP (2022b).

Model sectors	Company sectors
Energy supply - Electricity production - Heat production - Fossil fuel production - Mining - Hydrogen production	- Fossil fuels - Power generation - Materials (e.g. mining)
Industry - Steel - Cement - Plastics (non-energy) - Pulp & Paper - Food processing - Other	- Apparel - Biotech, health, care & pharma - Materials - Food, beverage processing & agriculture - Hospitality - Infrastructure - Manufacturing - Retail - Services - Materials (e.g. chemicals)
Transport (passenger/freight) - Cars, LDVs, two-wheelers - Trucks - Trains - Shipping - Aviation	- Transportation services
Buildings - Residential - Service (commercial/government)	- Food, beverage & agriculture





Agriculture - Land use - Energy	- Food, beverage processing & agriculture
Waste	- Infrastructure
International transport - Aviation - Shipping	- Transportation services
Other	- International bodies

Case study 1 – Aggregation of individual company commitments

To illustrate the model implementation of aggregated actor targets, we collected company Scope 1+2 emissions and targets from the 2022 CDP Climate Change questionnaire (CDP 2022a) that asks companies to disclose information about environmental performance, governance, and business strategy. The CDP dataset includes 3,518 companies that disclosed information on absolute emissions reduction targets, with a total of 5,954 targets. After cleaning and processing, the final dataset used in this case study comprised of 2,544 companies (see Supplementary Information). The emissions and targets from this dataset were aggregated to the global level for input in the IMAGE energy model TIMER (Stehfest et al. 2014). We assumed company CO₂ emissions occur in the energy supply, industry, freight transport and service buildings sector that represent approximately 80% of total CO₂ emissions in 2020. This was done by using simplified assumptions (see below) on what share of global emissions is attributable to companies, along with the necessary translations to the model sectors (figure S-3 in Supplementary Material). By applying the aggregation methods and incorporating the resulting emissions and targets into TIMER, the case study provides insight into global company ambition relative to current national policies (CP). For this purpose, two scenarios were defined:

1. *CP and Company Commitments (CP-CC)*. This scenario projects the impact of the collected company commitments, assuming they are fully met.
2. *Scaled-up Company Commitments (SCC)*. This scenario scales up the ambitions of the collected company commitments to represent all companies globally.

Scope 1 emissions from individual power generation and energy utility companies, as well as scope 2 emissions from all individual companies, were aggregated under electricity emissions, accounting for potential overlaps (see Supplementary Material). For each company, one target scope — covering Scope 1, Scope 2 or both — was selected, often spanning multiple target years (see ANNEX for details). Scope 1 emissions were included in 2,432 targets, whereas Scope 2 were included in 2,334 targets. Most targets (87%) had a target year before or in 2030 with only 22% of targets being set beyond 2030. In total, 4.3 GtCO₂e of emissions were covered in the dataset for the reporting period of 2021. Of this, 2.2 GtCO₂e were attributed to electricity emissions, after applying an overlap of 3% between electricity-generating companies and electricity-consuming companies, and 2.1 GtCO₂e covered non-electricity related emissions.





Individual company pathways were constructed by linearly interpolating between the last reporting year and final target year, and assuming CP growth after the target year. These individual pathways were then globally aggregated across all companies in the dataset.

Before implementing the aggregated pathways in TIMER, the model's CO₂ emissions that represent global company emissions were attributed to selected company sectors, including electricity and transfer losses, industry and industrial processes, service buildings, flaring, and freight transport. The emissions were grouped into two categories:

1. *Electricity emissions*, which included electricity and transfer losses.
2. *Non-electricity emissions*, which consist of the emissions for the remaining sectors.

Using the CP scenario from Dafnomilis et al. (2024) as a baseline, the two defined scenarios were implemented in the TIMER model based on the aggregated pathways. The *CP and Company Commitments (CP-CC) scenario is implemented* based on the aggregated company commitments, assuming all other companies globally follow the CP scenario. The *Scaled-up Company Commitments (SCC) scenarios* attributes the company emissions in TIMER between 2021 and 2050, assuming they grow with the ambition (in percentages) from the aggregated individual pathways. The implementation of the aggregated pathways in TIMER was done by iteratively adjusting sectoral carbon prices for the electricity sector and other sectors to simulate the aggregated individual pathways.

The results show that, if the collected companies fulfil their commitments (CP-CC scenario), a total reduction of 2% (0.5 GtCO₂e) compared to the current policies in 2030, doubling to 4% for 2050 (1.3 GtCO₂e) (see Figure 2). If all companies globally adopted the average ambition of the companies in the dataset (SCC scenario), total global company emissions could be reduced by 25% (8.2 GtCO₂e) by 2030 and up to 49% (17.2 MtCO₂e) by 2050 compared to current policies.

The results show similar reductions in electricity and non-electricity emissions for the CP-CC scenario by 2030, with both showing again a total reduction of 2% relative to current policies. By 2050, for electricity emissions this doubled to a 4% reduction, while non-electricity emissions remained consistent at a total reduction of 2% compared to current policies. The differences between electricity and non-electricity emissions become more pronounced in the SCC scenario, particularly by 2050, with a 43% reduction in non-electricity emissions and a 52% reduction in electricity emissions. While these findings highlight the significant potential for emissions reductions from voluntary company climate action, particularly by 2050, it is important to note that only 22% of the company targets that are included in the dataset extend beyond 2030. Consequently, much of the projected reductions rely on extrapolating current policies rather than actual company commitments, which assumes current policies are not rolled back (in line with the scenario narrative).



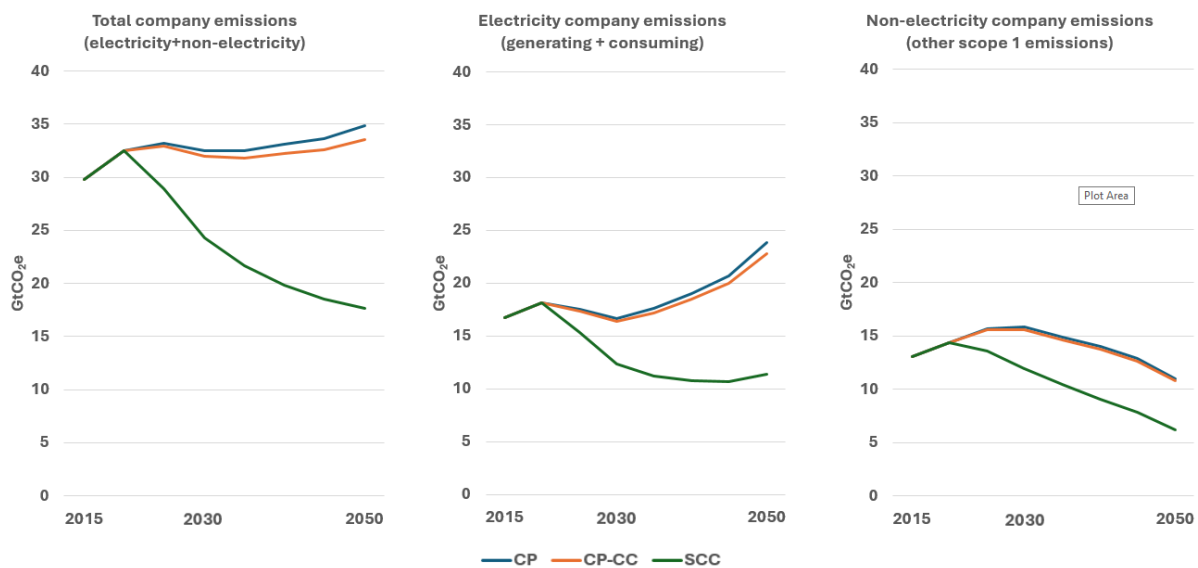


Figure 2. Pathways for total company emissions (left), electricity company emissions for S1 power generating and energy utility companies with all S2 emissions (middle), and non-electricity company emissions for all other S1 emissions for the three scenarios

3.3 Downscale IAM results to actor groups

IAMs generally report results at the global or macro-regional level (see Section 2). However, disaggregated data could be helpful in presenting IAM results for non-state actor groups, for example, by benchmarking or city stakeholder engagement. For this purpose, existing IAM results can be downscaled. Downscaling refers to distributing coarse-scale data to a finer scale, which, in the context of IAMs, has primarily involved disaggregating macro-regional data to individual countries (Gidden et al. 2019; van Vuuren et al. 2007). This process is often applied to greenhouse gas emissions and energy use (Sferra et al. 2021).

When assessing non-state actor groups, emissions and energy data need to be downscaled to actor groups at the country level or groups with similar characteristics (e.g. city size). The approach varies for each type of actor group as described in the paragraph below, (first for companies and then for cities and subnational regions).

Downscaling to groups of *companies* is challenging due to a lack of emissions inventories or precise information on company headquarters, branch locations, and corresponding greenhouse gas emissions at the country level or finer spatial resolutions. Addressing this limitation requires a detailed analysis of spatial, and temporal conditions. Unfortunately, such data is not easily or publicly available, particularly for companies. This is particularly difficult for Scope 3 emissions in the companies' value chains. The only feasible approach we present involves labelling emissions in the IAM results as being attributed to companies or not and not assigning them to Scopes 1 and 2 (see Section 3.2). However, these attributions lack the granularity to establish benchmarks for actor groups operating in less energy-intensive sectors that are not explicitly modelled (e.g., manufacturing).

The downscaling methods for *cities* and *subnational actors* build upon those for countries. Therefore, we describe these first. One common method for downscaling macro-regional





greenhouse gas emissions to the country level employs the IPAT equation¹ (Ehrlich and Holdren 1971)), which considers population, GDP, and GHG emissions. The process uses recent historical emissions at a finer level (e.g. countries, grid-level) than available in the models. This serves as the start year for downscaling model-based projections. Readily available country-level datasets for sectoral greenhouse gas emissions include those from Gütschow et al. (2019) the European Commission et al. (2024), and the UNFCCC (2025). Downscaling in this case involves either using existing disaggregated projections for population and GDP or making assumptions regarding the convergence of these values from region to countries (including emissions per GDP). For country population projections, Van Vuuren et al. (2007) rely on the World Population Prospects (UN 2022) to scale regional model results, incorporating assumptions about the convergence of country GDP per capita and emissions per GDP to the regional levels based on the scenario narrative for which the results are being downscaled. Similarly, Gidden et al. use existing country-level projections for population and GDP (Kc and Lutz 2017) from the SSP framework (Moss et al. 2010), along with assumptions regarding emissions per GDP convergence (Fujimori et al. 2017).

The described downscaling method can be extended to downscale IAM results to *cities and subnational region* actor groups. We sketch three methods of increasing complexity. These methods require further elaboration, such as matching narratives between emissions sources used in the projections, before they can be implemented, which falls outside the main objectives of this paper.

1. **IPAT extension.** This method applies the downscaling approach from Van Vuuren et al. (2007) to grid-level data and aggregates it back to city and region areas and groups. Grid-level data refers to spatial data represented in a grid format, corresponding to specific geographic locations, often at a finer resolution than (large) cities, subnational regions and countries. Grid cells are typically 0.1° by 0.1°, covering approximately 124 km² at the equator and 62 km² at Oslo, Norway. Historical emissions for grid-level inventories that can be used as starting year for projections are available, such as the EDGAR emissions database (Crippa et al. 2024; JRC 2021) or urban-level datasets (Crippa et al. 2021; Crippa et al. 2024). In addition, grid-level projections exist for population (Hsu and Wang 2022) and GDP (Jiang and O'Neill 2017). These sources can be used to downscale emissions projections to grid-level data by ensuring alignment with scenario narratives and making assumptions about convergence years for emissions per unit of GDP. The final step is to aggregate results in grid cells to groups of cities and subnational regions using current (Simplemaps 2024) and projected (Huistee et al. 2018) cities/region contours (see Figure 4).

¹ emissions = population X (population/GDP) X (emissions/GDP)



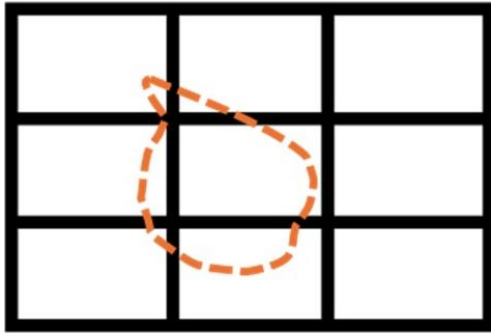


Figure 3. Aggregation of grid cells to city contours

2 Adding actor characteristics. This second method advances the IPAT breakdown of emissions by adding further actor characteristic. For instance, Hsu et al. (2022) demonstrate that in addition to population and GDP per capita, factors such as fossil CO₂, population density, and Heating Degree Days (HDD) are correlated with cities' CO₂ emissions. These factors are then incorporated into a machine learning model utilizing cities' self-reported emissions data as training data to understand how these underlying predictors relate to a subnational government's carbon dioxide emissions data (ibid).

3 Incorporating physical infrastructure. This method takes the previous method a step further by incorporating physical infrastructure such as power plants, factories or roads, as shown in Trombetti et al. (2017). For example, Climate Trace (Climate Trace 2024) has published satellite data on various types of infrastructure.

Case study – Downscaling global CO₂ emissions to urban centres

We devised an example to illustrate the downscaling method that is more simple than the ones discussed above. It primarily illustrates the potential applications. The analysis focuses solely on CO₂ emissions in urban city centres and makes straightforward assumptions for the projections.

To downscale the IMAGE CO₂ emissions to urban emissions, we used the EDGAR urban emissions dataset from Crippa et al. (2024). This dataset provides CO₂ emissions per country and sector for urban centres, semi-dense clusters, and suburban areas (see EC, Eurostat (2021) for definitions). The last reporting year in this dataset is 2015. We focused on urban centres for this case study, representing 35% of global emissions in 2015 (Crippa et al. 2021). If the larger urban areas were included, this share would increase to 50%-62%.

The EDGAR dataset categorises urban emissions into four main sectors: energy-industry, buildings (including both residential and service buildings), transport, and other. Based on the IPCC GHG categories for these sectors (See City Climate Finance Gap Fund (2022), the EDGAR urban sectors were attributed to the 2015 IMAGE sectoral emissions (see Table 3), which allowed us to calculate the percentage of urban emissions for each sector. Instead of applying the IPAT equation in the projections, as described in Section 3.3, we simply assumed that the percentage of urban emissions per sector remained constant. This assumption was applied across three climate policy scenarios: Current policies, NDC and 1.5 °C scenarios (Dafnomilis et al. 2024).





Table 3. Attributing IMAGE sector emissions to EDGAR urban-centre data based on (Crippa et al. 2024)*; based on Climate Finance Fund (2022).

EDGAR CO ₂ emissions	CO ₂ emissions from IMAGE
ENERGY-INDUSTRY	Energy Supply
	Energy Demand Industry
	Flaring
OTHER	Energy Demand Industrial Processes
BUILDINGS	Energy Demand Residential and Commercial
	Energy Demand Other Sector
TRANSPORT	Energy Demand Transportation (w/ bunkers)

* Agricultural and Waste CO₂ emissions represent only 3.1% of total CO₂ emissions in 2015, and are attributed to ENERGY-INDUSTRY in this case study

The emissions projections were downscaled by assuming the percentage of the last reported historical urban emissions (Crippa et al. 2024) per sector remains constant. The results show that the emissions gap between current policies and 1.5 °C requires 107% emissions reductions from the CP scenario by 2050, while this is 105% for the urban level². This is, respectively, 47% and 50% by 2030.

² Note that this is a simple downscaling and more elaborated methods presented in this section could lead to different outcomes



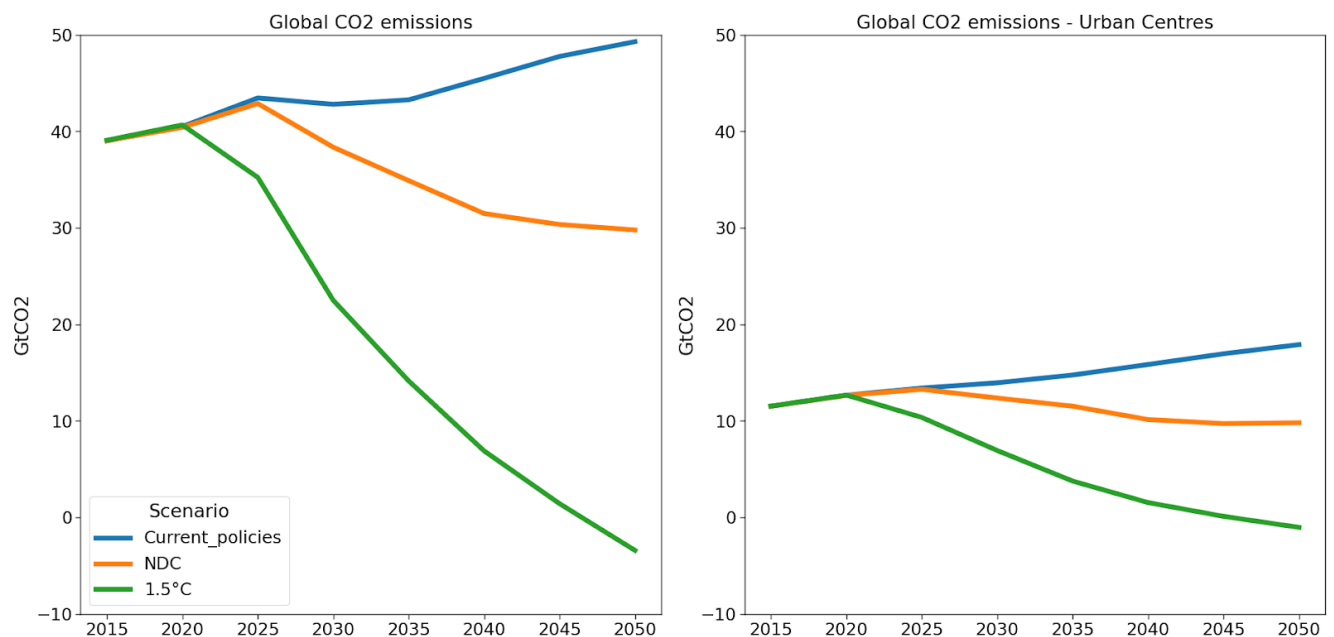


Figure 4. Downscaled results for urban level emissions in integrated assessment models; downscaling consisted with determining percentage of urban emissions in 2015 per sector based on Crippa et al. (2024) and keeping this percentage constant over time

3.4 Endogenize investment decisions

While aggregation and downscaling rely on existing IAM scenarios to assess non-state actors' climate action, including decision-making algorithms for different actor groups within the models could further increase the models' realism. This could entail developing new scenario narratives, modifying a small set of decision variables, or integrating the multi-actor decision process into the models. Based on De Cian et al. (2020), we identify opportunities, with increasing complexity and actor interactions, to integrate non-state actor decision-making into IAMs. Unlike Sections 3.2 and 3.3, this section does not provide detailed guidelines but rather offers suggestions for incorporating multi-actor decision-making into these models. More research is needed to establish the exact data and methodologies.

1. **Develop narratives.** The SSP2 scenario framework (Riahi et al. 2017; van Vuuren and Carter 2014) is a set of consistent climate policy scenarios combining stylised climate policy outcomes with different narratives. This framework includes the option of shared climate policy assumptions to specify climate policy goals, policy regimes and measures, and limits and obstacles to implementation (Kriegler et al. 2014). However, these scenarios primarily focus on macro-regions and countries, with no explicit representation of subnational or non-state actors. In contrast, Sluisveld et al. (2020) have developed quantitative scenarios that draw insights from socio-technical transition studies, creating plausible storylines on actor positioning. Narratives for explorative scenarios could also be developed for subnational- and non-state actors, incorporating different storylines on climate participation. For example, these scenarios could explore varying group sizes for companies, distinguishing between those with high ambition implementing high-integrity climate action, as outlined by the High-Level Expert Group on the Net-Zero Emissions Commitments of Non-State Entities (HLEG) (2024; 2022), and those that merely





comply with minimum regulatory requirements.

Another critical issue that could be incorporated in the narrative is the use of carbon credits by non-state actors, which can dilute or even undermine their commitments due to the lack of secured additionality or permanence of reductions (Trouwloon et al. 2023). This issue is closely related to the challenge of addressing residual emissions (Arendt 2024), for which abatement remains economically or technically challenging (Buck et al. 2023). Non-state actors often purchase carbon credits to meet their climate targets and to claim climate-neutral products. In the context of incorporating voluntary climate action in IAMs, purchasing of carbon credits entails potential risks of double counting with national emission inventories and failing to properly reflect carbon transfers between regions (Ma and Duan 2024). Beyond emissions, forest-related carbon credit projects are often claimed to provide co-benefits for biodiversity protection. IAMs with detailed biophysical representation of land use, such as IMAGE, could offer opportunities to assess these co-benefits. This scenario storyline could be supported by assessing the impact of credit dilution, which could be estimated by collecting data on the number of purchased credits (e.g. reduction, avoidance or removal credits), their geographic origin, associated claims, and how these factors affect emissions accounting.

2. **Adding heterogeneity.** This approach introduces multiple representations of actor groups, differentiating their behaviour and associated choices. A straightforward approach is to divide the carbon price into multiple groups. The carbon price in IAMs functions as a shadow price for mitigation measures, representing a stylised way to integrate climate policy choices into the model. For example, companies can be divided into innovators and laggards, each facing varying carbon prices. McCollum et al. (2017) and Edelenbosch et al. (2018) extend this concept by incorporating consumer behaviour, such as preferences towards new technologies, into optimisation and scenario IAMs. Fisch-Romito et al. (2025) demonstrate that including actors and decision-making factor into energy models could increase the explanatory. In optimisation models, these approaches demonstrate that actors can be included in decision-making by adding distinct variables to the optimisation function. For simulation models, the decision algorithm can be extended with additional factors. For example, the IMAGE and PROMETHEUS models employ discrete choice methods, such as the multinomial logit (McFadden 1973), to determine technology investments, allocating the largest market share to the lowest-cost option. These choices can be refined by adding premium costs to the economic costs (van Vuuren 2007) or introducing additional factors into the choice algorithm differentiated by consumer or company groups.

Some recent developments in IAMs have integrated social norms and value-based decision-making processes (Hernandez et al. 2024), and peer effects (Cultice et al. 2023). These additions provide a more realistic simulation of how individuals, companies and communities respond to climate policies and change their behaviour or consumption patterns to influence emissions. Incorporating these behavioural and consumption elements into IAMs would potentially provide more accurate policy scenarios by accounting for the complex interplay between individual choices, societal norms, and other factors, which can occur across multiple levels and scales.

3. **Agent-based integrated modelling.** Since IAMs make decisions based on economic cost and only implicitly account for non-economic costs, the most advanced approach involves re-engineering existing models or building new ones from scratch, which could become integrated agent-based assessment models. This enables incorporating sophisticated decision-making frameworks which account for the interactions between





actors and governments, global decision-making, and consumer demand representation (Sequeira and Reis 2019). The result is an agent-based model that explicitly represents multiple agents (e.g. groups of actors) and their interactions by capturing the agents' perceptions on the environment (De Cian et al. 2020). These models are better capable of integrating policy acceptance and innovation (Giarola et al. 2022). However, most agent-based models only cover specific countries or sectors (De Cian et al. 2020). One exception is the MUSE model (Giarola et al. 2022), which is an integrated assessment model that accommodates actor-group climate goals, bounded rationality, and limited knowledge during the decision process.





4 Discussion and conclusions

This study demonstrates how integrated assessment models can be utilised to assess non-state actors' transition pathways. These pathways can be developed by implementing aggregated actor goals and targets, downscaling scenario projections to groups of actors, and adjusting decision-making algorithms to incorporate actor heterogeneity. Although these models have inherent limitations in their level of detail, they offer valuable insights for the UNFCCC negotiations, support benchmarking, and provide tools for a dialogue with non-state actor stakeholders. Policymakers and other stakeholders gain insights into implementation and ambition emissions gaps among actor groups and assess groups of cities and/or companies through benchmarking.

Four areas require further research in addition to the described methodologies. These are the assumptions regarding overlap and additionality in the context of aggregation of city, region, and company voluntary climate commitments, the integrity of self-reported data, handling Scope 3 emissions, and collecting large datasets.

First, in terms of overlap between emissions and additionality of targets by non-state and state actors, we have assumed in this study that when aggregated city, region, and company commitments exceed overlapping national targets of policies, this difference will manifest at the end of the target year, provided non-state actions do not replace climate action elsewhere. This assumption is based on Kuramochi et al. (2020) and has been valid up until now as national governments and non-state actors did not coordinate much on climate policy (Hsu et al. 2019). However, with the recent implementation of reporting and due diligence directives in the EU (EFRAG 2022; EU 2024; European Commission 2022) and the growing adoption of international standards for greenhouse gas accounting, such as the ISO standards (ISO 2018), voluntary action is more and more influenced or replaced by regulations, and the assumption on additionality is becoming less valid. New methods that account for the overlap and additionality between national and non-state climate actions need consideration. Also, the overlap assessment between different types of actors could be improved, for example by identifying green procurement of city governments and the overlap with power companies.

Second, self-reported data from non-state actors has been scrutinised for its reliability (Bendig et al. 2024; Gieseckam et al. 2021; Talbot and Boiral 2018) or self-selection (Matsumura et al. 2014). This data is not independently audited, raising concerns about their accuracy, credibility, and consistency. For example, Bendig et al. (2024) emphasise that while verified data is the most accurate among verified, self-reported and estimated data on emissions for companies, it is also available at much lower rates than self-reported data. As such, when working with self-reported data, it must be checked for inconsistencies and outliers. This issue is particularly significant when companies are subject to structural changes (e.g. mergers), which can complicate the use of temporal datasets. However, outliers are often not applicable to identify misreporting, as some companies have very high emissions. For this purpose, intensity-based, sector-based or activity-based data could provide better and more relevant insights.

Third, Scope 3 emissions are excluded in our study on aggregating emissions and targets of non-state actors. Although for many non-state actors they represent a large proportion of total emissions, the main reasons to exclude them are underreporting and large uncertainties around Scope 3 emissions and overlaps in reporting emissions by nonstate actors. Still, given their relevance, it is important to develop methods to better account for Scope 3 emissions in the future. There are several starting points. First, Scope 3 targets that can relatively easily be quantified in IAMs could be a starting point (e.g. EV sales targets), data availability permitting. This would focus on selected Scope 3 targets only. Second, some Scope 1 reduction targets may





lead to an increase in Scope 3 emissions. For example, if steel companies shift to hydrogen-based steel production with imported fossil fuel-based hydrogen, then emissions of producing this hydrogen would be counted as upstream Scope 3 emissions. Such effects from shifting production and emission accounting could be assessed in IAMs. Third, environmentally extended multi-regional input-output (EE-MRIO) modellers have developed approaches to estimate Scope 3 emissions of industry sectors (Lefèvre 2024) and recently also of individual companies (Li et al. 2024). While the latter focuses on upstream Scope 3 emissions only, these estimates could be used to systematically add Scope 3 emissions of companies included in the case study, similar to how Scope 1 and 2 emissions are now used. A key advantage of EE-MRIO is that it becomes possible to assign Scope 3 emissions to sectors and different regions, potentially also being able to clarify emission overlap.

Fourth, data collection is time-consuming. However, the emergence of Large Language Models (LLMs) could foster data collection for large sets of cities, regions, and companies. However, this might not solve the data integrity issues discussed, since existing generic LLMs may pull indiscriminately from self-written reports, websites, or news media that may not provide accurate data or information regarding an actor's climate efforts (Cenci et al. 2023; Hsu and Wang 2022). Climate-domain specific LLMs are starting to constrain the underlying data being used to train such models (e.g., ClimateGPT, ChatNetZero.AI, ChatNDC.org). These tools may allow for future efficiencies in large-scale textual data mining, although the energy-consumption footprint of generative AI chatbots and LLMs is a major concern. Another concern is the replicability of results. Beyond data collection, Machine Learning (ML) and Deep Learning (DL) techniques offer new avenues for modelling and scenario generation. For example, ML frameworks have demonstrated the ability to predict city-level emissions and evaluate mitigation performance by combining limited self-reported data with spatial predictors, effectively addressing data scarcity issues (Hsu et al. 2022). Additionally, generative DL models can complement traditional IAMs by rapidly producing large ensembles of synthetic scenarios that replicate key variable distributions and correlations, thereby reducing computational burdens while expanding the diversity of potential pathways (Li et al. 2025).

To further operationalize these areas, future IAM applications can build on the observations from the empirical trends in D1.1. For example, aggregation methods could prioritize the verified mitigation initiatives to mitigate dilution risks associated with opaque credit usage. D1.1's analysis of functional effectiveness, specifically that standard-setting initiatives are more effective than lobbying groups, can also potentially be used by applying differentiated confidence weights when downscaling global emissions to specific sectors or regional actor groups. Finally, to endogenize decision-making for future scenarios, models can try incorporating the empirical 'network effect, where network participation makes cities more likely to adopt targets, as a specific proxy parameter to distinguish between 'innovator' populations and 'laggards' within the model's investment algorithms. To ensure better integration of the outputs of D1.1 and other relevant ACHIEVE research, the modelling teams will identify relevant research lines from the general assembly (M24) and set up subsequent brainstorming meetings to identify suitable approaches of integration in future modelling exercises.

In conclusion, IAMs have significant potential to enhance the assessment of non-state actors' climate actions by integrating their commitments into global climate policy scenarios. While challenges such as data quality and assumptions on overlap persist, advancing these models can provide valuable insights for the UNFCCC climate negotiations, national policy development, sub-national climate strategies, and stakeholder engagement. Future research should prioritise developing robust methods for handling data inconsistencies and overlaps.







ANNEX

Model descriptions

IMAGE model

Based on (PBL n.d.)

The Integrated Model to Assess the Global Environment (IMAGE) 3.0 is a comprehensive integrated modelling framework of interacting human and natural systems. The model framework is suited to large scale (mostly global) and long-term (up to the year 2100) assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. The impacts of human activities on the natural systems and natural resources are assessed and how such impacts hamper the provision of ecosystem services to sustain human development.

The model identifies socio-economic pathways, and projects the implications for energy, land, water and other natural resources, subject to resource availability and quality. Unintended side effects, such as emissions to air, water and soil, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections.

Detailed model documentation can be found at <https://www.pbl.nl/en/image/about>

PROMETHEUS model

PROMETHEUS is a global energy system model covering in detail the complex interactions between energy demand, supply and energy prices at the regional and global level. Its main objectives are: 1) Assess climate change mitigation pathways and low-emission development strategies for the medium and long-term 2) Analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector 3) Explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices. The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system. PROMETHEUS is a fully fledged energy demand and supply simulation model aiming at addressing energy system analysis, energy price projections, power generation planning and climate change mitigation policies. PROMETHEUS contains relations and/or exogenous variables for all the main quantities, which are of interest in the context of general energy systems analysis. These include demographic and economic activity indicators, primary and final energy consumption by main fuel, fuel resources and prices, CO₂ emissions, greenhouse gases concentrations and technology dynamics (for power generation, road transport, hydrogen production and industrial and residential end-use technologies).

PROMETHEUS quantifies CO₂ emissions and incorporates environmentally oriented emission abatement technologies (like RES, electric vehicles, CCS, energy efficiency) and policy instruments. The latter include both market-based instruments such as cap-and-trade systems with differential application per region and sector specific policies and measures focusing on specific carbon emitting activities. Key characteristics of the model, that are particularly pertinent for performing the analysis of the implications of alternative climate abatement scenarios, include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements (increased uptake of a new technology in one part of the world





leads to improvements through learning by experience which eventually benefits the energy systems in other parts of the World).

PROMETHEUS is designed to provide medium and long term energy system projections and system restructuring up to 2050, both in the demand and the supply sides. The model produces analytical quantitative results in the form of detailed energy balances in the period 2015 to 2050 annually. The model can support impact assessment of specific energy and environment policies and measures, applied at regional and global level, including price signals, such as taxation, subsidies, technology and energy efficiency promoting policies, RES supporting policies, environmental policies and technology standards.

CDP Dataset Preparation

The data used in developing the ambition pathways were taken from chapters C4 – Targets and performance and C6 Emissions data of the questionnaire (CDP 2022a). The emissions inventory (C6) was filtered to show only the most recent reporting year (as companies could disclose information for multiple years). Reporting year and base year emission outliers for each scope of emissions (S1, S2, and S3) were visually investigated, comparing orders of magnitude to previous reporting periods and disclosure cycles where possible. If no additional comments or comparisons (with at least 2 other reporting periods) were available, the emissions were removed. This was done until an acceptable spread of emissions remained (see figure S-1), and the remaining outliers had verifiable (publicly available ESG and/or emissions reports) or consistent data (magnitude of emissions was consistent across multiple questions and years). This was also done for base year emissions as reported in C4 (figure S-2). This process identifies only high emission outliers and is not able to identify inconsistencies hidden within the bulk of the data which would require a more detailed analysis zooming in on sectors and industry which was not the purpose of this case study.

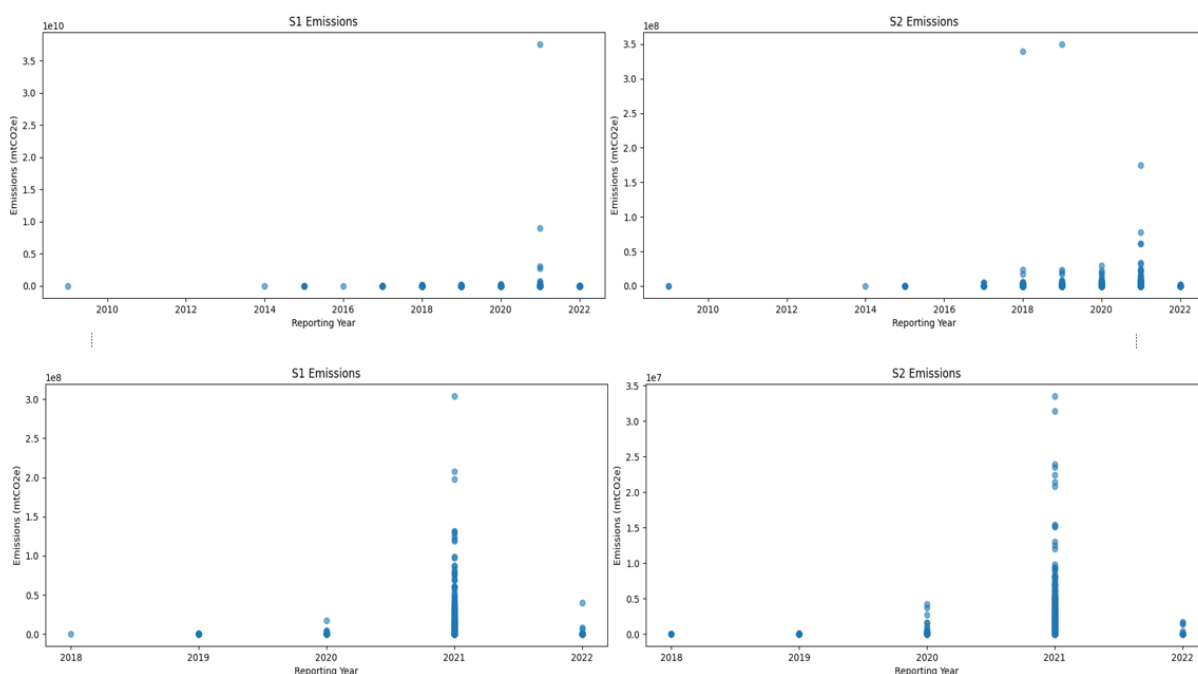


Figure S-1 Scatter plots of reporting year emissions by scope before (top) and after (bottom) outlier removal.

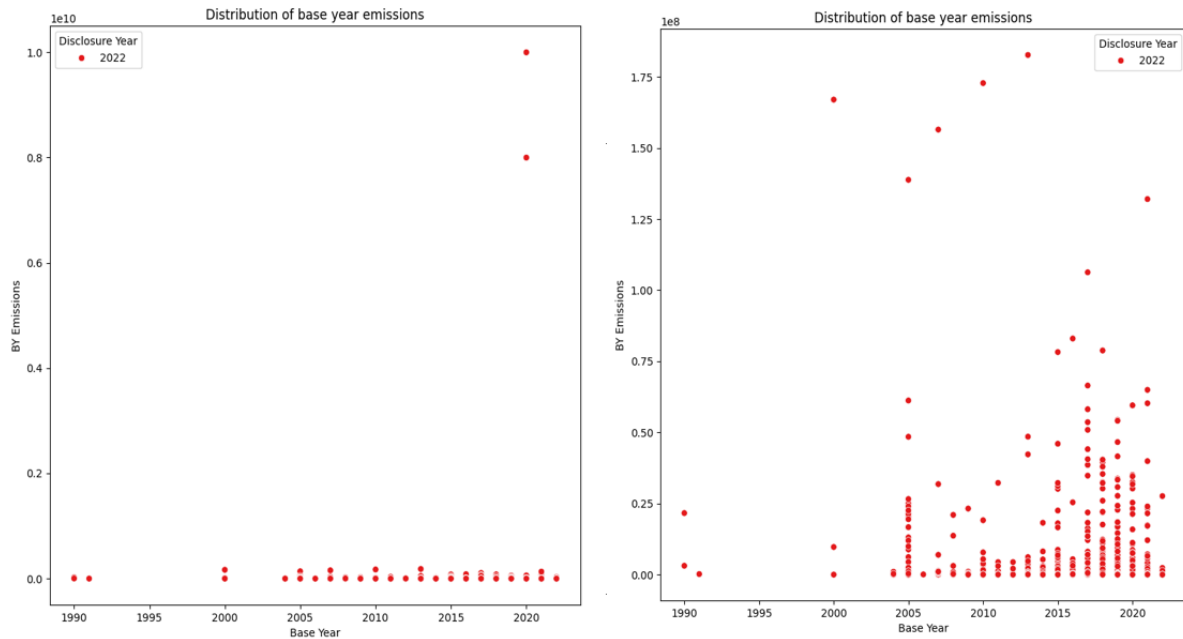


Figure S-2 Scatter plots of base year emissions for absolute targets before (left) and after (right) outlier removal.

Following the emissions cleaning process, companies with active and quantifiable targets were then selected based on the following:

- Companies that did not report information for base year, target year, scope (also if S2 reported without a specific category) or targeted reduction were removed
- Companies with a reporting year and/or base year emissions of 0 were removed.
- Target statuses of 'Expired', 'Retired', 'Replaced' or left blank were removed.
- Target year must be after or equal to the year of disclosure (2022).
- Target scope includes S1 and/or S2. S3 only targets were removed.
 - Targets that included scope 3 in addition to scopes 1 and/or 2 were removed by simply using the information given in C4 for scopes 1 and 2 regarding base and reporting year emissions. If no C4 information was disclosed, the ratio of S3 emissions to S1 and/or S2 emissions was calculated from the inventory (C6) and subsequently removed. Assumed all scopes targeted consistently.
- Base year must be before or equal to the reporting year and before the target year.
- Annualized progress values (described below) lower than -100% (doubling emissions every year) are removed.
- Annualized remaining ambition values (described below) lower than -100% are removed.
- Duplicates removed. In the case of duplicates for different scopes (i.e., the same base year emissions, targeted reductions, percentage of emissions covered by target but targeting different scopes), both entries are removed as unable to make a reliable distinction.



A general rule: reporting year emissions are taken where possible from the information disclosed together with the target (C4). However, if companies did not disclose emissions with their targets, emissions were taken from the inventory (C6) for the corresponding scopes after correcting for the percentage of base emissions covered by the target.

Annualized progress and remaining ambition values were calculated and values less than -100% (doubling emissions every year) were removed to filter companies with high likelihood of inconsistent reporting or structural changes in the company -> future research. The following equations were used to calculate annualized progress (1) and remaining ambition (2):

$$(1) \text{ annualized progress} = \frac{\left(\frac{Emissions_{base} - Emissions_{reporting year}}{Emissions_{base}} \right) \times 100}{(reporting year - base year)}$$

$$(2) \text{ annualized remaining ambition} = \frac{\left(\frac{Emissions_{reporting year} - Emissions_{target year}}{Emissions_{reporting year}} \right) \times 100}{(target year - reporting year)}$$

Additionally, to avoid overlapping scopes between targets set by the companies, the following filtering was applied in order of preference:

1. 'Company-wide' target coverages
2. S1S2 targets
3. S1S2S3 targets
4. Higher percentage of base emissions covered by target
5. Higher absolute base emissions
6. Targets with most target years set for a specific scope
7. Targets with the highest targeted reduction (for the last target year specified)

Finally, to further aid in the analysis, the remaining targets were then split so that every target dealt with a singular scope (S1S2 target -> S1 target and a separate S2 target). This was done with the assumption that the scopes in the original target are targeted consistently (i.e., 50% targeted reduction by 2030 = 50% reduction in scope 1 emissions proportion and 50% reduction in the scope 2 proportion). The absolute emissions values for reporting year and base year emissions were adjusted based on the ratio of scope 1 to scope 2 emissions reported in the emissions inventory (C6). This was done for consistency as not all companies disaggregated their base emissions for each scope within section C4.

Attribution of CDP company sectors to TIMER sectors

Figure S-3 shows an overview of the aggregation process for both the TIMER sectors and company data. We assumed all electricity and transfer losses, heavy industry, industrial processes, services, flaring, and medium-heavy freight transport emissions are attributable to global company emissions. We aggregated industry, services, flaring and freight transport (medium and heavy freight trucks) into one variable - non-electricity emissions. After running the CP scenario, we calculated the average annual growth rate for the electricity sector and for the aggregated non-electricity emissions. These would then apply to the corresponding aggregations of the CDP data (as shown in figure S-3).

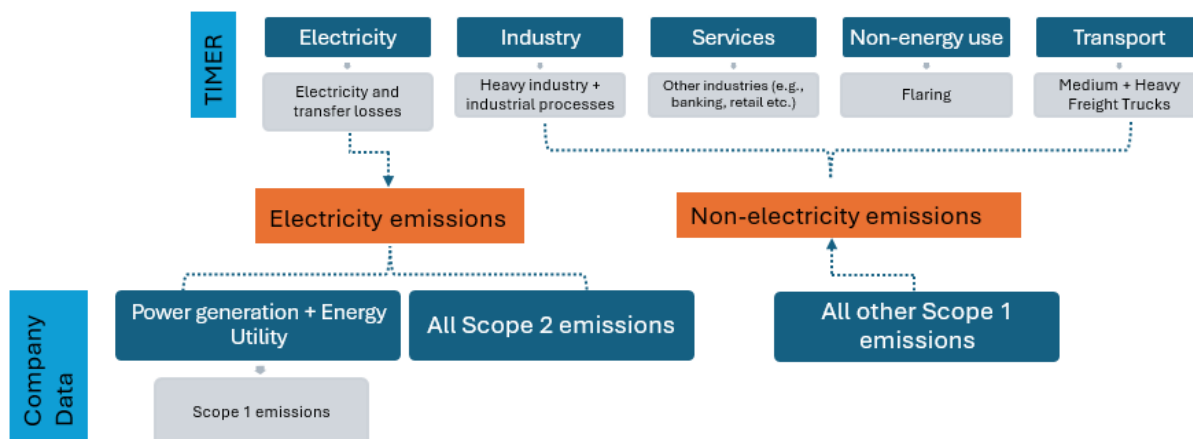


Figure S-3 Aggregation steps for TIMER sectors and individual company commitments

Overlap - company electricity emissions

Overlap, specifically regarding electricity-generating companies (scope 1) and electricity-consuming companies (scope 2) was then quantified. Adapting from (Kuramochi e.a. 2020) we have assumed that companies, both generating and using electricity, are geographically evenly spread over regions, i.e., an electricity-generating company with scope 1 emissions located in country A, generates electricity for country A, and similarly for electricity-consuming companies. Figure S-4 depicts the assumptions regarding electricity-related emission overlap for a country.

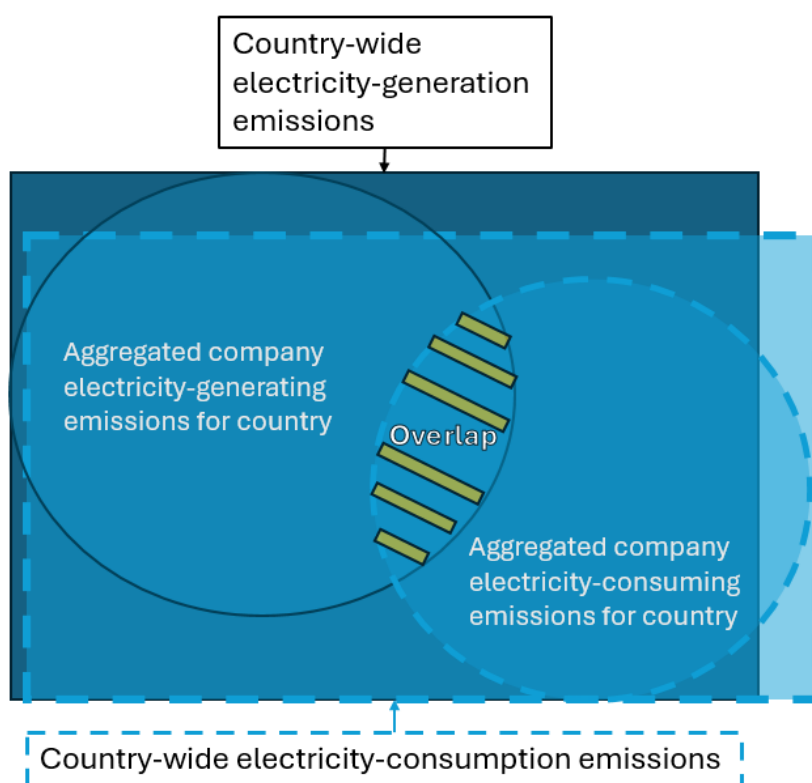


Figure S-4 Overlap quantification of electricity-related company emissions



Following the CDP-ACS classification of industries and sectors (CDP 2022b), we have assumed electricity-generating companies to be attributed to companies that indicated ‘power generation’ as their industry or ‘energy utility networks’ as their sector as this corresponded with the electric utilities questionnaire. Company country emission data for scope 1 and scope 2 emissions were taken from C7 for the selected companies and categorised as electricity-generating (described above) and electricity-consuming (all Scope 2 emissions in the selected companies) and aggregated by country accordingly. We assumed that all targets were consistent across all countries where a company reported for, i.e., assumed all targets were company-wide targets when in reality 90% of the targets were company-wide, 4% targeting a specific country/region, 2% targeting a specific business division/activity with another 2% addressing a site/facility.

Country-wide electricity emission data was taken from (Ember 2024a, 2024b). We used the carbon intensity of electricity from Ember (2024a) for conversions to gCO₂. Heat to electricity ratios for generation were taken from the IEA database (2024) using the flows *Electricity, CHP and heat plants (PJ)* for heat and electricity. Heat to electricity ratios for consumption were also taken from IEA (2024) using *Total final consumption (PJ)* for heat and electricity. The country-wide electricity emissions data was then corrected to include heat using the IEA ratios calculated as it is assumed CDP does not exclude heat. Wherever country-wide data was not available, the global average was used for that country.

The net coverage of emissions for electricity-generating companies was then calculated per country and multiplied with the net coverage of emissions for electricity-consuming companies to get an overlap for each country (equation 3).

$$(3) \text{ overlap, country}(\%) = \frac{\Sigma_{elecCDP_{country}}}{gen_{country}} \times \frac{\Sigma_{consCDP_{country}}}{cons_{country}}$$

Where the numerators consist of emissions from the CDP data used and the denominators from the country-wide data. *elecCDP* is electricity-generating companies for a country, *consCDP* is electricity-consuming companies for a country, *gen* and *cons* is total generation and demand (consumption) for a country.

The overlaps for all countries were then summed, adding a weighting for the emissions the country is responsible for (equation 4).

$$(4) \text{ overlap, total}(\%) = \Sigma \left(\text{overlap}_{country} \times \frac{\Sigma_{emissions_{country}}}{total \text{ emissions}} \right)$$

Where *overlap* is the value calculated in (3), *emissions_{country}* is the total emissions all companies reported for that country and *total emission* is all emissions reported for all countries.



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