

Net0Pathways through impRoved IAMs across Sectors, diMensions, and scAles

Report on Near-Term Sectoral Transitions

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Executive Summary

Project Context and Objectives

This deliverable presents critical research on near-term sectoral transitions within the EU energy system, addressing the urgent need to accelerate decarbonization pathways toward international climate goals. With the compressed timescale for achieving net-zero emissions, research focus has shifted from long-term characteristics of energy systems to the dynamics of near-term transitions, examining required transformation rates for specific sectors, technologies, and end uses.

The work addresses fundamental challenges in integrated assessment modeling (IAM), particularly improving near-term realism and developing validation methodologies that benchmark model results against bottom-up assessments and empirical observations. This research is conducted under PRISMA Task 2.2, which focuses on enhancing IAM realism in areas crucial for near-term developments.

Key Research Contributions

Validation Tool Development: The deliverable introduces *piamValidation*, an open-source R package designed to systematically compare IAM scenario data with historical observations and feasibility bounds. This tool addresses growing criticism of IAMs regarding their ability to capture technology diffusion dynamics and near-term trends. Applied to the REMIND model, the tool identified significant deviations in CO₂ transport and storage, electric vehicle deployment, and offshore wind capacity, leading to model improvements that enhanced near-term realism.

Lifestyle Change Impact Assessment: Comprehensive analysis of lifestyle changes in Europe's residential buildings sector reveals substantial potential for emission reductions. Using enhanced PRIMES-BuiMo and EDGE-Buildings models, the research demonstrates that lifestyle changes could reduce residential energy use by 15-30% by 2050 under baseline scenarios. Key measures include thermostat adjustments (1-2°C), reduced dwelling sizes (convergence to 30-40 m²/capita), and improved appliance efficiency. The analysis shows that lifestyle changes provide greater benefits under current policies than in stringent decarbonization scenarios, suggesting their role as complementary drivers to climate policies.

Methane Mitigation Assessment: Analysis of short-term methane mitigation potential reveals that the Global Methane Pledge target of 30% reduction by 2030 is extremely ambitious and likely unattainable without unprecedented policy implementation. Current national commitments support only 3-7% of the required reductions, with limited regulatory frameworks or financial incentives. The research provides sector-specific reduction

potentials, indicating maximum feasible reductions of 48-66% in oil and gas sectors and 9-47% in agricultural sectors by 2050.

CCS Economic Analysis: The Poland case study demonstrates that carbon capture and storage (CCS) deployment yields positive macroeconomic impacts while achieving additional CO₂ reductions of 25-50 Mt annually by 2050. CCS enables emissions-intensive industries to remain economically viable, resulting in higher GDP, employment, and export performance compared to scenarios without CCS. The analysis shows particular benefits for cement and steel industries, where CCS represents the primary viable decarbonization pathway.

Methodological Innovations

The research presents significant methodological advances including: enhanced representation of behavioral factors in building energy models through bottom-up engineering functions; systematic validation frameworks enabling continuous IAM improvement; and integrated energy-economy modeling combining partial equilibrium energy models with dynamic stochastic general equilibrium macroeconomic models. These innovations enable more realistic representation of near-term transition dynamics and better quantification of policy impacts.

Policy Implications and Recommendations

Validation Integration: The piamValidation tool should be systematically integrated into multi-model scenario activities and policy assessments to improve model reliability and transparency. Regular benchmarking against empirical data can enhance policy credibility and identify areas requiring model refinement.

Demand-Side Policy Development: Current EU climate policies inadequately represent lifestyle changes and demand-side transitions. The research demonstrates significant potential for behavioral measures to complement supply-side technologies, particularly in residential buildings. Policy frameworks should incorporate characteristics of low energy demand transitions while addressing implementation barriers and costs.

Methane Strategy Revision: The Global Methane Pledge requires substantial strengthening of national policies and regulatory frameworks to achieve stated targets. Priority should be given to developing quantitative targets with clear timelines, particularly in agricultural sectors where technical potential exists but policy implementation lags.

Industrial Decarbonization: CCS emerges as essential for deep decarbonization of emissions-intensive industries. The Poland case study suggests that strategic CCS

deployment can preserve industrial competitiveness while achieving climate goals, supporting arguments for EU-wide industrial carbon management strategies.

Future Applications and Impact

This research provides essential tools and insights for upcoming multi-model intercomparisons, including next-generation shared socio-economic pathways for Earth System Models. The validation methodology offers a platform for knowledge sharing within the IAM community and continuous improvement of model performance. The lifestyle change analysis informs demand-side mitigation strategies across European residential sectors, while the CCS assessment guides industrial decarbonization policies.

The work contributes to evidence-based policy development by providing quantitative assessments of near-term mitigation potential across multiple sectors and intervention types. By bridging the gap between bottom-up technical assessments and top-down integrated modeling, this research enhances the reliability of climate policy analysis and supports more effective transition strategies toward EU climate neutrality goals.

1. Introduction

1.1. Motivation

Years of delay in taking meaningful action on climate change, combined with the increasing impetus to pursue the goal of limiting warming to 1.5°C, have compressed the timescale for decarbonizing the energy system to net-zero to a few decades. The focus of research must therefore shift from the fundamental long-term characteristics of net-zero energy systems to the dynamics of the near-term energy transition: What are the required transformation rates for specific sectors, technologies, and end uses according to energy transformation pathways toward national and international climate goals?

There is increasing research and evidence on the scaling properties of technologies, which shows that granular technologies with less need for customization tend to feature faster technological learning and faster scale-up than lumpy technologies, technologies with higher design complexity and greater need for customization (Malhotra and Schmidt, 2020; Wilson et al., 2020). Further, bottom-up assessments and near-term projections of technology up-scaling are increasingly available and help to constrain the range of plausible developments (Kazlou et al., 2024; Odenweller et al., 2022).

Bottom-up analyses show that the near-term deployment of carbon capture and storage (CCS) tends to be overestimated by IAMs (Kazlou et al., 2024). A refinement and detailed

analysis of plausible CCS deployment pathways on the global, regional and national scale is therefore warranted.

Given the proximity of the 1.5°C limit, near-term developments will also strongly affect the degree to which this temperature level will be overshoot. Due to the high contribution to radiative forcing in combination with the relatively short atmospheric lifetime of methane, near-term emissions of this greenhouse gas have a disproportionately large impact on near-term warming. Its ambitious abatement could thus be key for limiting peak warming, but hinges critically on the degree to which methane abatement is feasible in the near-term.

The latest IPCC Sixth Assessment Report emphasized the importance of demand side mitigation actions. Low energy lifestyles have a significant potential for reducing emission reductions in the buildings sector particularly in the short to medium term, but so far remain underexplored in the context of IAMs.

Task 2.2 of PRISMA focuses (1) on improving the realism in IAMs and developing methods in areas that are crucial determinants of near-term developments, and (b) on developing validation tools for facilitating IAM improvements by benchmarking their near-term results against projections from bottom-up studies.

1.2. Outline of the deliverable

This deliverable is structured as follows. Chapter 2 documents the tool *piamValidation*, which was developed to systematically benchmark IAM results against bottom-up assessments, and thus facilitate model improvements to better account for near-term trends. It demonstrates the application of the tool for the improvements in the latest REMIND model version 3.5. Chapter 2 is based on a manuscript currently under review at *Geoscientific Model Development* (Weigmann et al., 2025). *piamValidation* is increasingly integrated in multi-model scenario activities, and will also be used for forthcoming multi-model intercomparisons conducted in PRISMA. Chapter X describes the application of *piamValidation* for the development of next-generation shared-socio-economic pathways developed in the ScenarioMIP exercise for utilization by Earth System Models (Van Vuuren et al., 2025).

Chapter 3 describes a deep dive study into the impact of lifestyle changes on near to medium term energy demand from the buildings sector of the EU. Chapter 4 documents ongoing efforts to improve the representation of short-term methane emissions reduction potentials. Chapter 5 presents a deep-dive study on the interrelation between carbon capture and storage (CCS) and economic development for the case of Poland.

2. Validation of climate mitigation pathways

Based on Weigmann et al. (2025), currently under review at *Geoscientific Model Development*

Authors: Pascal Weigmann, Rahel Mandaroux, Fabrice Lécuyer, Anne Merfort, Tabea Dorndorf, Johanna Hoppe, Jarusch Müßel, Robert Pietzcker, Oliver Richters, Lavinia Baumstark, Elmar Kriegler, Nico Bauer, Falk Benke, Chen Chris Gong, Gunnar Luderer

2.1. Introduction

Integrated assessment models (IAMs) play a prominent role for science-based and climate policy advice. Early IAM applications date back to the late 1990s (Cointe et al., 2019) and evolved towards the formulation of mitigation targets and the monitoring of political ambition (Van Beek et al., 2020). IAM scenarios are also an important pillar of the assessments conducted by the Intergovernmental Panel on Climate Change (IPCC), in particular with regard to transformation pathways towards achieving climate policy goals. Therefore, they are a central component of climate change mitigation oriented policies. Edenhofer and Minx (2014) also point out that the Summary for Policymakers (SPM) established a collaborative environment where political discussions link with relevant scientific material. Relating the Conference of the Parties (COP) through a metaphor, "the COP operates as navigator, navigating a terrain charted by the IPCC" (Beck and Oomen, 2021, p. 172).

Despite the prominent role of IAMs in the climate science-policy interface, IAMs have faced increasing scrutiny. Particularly 20 in policy advice, central criticism ranges from shortcomings regarding model representation (e.g., heterogeneous actors and capital markets) to their ability to capture technology diffusion and dynamics (Keppo et al., 2021). On the one hand, global and national models have often underestimated the rapid technological change in novel renewable power and demand electrification technologies: for instance, the cost of solar electricity and battery storage has declined by almost 90% (Creutzig et al., 2023) and renewable electricity generation in Asia has more than doubled (IRENA, 2024) in the last decade, far exceeding model 25 results. National models face the additional challenge of making assumptions about technology innovation and cost declines, which are largely driven by global developments and trends. Accurately capturing recent trends in technology capital costs is therefore crucial, as they play a predominant role in the sensitivity of model outputs (Giannousakis et al., 2021).

On the other hand, near-term IAM scenarios results exceeded the rate at which economies are transitioning away from fossil fuels: for example, due to factors beyond pure market-based energy economics, coal power capacities are still being developed 30 in some regions despite the declining renewable energy costs. In particular, China and India alone

account for 86 percent of worldwide coal power capacity under development (Carbon Brief, 2024).

Not only techno-economic parameters but also the technology representations more generally impact technology trends in IAM scenarios and vary strongly between IAMs, illustrated by Krey et al. (2019) for electricity generation. They first highlight the need for caution in harmonizing techno-economic assumptions, as they must fit model-specific technology representations and associated projection methods. Second, Krey et al. (2019) participate in the transparency debate (Stanton et al., 2009) by urging the IAM community to publish and openly discuss techno-economic parameters, their definitions and model technology representations.

This paper introduces the Potsdam Integrated Assessment Modeling validation tool for IAMs, *piamValidation*. Our objective is to enable a broad use of that tool in the IAM community to enhance transparency and reliability. By aligning with the key evaluation criterion outlined by Wilson et al. (2021), the *piamValidation* tool can contribute to increasing IAMs near-term realism. This tool and the related input data are meant to be a community resource, where the distribution of the *piamValidation* configuration files can serve as a knowledge sharing platform and as a performance metric, offering continuous feedback on modeling progress.

In section 2, we present the *piamValidation* open-source R package. The tool enables users to systematically compare variables of large IAM datasets with historical data and feasibility bounds, or across scenarios and models. This is primarily useful for harmonizing national and global IAMs in the short and medium term, particularly for current policy scenarios that capture implemented government policies. In addition, the tool allows for systematic comparisons of near-term technology dynamics with external observational data as historical, near-term trends and stylized facts. The *piamValidation* tool is particularly

user-friendly and requires only a single command to generate the full HTML report featuring validation heat maps. In section 3, we apply the *piamValidation* tool to validate near-term technology dynamics in the IAM REMIND (REgional Model of Investment and Development, see Baumstark et al. (2021) for details). Within our application case, we generate interactive heat maps presenting technology trend capture performance in the form of a traffic light evaluation. The heat maps, combined with the tool's configuration file, contain central information regarding observational data, defined bounds and scenario deviations.

We select central variables related to CO₂ transport and storage, electric vehicles and offshore wind power. The choice of these technologies is twofold: first, the feasibility of their near-term scaling has severe implications for scenarios with high ambition for emissions reduction (Brutschin et al., 2021; Bertram et al., 2024); second, the *piamValidation* tool highlights deviations of REMIND scenarios from historical data and current technology

trends. We then present strategies that have been implemented to improve REMIND, and we demonstrate that subsequent scenarios improve their near-term realism.

2.2. PIAM validation tool

2.2.1. Overview

The package `piamValidation` provides validation tools for the Potsdam Integrated Assessment Modeling environment. It is written in R, with the source code being openly available under the LGPL-3 license on GitHub¹.

Users provide the tool with IAM scenario data and relevant reference data for historical or future time periods. Criteria for checks are defined in a configuration file to perform a vetting. This configuration file serves as a flexible interface, which allows for various use cases:

- Deviations of scenario to reference data
- Deviations between:
 - Models (same scenario, same periods);
 - Scenarios (same model, same periods);
 - Periods (same model, same scenario).
- Conformity to scalar thresholds, such as an absolute value or growth rate.

Deviations can be defined as either absolute or relative deviations. The function `validateScenarios` takes the inputs mentioned above and evaluates the validation checks. In the standard setting, this results in a dataset that contains an evaluation of either "green" (test passed), "yellow" (warning), or "red" (fail) for each data point to be evaluated. Optionally, additional colors can be used to differentiate violating a lower bound from violating an upper bound. In that case, "blue" and "cyan" are used to hint toward values below thresholds, and "yellow" and "red" remain to capture upper exceedances.

The function `validationHeatmap` makes these results accessible by arranging them for one variable on an interactive heat map using the R library `ggplotly`. Depending on the category of checks that are being performed, data underlying the evaluation is available for each data point by hovering over the respective square in the heat map. Finally, `validationReport` can be used to perform the validation calculation and plot all heat maps in one HTML report, which is automatically rendered from an RMarkdown file provided by the package.

After successfully installing the `piamValidation` R package in an appropriate R environment,

¹ <https://github.com/pik-piam/piamValidation>

the tool structure can be described along three dimensions: Input, data processing, and output, as illustrated in Figure 1.

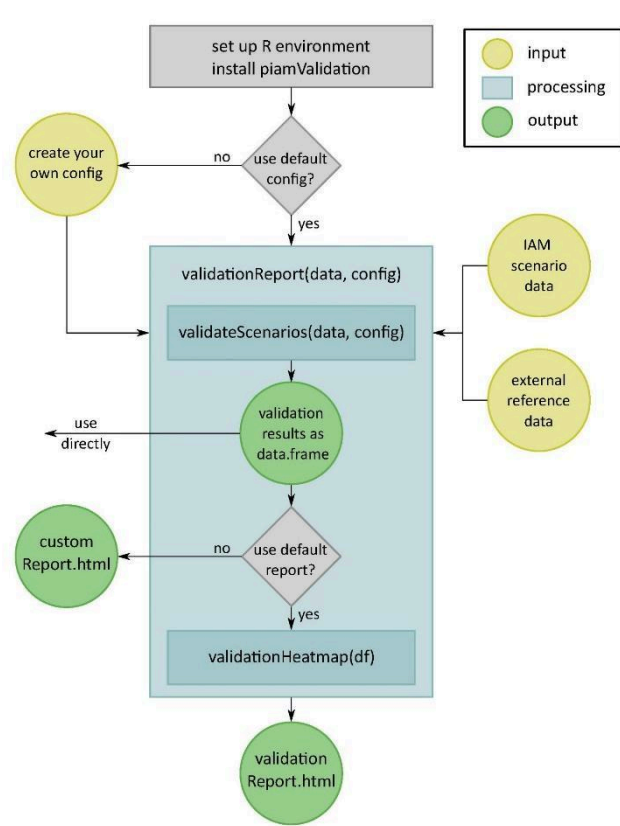


Figure 1. Validation workflow with respective inputs, processing steps and outputs.

2.2.2. Data Input

The input data for the piamValidation tool comprises three key components. First, the IAM scenario data to be validated. Second, the reference data, which is used to compare the initial IAM scenario data. This reference data may include outputs from other IAM models or scenarios, as well as third-party external datasets, such as historical, observational or other prediction data. Third, a configuration file is necessary to specify the details of the validation. The piamValidation R package provides a standard set of configuration files for general use. However, users seeking greater flexibility can create and customize their own configuration files to address specific validation requirements.

To facilitate use by different IAM communities and external users, the standardized way of

organizing IAM data following the Integrated Assessment Consortium (IAMC) format² is used. It organizes data along the dimensions of "model", "scenario", "variable", "region" and "period". Thus, the validation process works with 5-dimensional data objects, expecting a data point to be uniquely defined as $x(m,s,v,r,p)$, with the indices referring to these five dimensions.

2.2.2.1. Configuration file

The `piamValidation` framework allows for a wide range of different validation approaches. They are defined via a configuration file with predefined columns as described in Tab.1. This is intended to enable users with minimal programming knowledge to use the tool, as the structure of the validation configuration file follows the intuitive idea of a validation process, answering the following three guiding questions:

1. Which type of validation should be performed using which metric?
2. Which data should be validated?
3. What is the reference being used for the validation?

These questions are answered by filling in the columns of the configuration file as described in Tab.1.

Column	Description
metric	Decide which type of comparison will be performed, currently supported: "relative", "difference", "absolute", "growthrate".
critical	Is it considered to be a critical check? The function <code>validationPass</code> will report failed checks only if this is set to "yes".
variable	Choose one or multiple variables to be checked: Define multiple variables via "*" (one sub level) or "***" (all sub-levels), e.g. "Final Energy *" for "Final Energy Industry" and "Final Energy Transportation", etc. and "Final Energy ***" for "Final Energy Industry Electricity", "Final Energy Industry Electricity Cement" and so on.
unit	This is an optional column that allows to verify that scenario - and reference data are consistent in their use of units.
model	Choose one or multiple (comma-separated) models, or leave empty to choose

²<https://www.iamconsortium.org/scientific-working-groups/data-protocols-and-management/iamc-time-series-data-template/>

	all.
scenario	Choose one or multiple (comma-separated) scenarios, or leave empty to choose all.
region	Choose one or multiple (comma-separated) regions, or leave empty to choose all.
period	Choose one or multiple (comma-separated) periods, or leave empty to choose all (generally "all" de faults to ≤ 2100 in this case, for historical checks 2005-2020). A range of periods can be defined via "yyyy-yyyy".
min/max_yel/red	Define minimum and maximum thresholds which decide whether a check is passed (green), produces a warning (yellow) or is failed (red). If reference data is missing, the result will be gray. Each line needs at least one threshold. Relative thresholds can be given either as percentage (e.g., 20%) or decimal (e.g., 0.2).
ref_model	For model intercomparison, set one or multiple reference model here, all models chosen in the column "model" will be compared to it.
ref_scenario	This column can be used in two ways - either compare two scenarios produced by the same model to one-another (similar to the model intercomparison), or set it to historical to compare model data to observational data provided by one or multiple external sources. It is recommended to choose a historical reference source explicitly in the "ref_model" column for historical comparisons.
ref_period	Compare data between different periods, set one or multiple reference periods here.
notes	An optional column that allows leaving comments about the thresholds or checks in this row.

Table 1. Column description of configuration file. Note: Each described column must be filled in accordance to the use case to ensure successful operation of the piamValidation tool.

2.2.2.2. Validation types and metrics

A common validation procedure consists in comparing IAM results to benchmarks, such as observational data from external data sources. Such reference data can be handed to the validation tool in large quantities by supplying a CSV, Excel or MIF file that is structured along

the same five dimensions as the IAM data, with the specific requirement that the "scenario" column reads "historical" for all data points. This way, the tool can also differentiate between a model intercomparison exercise, where the same scenario is compared between two or more models and a comparison of multiple scenarios to one or multiple reference model scenarios, which don't require the same scenario name. In terms of data dimensions, a relative deviation can thus be expressed as

$$\text{rel\_deviation} = \frac{x(m_i, s_j, v_k, r_l, p_m) - x(m_{\text{ref}}, s_{\text{hist}}, v_k, r_l, p_m)}{x(m_{\text{ref}}, s_{\text{hist}}, v_k, r_l, p_m)}$$

where $x(m_i, s_j, v_k, r_l, p_m)$ are the IAM values using the notation introduced in 2.2 and $x(m_{\text{ref}}, s_{\text{hist}}, v_k, r_l, p_m)$ are the observational data values from one or multiple reference models. In an analogous way, a "difference to historical" check can be performed by defining an absolute deviation to the reference data as

$$\text{abs\_deviation} = x(m_i, s_j, v_k, r_l, p_m) - x(m_{\text{ref}}, s_{\text{hist}}, v_k, r_l, p_m).$$

Mathematically similar, checks with the metric "relative" or "difference" can also be performed against subsets of the scenario data itself, which then functions as reference data. This can in turn be performed in three different ways - comparing to a selected period, scenario or model:

$$\text{abs\_deviation\_period} = x(m_i, s_j, v_k, r_l, p_m) - x(m_i, s_j, v_k, r_l, p_{\text{ref}}),$$

$$\text{abs\_deviation\_scen} = x(m_i, s_j, v_k, r_l, p_m) - x(m_i, s_{\text{ref}}, v_k, r_l, p_m) \text{ or}$$

$$\text{abs\_deviation\_model} = x(m_i, s_j, v_k, r_l, p_m) - x(m_{\text{ref}}, s_j, v_k, r_l, p_m).$$

Relative comparisons again divide this difference by the reference value. Note that all other dimensions are the same between scenario and reference data with only one dimension (period, scenario or model) acting as validation dimension (it is not possible to compare scenario s_j of model m_i with scenario s_{ref} of model m_{ref}). The reference of this dimension can be either a single period/scenario/model or a comma-separated list of them. Furthermore, when choosing multiple sources the user can decide whether the validation thresholds should be based on the range of the reference values, where the maximum value of the group is used as the reference for upper and the minimum as the reference for lower thresholds or their mean will serve as reference for all thresholds.

For instance, in a near-term validation study, multiple data sources can be chosen as references by selecting the following expression in the config file as `ref_model`³:

³ Note: The same holds for `ref_scenario` and `ref_period`.

$$range(m_i, m_j, \dots, m_x).$$

The metric “absolute” does not require any reference data, as it contains the absolute values of the thresholds directly in the 135 threshold columns of the configuration file. This means that no calculations are required.

Lastly, the “growthrate” metric can be used to perform validation checks with respect to average yearly growth rates. For a time step of dt between periods, the growth rate is calculated as

$$\text{growthrate} = \left(\frac{x(m_i, s_j, v_k, r_l, p_m)}{x(m_i, s_j, v_k, r_l, p_{m-dt})} \right)^{\frac{1}{dt}} - 1 .$$

Depending on the metric of the validation check and whether it is a comparison to observational data, different columns of the configuration file need to be filled as shown in Figure 2.

Decide type of comparison		Define scenario data to be compared						Set thresholds				Set reference		
metric	critical	variable	unit	model	scenario	region	period	min_red	min_yel	max_yel	max_red	ref_model	ref_scenario	ref_period
relative	yes/no											IEA_max	historical	
difference	yes/no											IEA_min	historical	
relative	yes/no													
difference	yes/no													
absolute	yes/no													
growthrate	yes/no													

necessary
 at least one of these is needed
 exactly one of these is needed
 optional, empty means “all”
 not used

Figure 2. Overview of required and optional columns of the configuration file, depending on metric.

2.2.3. Data Processing

The validation configuration file allows users to define a wide range of validation checks, many of which might not be anticipated during creation of the validation tool. On the one hand, this requires the data processing and evaluation to be consistent and flexible at the same time, e.g., if only some checks require an intermediate calculation step but the output needs to be a single harmonized data object containing all checks. On the other hand, users might supply the validation tool with data and configuration files that are either internally inconsistent or exceed the scope of the currently supported use cases. In such cases, it is

crucial to ensure transparency by allowing the user to comprehend the issue through clear mechanisms and the inclusion of essential information in error messages.

These requirements are met by the modular structure of the tool, where each data processing step is carefully separated from the next. The structure of the central data processing function of the validation tool, `validateScenarios`, is sketched using pseudocode in Alg.1.

At the beginning of a validation process using the `validateScenarios` function, the configuration file and scenario and reference data are imported and checked for consistency (see Algorithm 1). The loop starting in line 4 takes information from one row of the configuration file and assembles the scenario and reference data needed for the validation check defined. It connects the thresholds that are relevant for each data point to the scenario data. In case a validation check is performed against a reference value (either historical or period/scenario/model intercomparison), also this value is appended for each data point. The resulting data slices for all rows are combined and checked for any duplicates that can result from overlapping definitions in the configuration file. Lines 11 and 12 contain the calculation and evaluation of the actual validation check, according to the respective metrics. Finally, data can be either exported as CSV or returned as an R `data.frame`.

Algorithm 1 `validateScenarios` is the core of the `piaValidation` framework.

Input: `scenarioData`, `referenceData`, `validationConfig`

Output: `data.frame` or CSV file containing original data, reference values and validation result

function `validateScenarios()`

```

1: data = read(scenarioData, referenceData)
2: cfg = read(validationConfig)
3: cfg = check, clean and expand cfg
4: for all row in cfg do
5:     slice data according to filters in row
6:     left join config thresholds to data slice
7:     left join reference values to data slice (if applicable)
8:     valiData = bind all data slices
9: end for
10: valiData = removeDuplicateRows(valiData)
11: calculate value to be checked against threshold (depending on metric)
12: evaluate check and append validation result (colour) to valiData
13: (optional: export valiData as CSV file)
14: return(valiData)

```

2.2.4. Output and Visualization

While the data output of `validateScenarios` can be used in any preferred way, two specific visualization approaches are offered to users of `piamValidation`. The function `validationHeatmap` has the goal of providing a quick overview of the general outcome of a validation by laying out the validation result colors across up to four dimensions. This means that the five-dimensional IAM data objects need to be reduced to a single element in only one dimension. By default, the "variable" dimension is chosen for this. An example can be seen in Fig. 3 where "region" and "period" are chosen for the x- and y-axis respectively and "scenario" and "model" are plotted as x- and y-facets.

Alternatively, the function `linePlotsThresholds` offers an easy way to plot the thresholds as colored background areas behind line plots of the scenario data and, if applicable, the corresponding reference data. For this type of plot one additional data dimension needs to be singular, by default this falls to the "region" dimension.

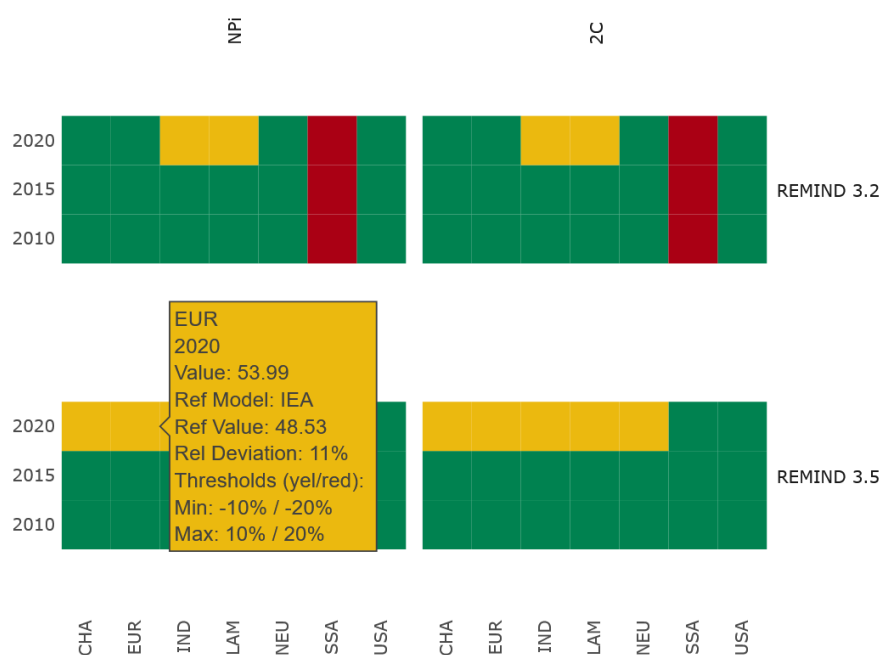


Figure 3. Example of an interactive validation heat map. Data along four dimensions. Hovering over a data point shows additional information in a tooltip. In this example, the Final Energy (FE) in two versions of the REMIND model for two different policy scenarios (National Policies implemented (NPI) and "well below" 2 degrees (66% likelihood) of temperature rise by the end of the century (2C) are compared with the historical IEA data.

The heat map plotting routine makes use of the ggplot2 library using the `geom_tile` function in combination with plotly which enables interactive access to additional information by showing tooltips when hovering over a tile. This allows users to first get a quick overview of the general validation outcome by scanning the colors of the heat map and identifying areas of interest (e.g., a region with many red tiles). In a second step, the exact value of a data point as well as the corresponding thresholds and reference values, including their origin, are shown in the tooltip. This two-step process is a particular strength of the chosen visualization approach, as it makes validation results of large datasets accessible without overcrowding the plot or distributing the data over many different plots (line plots are usually not useful for visualizing data along four dimensions, often it is the "region" dimension which is spread over multiple plots).

The heat map tiles are chosen to always be squares, which has the side effect that the plot layout is dependent on the lengths of the data dimensions. In cases where a high number of scenarios or models is being validated, this can lead to gaps between heat map facets and inefficient use of space in the validation document. To alleviate this, `validationHeatmap` allows the user to manually specify the arrangement of the data dimensions by defining the function arguments `"x_plot"`, `"y_plot"`, `"x_facet"` and `"y_facet"`. If they are not manually set, the function tries to find the optimal layout by analyzing the length of dimensions within the data passed to it.

2.2.5. Accessibility

One of the primary objectives of the `piaValidation` package is to enable broad application of the tool and support IAM 190 capacity building for developers and users of scenarios. To achieve this, the tool is published under an open-source license on GitHub and designed with user-friendliness as a central design criterion. For basic usage, a validation process can be executed with a single command, ensuring accessibility and ease of use for a broad range of users.

For the first application, users can follow four straightforward steps: First, ensure a working R environment. If it is not already installed, one possibility could be to install R and the

integrated development environment RStudio⁴. Second, install the `piaValidation` package by running the following R command:

```
install.packages("piaValidation", repo = "https://rse.pik-potsdam.de/r/packages")
```

The third step consists of the data preparation. Verify that the IAM data that needs to be

⁴Download the freeware here: R <https://www.r-project.org/> and RStudio <https://posit.co/products/open-source/rstudio/>

validated as well as the reference data 200 follow the IAMC standard format. In addition, prepare the configuration file by defining the validation checks to be performed as described in Section 2.2.1 and Section 2.2.2.

In the final step, the following R command must be executed to generate the HTML validation report including interactive heat maps. This command consolidates the file paths for the IAM data to be validated, the reference data, and the appropriate configuration file into a single operation.

```
validationReport(c("path_to_IAM_data", "path_to_ref_data"), "path_to_your_config")
```

For advanced users, the post-processing and visualization can be modified according to individual validation requirements by using the R data.frame containing the validation results directly. In addition, we encourage users to participate in ongoing 210 discussions and package developments on GitHub:

<https://github.com/pik-piam/piamValidation/issues> .

2.3. Application case: Validate short-term technology trends

This section presents an application of the `piamValidation` tool to the Integrated Assessment Model REMIND (see Baumstark et al. (2021) for a detailed description). To illustrate the validation process, we validate model scenarios against historical data and observational or third-party technology trend data until 2030, focusing on three key technology trends: capacity of CO2 transport and storage (CTS), sales and stock of battery electric vehicle (BEV), and capacity of offshore wind power. These technology trajectories represent some of the key energy system transformations that Luderer et al. (2022) describe: the potential for carbon management, the electrification of end-use sectors, and the composition of the electricity mix.

In scenarios of the REMIND 3.2 release (Luderer et al., 2023), all three technologies exhibit significant deviations compared 220 to historical and reference data. Figure 4 shows a heat map with yellow blocks for moderate deviations, red blocks for large upper deviations and blue blocks indicating large lower deviations. Upon identifying significant deviations, the focus shifts to improving the model and refining its underlying assumptions. The key strategies for achieving these improvements can be summarized as follows:

1. Updating the model input data;
2. Validating socio-economic assumptions to ensure alignment with observed trends;
3. Revising and verifying associated cost estimates;

4. Revising the representation of the inertia in up-scaling new technologies.

All adjustments have been incorporated into the REMIND 3.5 release (Luderer et al., 2025). We select two climate policy scenarios spanning a wide range of policy ambition: National Policies implemented (NPI) and "well below" 2 degrees (66% likelihood) of temperature rise by the end of the century (2C)⁵. Both scenarios follow the Shared Socioeconomic Pathways 2 called Middle of the Road. The 2°C stylized climate policy scenario assumes a peak budget of 1000 Gt CO₂ on total CO₂ emissions from 2020 to 2100. Figure 4 illustrates how the model enhancements improve the near-term realism measured as performance against the reference data within the piamValidation tool.

More dynamic insights on model to trend deviation are presented in Figure 5. The key developments in the updated model are described below.

⁵ The exact original scenario names are "SSP2EU-NPI" and "SSP2EU-PkBudg1150" in REMIND 3.2 and "SSP2-NPI2025" and "SSP2-PkBudg1000" in REMIND 3.5 for NPI and 2C respectively. They have been renamed for clarity and brevity.



Figure 4. piamValidation heat map of selected technology trends. Each heat map presents the performance of REMIND 3.2 (top) compared to updated version REMIND 3.5 (bottom) for the two climate policy scenarios: National Policies implemented (NPi, left) and "well below" 2 degrees (2C, right). For BEV we validate historical modeling values against IEA Global Electric Vehicle Outlook (GEVO) Historical data. For the outlook, the modeling values are validated against the IEA GEVO Announced Pledges Scenario (APS) and Stated Policies Scenario (STEPS). Similarly, wind offshore capacity is historically compared to International Renewable Energy Agency (IRENA) data and the outlook validated Global Wind Energy Council (GWEC) data. Carbon management capacity is validated against IEA CCUS data. An overview of all thresholds is provided in the validation config file (<https://github.com/pik-piam/piamValidation>). In addition, a detailed description and community discussion on the thresholds they can be accessed here: <https://github.com/pik-piam/mrremind/discussions/544>.

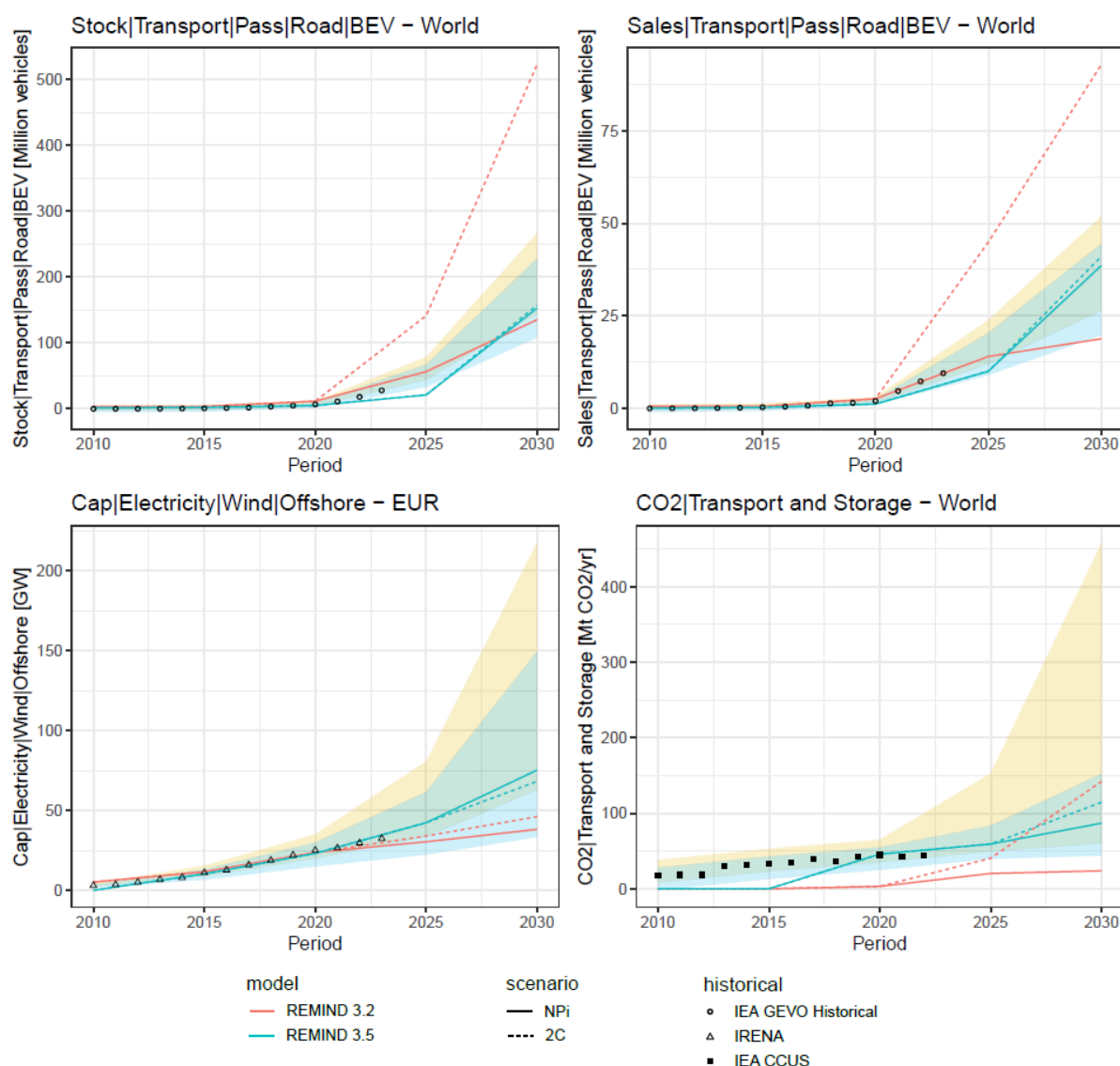


Figure 5. Historical and near-term realism. The REMIND scenarios and thresholds presented are identical with those in Figure 4. Scenarios updated refer to the improvements in REMIND 3.5.

2.3.1. CO2 transport and storage

CO2 transport and storage comprises the capture, transport and storage or use of CO2 from different CO2 sources. All CO2 that is captured, transported and stored is accounted in the variable "CO2|Transport and Storage". The carbon transport and storage infrastructure is represented as a single technology in REMIND. The construction of geologic carbon storage infrastructure is associated with long lead times, as the development of geologic storage typically takes 7 to 10 years from exploration to industrial-scale injection (Bui et al., 2018). Upscaling may be further limited by the availability of geo-engineers and drilling rigs (Budinis et al., 2018). In addition, a wide range of cost estimates have been documented. While studies on technical cost range between 3 and 20 USD/tCO2 (Budinis et al., 2018; Ippc, 2014), cost announced for projects reach up to 80 USD/tCO2 (Bellona, 2022; Jakobsen et al., 2017; IOGP, 2023).

There are thus two trends relevant for model improvement. First, storage potentials until 2030 are limited by projects announced today due to the long lead times. We thus refer to the database on Carbon Capture, Utilization and Storage (CCUS) projects, published by the International Energy Agency (IEA) in 2023 that is also used for the validation reference values. To improve the near-term realism of geologic storage in the model, we introduce regional lower and upper bounds. The lower bounds in 2025 and 2030 are based on the announced capacities of storage projects that are either operational or under construction (with announced start of operation before 2025 and 2030 respectively). The upper bounds for 2025 and 2030 additionally include 40% of the capacity of all announced projects that report a start of operation by 2025 or 2030 respectively. Note that for these, the final investment decision is often pending, thus a certain share of unrealized project capacities is assumed based on historic delay and failure rates. Furthermore, as the EU27 pursues a transnational, Europe-wide CCS infrastructure, the capacity of a given CCS project is not fully attributed to the respective member state within the model. Instead, the EU27 CCS capacities are pooled (including 50% of Norway's and 50% of UKs near-term potential) and redistributed across member states based on GDP. The second improvement concerns the costs of carbon transport and storage. The technical cost estimate in REMINDv3.2.0 of 7.5 USD/tCO2 appears too low, despite REMIND modeling the cost of upscaling through adjustment cost. We thus increase our capital cost estimate to reach 12 USD/tCO2 informed by the average in Budinis et al. (2018).

2.3.2. Electric vehicle stock and sales

REMIND's transportation sector is modeled by the simulation model "Energy Demand Generator-Transport" (EDGE-T) (Rottoli et al., 2021) that is integrated into the broader sociotechnical framework of REMIND. EDGE-T simulates technology and transport mode decisions relying on a multinomial logit approach. The decision tree, the logit, comprises a

nested structure of subsequent choices among comparable alternatives for modes and technologies. This established approach is handy for the modeling of end-consumer decisions under probabilistic conditions and allows for including non-economic factors, such as inconvenience costs, in the decision simulation.

In the transport sector, a prominent example is the increase in electric vehicles (EVs), which is not mainly driven by CO₂ prices and, consequently, fuel costs, but rather by technical innovations leading to up-front investment cost reductions, policy incentives, and shifts in how consumers assess this technology alternative. Model parameters were thus updated to reflect technology advancement and better understanding of the uptake dynamics of electric vehicles. Building on the Global EV Outlook (IEA, 2024) and its information about the shares of electric vehicles in car sales and car fleet in different world regions, the model representation of consumer attitudes (so-called inconvenience costs) towards electromobility was updated. Furthermore, input data processing was critically assessed, e.g. by screening for implausible outliers in input data, and correction routines were implemented. Given the scarcity of high-quality transport data such as total energy service demand in passenger-kilometers and ton-kilometers per transport mode, size distribution of the vehicle fleet, annual mileage of the vehicle fleet, investment and operation cost for vehicles for most countries of the world, checking input data plausibility by comparing data across countries, technologies and vehicle sizes is a crucial step for improving model and scenario quality.

2.3.3. Wind offshore capacity

The competition between onshore and offshore wind power is largely determined by factors like grid integration costs or the matching between generation profiles and demand. REMIND 3.2 – like other long-term global integrated assessment models – represents these drivers in a very aggregated and parameterized way, since it does not explicitly resolve the relevant spatial and temporal scales. Consequently, the model limits the share of offshore wind generation in total wind energy to a certain range. This share is constrained in the near-term to reflect the historical lag between onshore and offshore deployment.

In REMIND 3.2, historical capacities are available until 2020, at which point wind offshore is still a nascent technology with around 35GW of installed capacity world-wide. To prevent the model from deploying offshore earlier than observed in the real-world, only a portion of the total offshore wind potential is available: before 2010, none of the potential is available, then the available portion increases gradually until 2050. Conversely, specific equations ensure that the development of offshore capacity is not too slow compared to onshore after 2025: in a given region, if the available offshore potential is four times as high as onshore, the equations constrain the model to deploy each year at least twice as much offshore as

onshore new capacity.

The `piamValidation` tool has revealed that these constraints were overly pessimistic: wind offshore deployment in REMIND 3.2 is slower than observed in real data, particularly in Europe. To address this discrepancy, we updated the model to match the real data more closely. REMIND 3.5 uses newly released data by IRENA (2024) to compute consolidated historical capacities for 2020 and a lower bound for 2025 based on 2023 capacity. Moreover, the model allows for an accelerated phase-in of wind offshore by making the full potential available by 2030 instead of 2050. The equations linking offshore to onshore are maintained after 2030, in order to follow the rising trend of wind offshore despite its higher investment costs.

2.4. Conclusions

Integrated Assessment Models are central to the climate negotiations and play a key role in the IPCC assessments and thus at the interface between climate science and policy. However, they face challenges and criticism regarding their transparency (Robertson, 2021), their ability to capture technology trends (Keppo et al., 2021; Anderson, 2019) and their overall reliability (Wilson et al., 2021).

We introduce the open-source R package `piamValidation`, a versatile tool designed to address multiple use cases in the validation of IAM scenario data. This package facilitates validation across IAM scenarios, models, and temporal periods. Furthermore, it supports validation against historical, observational, and benchmark datasets, using time series, thresholds, or growth rates as a reference. To enhance reliability, `piamValidation` can be seamlessly integrated into the regular development workflow of IAMs, enabling comprehensive sanity checks and performance evaluations.

We outline the structure of the `piamValidation` package, emphasizing its user-friendly design to facilitate widespread adoption within the AIM community. The aim is to enhance the overall validity and reliability of IAMs through the systematic application of the tool. To support this objective, we provide a comprehensive and structured guideline, along with a standard use case demonstrating the application of the `piamValidation` tool through a single-command execution. We demonstrate the application of the `piamValidation` tool to assess the near-term realism of technology trends in the integrated assessment model REMIND. This analysis spans a policy range from nationally implemented policies to scenarios aligned with a well-below 2°C target. Our case study shows how near-term realism has been improved for wind offshore capacity, carbon management and electric cars in REMIND by using the `piamValidation` tool to first spot the deviations to historical and outlook data and then demonstrate performance improvements. Our application case reveals the application value of the tool for historical and benchmark validation critically depends on the

validation settings and availability of reliable reference data. Consequently, the utility of the `piamValidation` tool would be enhanced by broader adoption and the systematic documentation of configuration files within the IAM community.

The primary benefits of the `piamValidation` tool lies in its ability to efficiently provide an overview of variable deviations within large-scale datasets. It also facilitates systematic validation across IAM scenarios and supports sanity checks throughout model development processes. Furthermore, the tool serves as a potential platform for the IAM community to collaboratively build a repository of knowledge on reasonable validation thresholds.

The `piamValidation` tool is subject to several limitations. First, the identification of meaningful validation cases, reference data and thresholds is the responsibility of the user and substantially influences the results. Special attention is required in selecting the reference data regarding the projection method as well as technology resolution of the model (Krey et al., 2019). In other words, the usefulness of the validation test depends on the quality of the reference data. Since the tool identifies discrepancies between scenario and reference data, the user always needs to question the sources and reliability of the reference data as well as its meaning. Finally, the `piamValidation` tool is a performance measure that may motivate IAM improvements, but implementing them remains an additional modeling effort, as demonstrated in the REMIND application case.

Ongoing improvements are being made to the `piamValidation` tool, with continuous development efforts focused on enhancing its capabilities, including three central development features. First, within our application case, we used relative as well as absolute metrics to correct for scale-dependence of percentage deviation, especially for percentage deviations near zero. To reduce this scale dependency and increase the user-friendliness of the `piamValidation` tool, we are working on a new feature that includes a general tolerance. Our plan is that within the processing we include an optional lump sum buffer as a fraction of the largest reference value. Second, we would like to include a feature that enables the `piamValidation` tool to differentiate between different validation dimensions, for instance, feasibility, sustainability or equity. A third key development area centers around the identification ability of high-quality scenarios from an extensive scenario database. These improvements are designed to increase the versatility and usefulness of the tool within the IAM community.

Code availability. The REMIND-MAgPIE code is implemented in GAMS, whereas code and data management is done using R. The REMIND 3.2 code is archived at Zenodo (<https://zenodo.org/records/7852740>) Luderer et al. (2023) and REMIND 3.5 at (<https://zenodo.org/records/7852740>). The technical model documentation is available on the common integrated assessment model documentation website (https://www.iamcdocumentation.eu/Model_Documentation_-_REMIND-MAgPIE), and is published as open-source code (<https://github.com/remindmodel/remind>). A repository for

the source code of the `piamValidation` package is available via GitHub at <https://github.com/pik-piam/piamValidation>, the reproduction of the plots in this publication can be achieved with the RMarkdown file at https://github.com/pik-piam/piamValidation/blob/main/inst/markdown/validationReport_publication.Rmd. The validation in this study is performed with the configuration file at https://github.com/pik-piam/piamValidation/blob/main/inst/config/validationConfig_publication.csv.

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3. Evaluating the impact of lifestyle changes for Europe's residential buildings sector

Based on *Andreaou et al. (2025)*, published in *Environmental Research Letters*

Authors: Andreas Andreou, Panagiotis Fragkos, Faidra Filippidou, Eleftheria Zisarou, Georgios Avgerinopoulos, Robert Pietzcker, Robin Hasse and Ricarda Rosemann

3.1. Introduction

The Paris Agreement (PA) (UNFCCC, 2016) has set ambitious targets for countries to collectively limit the rise in average global temperature to well below 2 °C, and pursue 1.5 °C, above pre-industrial levels, in an effort to avert the adverse effects of climate change. At the same time, global pathways modelled with Integrated Assessment Models (IAMs) signify that drastic reductions in greenhouse gas (GHG) emissions are required across economic sectors to fulfill the PA's goals (Rogelj *et al.*, 2018; IPCC, 2023). In particular, the IPCC AR6 highlights the important role lifestyle changes and demand-side transitions can play in the decarbonisation of end-use sectors, including buildings and transport (Creutzig, Roy, *et al.*, 2022). Demand-side transitions can also support the achievement of Sustainable Development Goals (SDGs) and improve human well-being, through for example their positive effect on health and air quality (IEA, 2021; Creutzig, Niamir, *et al.*, 2022).

Buildings could have a major contribution towards system-wide decarbonisation in a 1.5 °C world (Wang, Chen and Shi, 2018; Cabeza *et al.*, 2022; Camarasa *et al.*, 2022). This could be delivered through GHG savings achieved based on energy efficiency advancements, electrification and the increased penetration of renewables, and sufficiency measures, including lifestyle changes. For the latter, research has shown that occupant behaviour is an important determinant of actual energy use in buildings (Yun and Steemers, 2011; Delzendeh *et al.*, 2017) and therefore behavioural changes may have a considerable GHG mitigation potential (Levesque, Pietzcker and Luderer, 2019; Ivanova *et al.*, 2020; van den Berg *et al.*, 2024).

Despite the potential contribution of future lifestyles in net-zero transitions, IAMs and Energy System Models (ESMs) – the computational tools typically used to investigate climate policy - focus more on technological supply-side solutions, while ignoring to a large extent the social aspects of energy transition (Creutzig *et al.*, 2018; Mathias *et al.*, 2020; Krumm, Süsser and Blechinger, 2022). The reasons behind this overlook are a) the inherent complexity with integrating complex social phenomena in quantitative modelling frameworks constrained to mainly represent technology-led transitions (van den Berg *et al.*, 2019; Keppo *et al.*, 2021), b) the unavailability of data on heterogeneous energy preferences and behaviours (Saujot, Le

Gallic and Waisman, 2021) and c) computational resource constraints (Wiese *et al.*, 2018). Furthermore, Mastrucci *et al.* (2023) argue that socio-behavioural interventions, such as lifestyle changes and social energy-saving practices, which support low energy demand transitions in the buildings sector are often represented partially and through exogenous assumptions in sectoral modelling tools.

Building on previous research (van Sluisveld *et al.*, 2016; Levesque, Pietzcker and Luderer, 2019; Andreou *et al.*, 2022; Gaur *et al.*, 2022; van den Berg *et al.*, 2024), this paper aims to move the literature forward by comprehensively examining the impact of lifestyle changes on European Union's (EU's) residential buildings sector under different climate policy contexts. This will be achieved through developing scenarios and enhancing sectoral energy models to better represent the drivers and impacts of behavioural changes. Quantification of lifestyle change impacts is based on the output of two modelling tools, namely PRIMES and EDGE-REMIND.

This study's innovation first lies in the development and presentation of scenarios combining multiple ambition levels for climate policy and lifestyle changes in the future. This is an extension of the work done by van Sluisveld *et al.* (2016), Grubler *et al.* (2018) and Bauer and Sterner (2025) which model a range of climate policy scenarios combined with a single lifestyle change variant, or the work by van den Berg *et al.* (2024) which incorporates lifestyle transitions in a single climate policy pathway. The examination of the interactions between the impact of lifestyle changes and climate policies on policy-relevant indicators allows this research to contribute to the emerging discourse to target behavioural shifts as part of effective climate mitigation strategies. Moreover, the modelling enhancements provide a more comprehensive representation of the effect of potential behavioural responses on energy demand for a set of residential end-uses. Lastly, comparison of results concerning key policy indicators between two well-established energy-system models aids in capturing the uncertainty governing the quantification of lifestyle changes and their impacts in the residential sector.

3.2. Methodology

The study focuses on the evolution of the residential buildings sector of EU-27 countries and the United Kingdom (UK). The analysis is carried out for six scenarios combining two ambition levels of climate policy with three tiers of assumptions about the future adoption rate and intensity of lifestyle changes in the residential sector. Lifestyle modules enhanced to better represent behavioural shifts in the residential domain are integrated in sectoral energy models. This allows for a comprehensive analysis of the effects of changing consumer behaviours on several policy indicators including final energy use, CO₂ emissions and system costs.

The sectoral energy models utilised in this study are PRIMES-BuiMo and EDGE-Buildings, which is interlinked with the REMIND-Buildings integrated-assessment model. These models have been previously employed to support policy impact assessments (EC, 2018), shape energy transition outlook scenarios (Capros *et al.*, 2021) and study energy-system transformations towards net-zero emissions (Levesque *et al.*, 2021; Rodrigues *et al.*, 2022).

3.2.1 Modelling improvements

PRIMES-BuiMo (Capros, 2018) is a hybrid economy-engineering model used for the development of scenarios for the residential and services buildings sector of EU member states under alternative policy futures (Fotiou, de Vita and Capros, 2019). Decision-making of agents concerning energy efficiency interventions, including choices about the upgrade of heating equipment, and the timing and depth of renovation, is modelled endogenously based on microeconomic theory, while respecting engineering constraints. The modelling framework represents market (i.e., true costs relating to hidden up-front investments and limited access to capital resources) and non-market (i.e., perceived costs relating to the lack of information, presence of uncertainty and economic factors related to individual consumers) barriers which influence energy efficiency investments. A range of economic (e.g., taxes and subsidies) and regulatory (e.g., minimum energy performance standards) measures to accelerate the energy transition are also modelled (Fotiou, Capros and Fragkos, 2022).

PRIMES-BuiMo treats consumer heterogeneity by splitting households into several categories, according to the location, age of construction, income class, and type of household (single or multi-story building). Deviating from the single representative consumer hypothesis, the model portrays agent groups with idiosyncratic behaviours and energy preferences. Subjective discount rates are differentiated by income class to reflect differences in the availability of funding opportunities, access to information and uncertainty. Moreover, PRIMES-BuiMo employs discrete choice theory to capture consumer heterogeneity within household groups. In this way, the model represents heterogeneous consumer decisions, respecting the purchase of energy-related equipment and technologies or improvement of building thermal insulation.

EDGE-Buildings is a simulation model that projects global energy demand for buildings, following a top-down approach driven by population, GDP and climate data projections (Levesque *et al.*, 2018; Levesque, Pietzcker and Luderer, 2019). Per capita useful energy demand for end uses is projected into the future based on the observed correlation with macro-economic drivers and, in the case of space heating and cooling, influenced by changing climatic conditions. The observed elasticity between the useful energy demand and macro-economic drivers can be altered to represent behavioural or legislative changes. The building shell efficiency is represented by an aggregated thermal transmittance indicator that improves over time. The effect of increased renovation activity is calibrated to pathways

with a known renovation rate. As EDGE-Buildings can only simulate scenarios that follow current trends, for transformative scenarios under stringent climate policy, assessments are performed using REMIND-Buildings. REMIND is a global multi-regional IAM which represents the full economy, with a detailed representation of the energy system (Baumstark *et al.*, 2021). REMIND-Buildings is calibrated to baseline scenarios of final energy demand devised with EDGE-Buildings.

Both the PRIMES and EDGE/REMIND modelling suite treat lifestyle transformations in the residential sector, not relating to energy efficiency measures, via ad-hoc exogenous assumptions. These assumptions are applied to model parameters controlling the activity level for different residential end-uses. More specific details on model characteristics can be found in the Supplementary Information (SI) in section S1.

For this study, both models have undergone enhancements first regarding the breakdown of energy demand to individual residential end-uses, especially for thermal services (i.e. including space and water heating, and space cooling). This is achieved through bottom-up engineering-based functions with an improved distinction between the behavioural and non-behavioural factors driving useful energy demand, that is the amount of energy that should be supplied to final consumers:

- For space heating and cooling, useful energy demand is derived through functions incorporating building-level technical values (e.g., thermal conductivity of building shell/U-value, air infiltration rates), climatic conditions (e.g., heating and cooling degree days – HDDs/CDDs- or the external temperature and length of heating/cooling season), adjusted to include potential behavioural shifts (e.g. changes in internal heating/cooling temperature).
- For water heating, the refined bottom-up functions decompose demand for hot water for personal hygiene purposes to the effect of technical (e.g., showerhead flow rate) and behavioural factors, including the option to reduce the duration of showers.
- In PRIMES-BuiMo, an additional step was taken for calibrating these functions to official energy data from Eurostat (energy balances and split of energy to end uses), thus enabling a more accurate quantification of the effects of behavioural change on useful energy demand.

Second, in order to assess alternative trajectories of floor space growth and their effect on space heating and cooling demand, regional upper limits of floor space growth were set in both models. These caps were defined based on sustainability-focused climate mitigation pathways (Fishman *et al.*, 2021; Mastrucci *et al.*, 2021) to reflect policies aiming to limit the expansion of building sizes. Third, the representation of electrical demand for appliances and lighting was improved to better incorporate the effect of behavioural changes. In PRIMES-BuiMo this was achieved by integrating in the scenarios energy saving estimates resulting from the choice of eco-mode over standard washing programmes for dishwashers

and laundry machines, and from eliminating standby power from appliances. The impact of these measures was reflected implicitly in the scenarios created by EDGE-Buildings.

3.2.2 Scenario development

Scenarios developed for the residential buildings sector of EU-27 countries and the UK extend from a historical baseline year common between the models (2015) to 2050, in 5-year intervals. To enhance comparability across scenarios, the sectoral models use harmonised socio-economic assumptions regarding GDP and population growth. Population estimates are based on Eurostat's EUROPOP2019 projections, updated in the short-term to reflect the influx of refugees from the Ukraine[1]. GDP projections are based on forecasts developed by the Directorate General for Economic and Financial Affairs (DG ECFIN, 2021, 2022). The scenario analysis for the residential sector considers two distinct climate targets based on the current EU climate policy landscape. On the one hand, the "Baseline" scenario (existing policy framework) considers only currently implemented climate and energy policies in EU Member States, such as those presented in their National Energy and Climate Plans (NECPs) and long-term renovation strategies. It follows the general energy, economic and emission trends presented in the latest EU Reference scenario of the European Commission (Capros *et al.*, 2021).

On the other hand, the "Decarbonisation" scenario assumes much more ambitious EU climate policies in 2030, including the 55% GHG emission reduction target relative to 1990, and stringent energy efficiency and renewable energy targets (as those presented in the Fit for 55 package (EC, 2021)). Furthermore, this scenario leads to climate neutrality by 2050 in line with the goals of the EU's Green Deal (EC, 2019). The decarbonisation scenarios assume that various regulatory (e.g. building energy codes, carbon tax) and non-regulatory policies (e.g. subsidies, information and education policies) facilitate the green transition supporting the up-take of clean energy technologies and corresponding investment. However, both the basic Baseline and Decarbonisation policy context overlook the potential energy and emission impacts from more ambitious lifestyle-led demand transitions.

On top of the two climate policy scenarios, three distinct assumptions have been imposed concerning future lifestyle changes: (a) a scenario that assumes no shift in consumer behaviours and a continuation of current trends in energy consumption habits, (b) a Low Ambition lifestyle change scenario variant assuming that a small share of consumers adopts lifestyle changes (gradually until 2050) to reduce their energy consumption and carbon footprint, and (3) a High Ambition lifestyle change scenario variant assuming that a larger share of consumers adopts lifestyle changes of similar or increased intensity compared to the low-ambition case. Combining the two levels of climate policy ambition ("Baseline" and "Decarbonisation") with the three levers of lifestyle change ("No", "Low" and "High"), results in six possible scenario configurations simulated with the two models (labelled as "Base", "Base_LC", "Base_LC_High", "Decarb", "Decarb_LC", and "Decarb_LC_High").

3.2.2.1 Selection of lifestyle changes

The identification of the most important lifestyle changes to be included in the scenarios for the residential sector is based on the findings of a recent literature review (Andreou *et al.*, 2022) and other research from the H2020 CAMPAIGNERS project[2] (Copinschi *et al.*, 2022; Andreou *et al.*, 2023). Results from literature reviews helped to identify the demand-side measures with the largest potential in reducing sectoral energy use and carbon emissions. Following the ASI framework (van den Berg *et al.*, 2021)[3], the focus was primarily placed on the “avoid” and “shift” type of mitigation actions, rather than on the “improve” ones. These require mainly voluntary actions from consumers, without needing large upfront capital investments. These findings were then complemented with experts’ insights and preliminary empirical information from the CAMPAIGNERS network on the lifestyle changes with the highest adoption probability by consumers.

The final list of lifestyle changes covers actions curtailing energy demand for heating and cooling in buildings, such as shifting the thermostat set-point for heating and cooling, and limiting hot water use for personal hygiene purposes. It also includes developments which lead to reduced floor space in residential buildings. For electrical uses, selected mitigation actions include the choice of eco-mode settings in laundry machines and dishwashers and elimination of standby power from appliances. Finally, we recognised that demand-side actions other than those strictly defined as lifestyle changes can contribute significantly to decarbonisation goals (Ivanova *et al.*, 2020). As a result, the LC variants also examine the effect of accelerating building renovation on decarbonisation goals; an action also included in the NAVIGATE study (Kriegler *et al.*, 2023).

3.2.2.2 Quantification of lifestyle changes

Scenario assumptions concerning lifestyle changes in the residential sector were translated into a compatible input to the modelling framework of PRIMES-BuiMo and EDGE-Buildings. The quantification of lifestyle changes draws from the results of a literature review performed for the H2020 CAMPAIGNERS (Andreou *et al.*, 2023) and NAVIGATE[4] projects and input from the H2020 MutliFutures[5] and PRISMA[6] (Pettifor *et al.*, 2024) projects. A cross-check assured that lifestyle change assumptions do not deviate significantly with those from similar modelling studies, like those in van den Berg *et al.* (2024). The following changes were imposed to the models:

- (a) Set-point temperatures for heating (cooling) in residential buildings reduce (increase) by 1 °C and 2 °C from their baseline levels until 2050 in the Low and High Ambition scenarios respectively. In PRIMES-BuiMo, baseline country-specific internal temperatures were derived from the EN ISO 13790:2008 calculation method for heating and cooling demand (Loga and Diefenbach, 2013). In EDGE-Buildings, thermostat setpoints are accounted for in the calculation of degree

days which is a driver of heating and cooling demand in the model. Baseline setpoints correspond to HDDs and CDDs calculated with an external balance temperature of 18 °C and 23 °C respectively also considering internal gains and heterogeneity in behaviour and comfort perception (Levesque *et al.*, 2018).

- (b) The renovation rate in buildings increases by 0.5%pt and 1%pt per year above the Baseline (or the basic Decarbonisation scenario) levels in the Low and High Ambition lifestyle change scenarios respectively. More frequent and deep renovation measures are adopted progressively over time, meaning that the maximum deviation from the basic scenarios is achieved in 2050. Based on PRIMES-BuiMo projections, the average renovation rate in 2050 remains low at around 1%/yr in the Baseline scenario, while more than doubles in the Decarbonisation case reaching 2%/yr. In EDGE-Buildings, the pace of improvement of the U-value is adjusted to reflect a 1%/yr in the baseline case, while it increases to 1.5%/yr and 2%/yr in the Low and High Ambition lifestyle change scenario variants respectively.
- (c) Flexible use of buildings, shared building spaces (e.g. co-housing and co-working) and policies limiting floor space in new constructions reduce the floor space used per capita in the residential sector. We assume a convergence to 30 (High Ambition) and 40 (Low Ambition) m²/cap by 2050 for residential floor space (in line with LED/SSP1 scenario assumptions in Grubler *et al.* (2018), Fishman *et al.* (2021) and Mastrucci *et al.* (2021)). In EDGE-Buildings regions that currently have a higher floor space per capita than the assumed cap maintain this level over time. In the Baseline and Decarbonisation scenarios without lifestyle change, the two models show a convergence of household space to 47-48 m²/cap in 2050 in the EU-27.
- (d) Hot water conservation: In PRIMES-BuiMo, average shower time is decreased down to 5 minutes in the Low Ambition scenario and down to 4 minutes in the High ambition scenario, similar to the Low and Very Low demand scenarios presented in Levesque, Pietzcker and Luderer (2019). This lifestyle change was simulated compared to a baseline showering time of 5.6 minutes, reported for UK households in Shahmohammadi *et al.* (2019). In EDGE-Buildings, reduced shower times from 8 minutes to 6 minutes in the Low Ambition scenario and 4 minutes in the High Ambition scenario are assumed in the bottom-up calculation of water heating demand saturation level. The different target shower time in the low-ambition lifestyle change case reflects the higher baseline showering time relative to PRIMES-BuiMo.
- (e) Choice of eco-mode for clothes and dish washing programmes: Based on data from the European Product Registry for Energy Labelling (EC, 2022), the average

eco-mode consumption of dishwashers in the market (C to G class) is around 0.85 kWh/cycle and that of laundry machines is 0.68 kWh/cycle. By ignoring class A to B, we isolate the effect of eco-mode without considering the best-performing products in the market. In PRIMES-BuiMo, electricity demand for dishwashers and laundry machines is adjusted according to the reduction in average cycle consumption between eco-mode and standard programmes using as baseline consumption levels those of “ordinary” technologies included in the model[7]. In the Low Ambition Lifestyle Change scenario, 50% of households are assumed to choose eco-mode programmes by 2050, while this percentage increases to 100% in the high-ambition case.

- (f) Eliminating standby electricity use: Annual energy savings are estimated based on a review of standby electricity consumption statistics for different product categories (LBNL, no date). In PRIMES-BuiMo, standby power estimates were transformed into avoided annual electricity consumption figures based on simplistic assumptions about the daily hours of standby of electric appliances and lighting. In the Low and High Ambition lifestyle change scenario, we assume that 50% and 100% of the households eliminate standby power by 2050 respectively. EDGE-Buildings represents all appliances and lighting as a single category and does not resolve their energy demand any further. The impact of lifestyle changes (e) and (f) is therefore implicitly reflected in the model as the less active use of appliances through a reduction of the elasticity between GDP per capita and the electricity demand of appliances and lighting overall.

Table 1 summarises the key assumptions regarding the lifestyle changes in the residential sector under the low and high-ambition scenario variant. For the high-ambition decarbonisation case, additional variants were created integrating individual lifestyle changes from Table 1. These variants incorporate changes in a) set-point temperature selection, b) dwelling downsizing, c) hot water conservation, d) more efficient appliance use, and e) increased renovation measures. This helps to decompose total energy savings achieved in the high-ambition LC case (Decarb_LC_High) relative to the basic Decarb scenario to the effect of individual measures.

Table 1 Lifestyle change scenario assumptions for the low and high-ambition variant.

Modelled lifestyle change	Low-ambition variant ^a	High-ambition variant ^a
Set-point temperature	1°C reduction in thermostat setting	2°C reduction in thermostat setting

Limiting floor space growth	Convergence to 40 m ² /cap	Convergence to 30 m ² /cap
Hot water conservation	Shower time set at 5 or 6 minutes	Shower time set at 4 minutes
Eco-mode consumption	50% of households switch to eco-mode for clothes and dishwashing programmes	100% of households switch to eco-mode for clothes and dishwashing programmes
Standby electricity use (appliances and lighting)	50% of households eliminate standby power	100% of households eliminate standby power
Renovation rates	0.5% p.a. increase above the Baseline/Decarbonisation scenario	1% p.a. increase above the Baseline/Decarbonisation scenario
^a . Assumptions refer to changes from the levels of scenarios without lifestyle changes in 2050.		

3.3. Model-based Results

3.3.1 Useful energy demand

Useful energy demand for residential thermal uses in the EU-27 & UK region increases slightly over time in the Baseline case, as shown in Figure 1. This is driven mainly by the growing floor space (see SI/section S3 for energy service level projections), while improvements in the thermal properties of building envelopes have a more limited effect. Integration of lifestyle changes leads to significant reductions in useful energy demand relative to the Baseline case, with the effect reaching a maximum level in 2050 when more households adopt energy-saving lifestyles. Relative to the Baseline case, useful energy demand in 2050 is projected to decline by 17% in the Low Ambition (Base_LC) and 29-34% in the High Ambition (Base_LC_High) scenario, with the two models showing similar trends.

Due to its magnitude, the largest contributor to the projected decrease is space heating (which is reduced via thermostat set-point adjustments, declining floor space and increased renovation), with a 80-90% contribution share (see SI/section 3 for detailed figures).

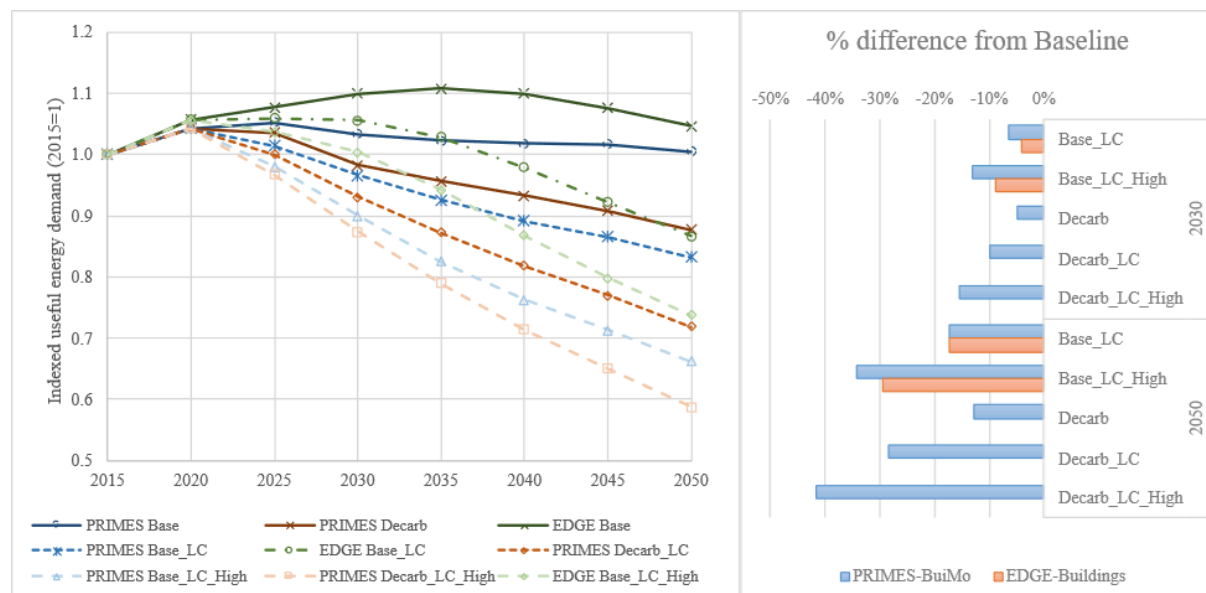


Figure 1 Projections of useful energy demand for thermal uses in the scenarios modelled via PRIMEs-BuiMo and EDGE-Buildings.

In the decarbonisation scenarios family generated with PRIMEs-BuiMo, useful energy demand in 2050 is reduced by 13-42% relative to the Baseline case, similarly driven by the declining space heating needs. The scenario achieving the strongest reduction in useful energy demand is as expected the Decarb_LC_High, which assumes high annual renovation rates and depth, and the most intense lifestyle changes combined with ambitious policies towards net-zero emissions. Decarbonisation scenarios from REMIND are not shown as the model does not report end-uses at sufficient granularity.

3.3.2 Final energy

Based on models' projections, final energy use in the residential sector of the EU-27&UK region in the Baseline case changes from 12 EJ/yr in 2015 to 10-12 EJ/yr in 2030 and decreases to 9 EJ/yr in 2050, representing a ~20% reduction from current levels (see SI/section 3 for a breakdown to fuel and end-use shares). PRIMEs-BuiMo shows that stronger energy savings are realised earlier compared to REMIND-Buildings. This is the result of ambitious energy efficiency and renewable energy policy targets in 2030 explicitly represented in the modelling framework of PRIMEs. REMIND-Buildings on the other hand projects higher mid-term baseline demand. There is however good agreement of the relative reduction from LC between the models, as shown in Figure 2.

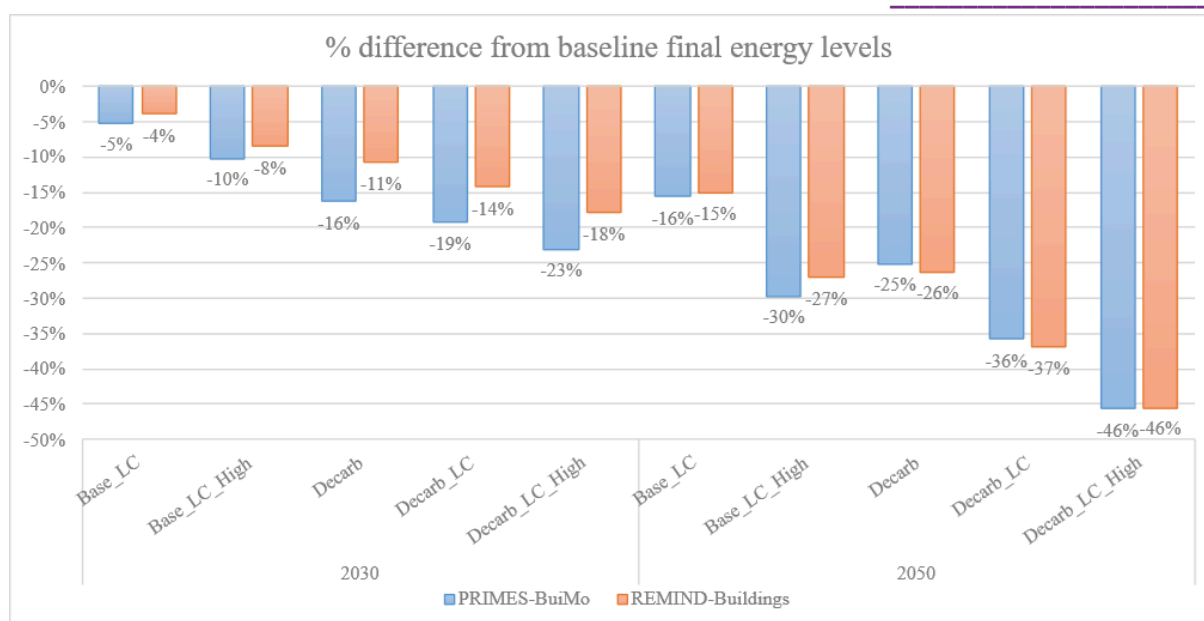


Figure 2 Change of EU-27&UK residential final energy use in 2030 and 2050 in the modelled scenarios, relative to 2015 levels.

The impact of lifestyle changes on energy consumption in the baseline scenarios is significant, especially in the long-term: in the low and high-ambition LC cases, residential energy use is respectively shown to decrease by 15-16% and 27-30% in 2050 relative to the Base scenario with no lifestyle change. The two models also agree about the relative decrease in final energy by 2050 under the decarbonisation scenario, projecting a 25-26% reduction with respect to baseline levels. Furthermore, the energy savings from behavioural shifts in the decarbonisation context are slightly smaller compared to baseline scenarios, as the reduction in final energy in 2050 relative to the basic Decarb case is only 14% and 26-27%, respectively for the low and high-ambition scenario variant.

Moreover, the two models agree about the additional benefits from raising the ambition level of lifestyle changes in the residential sector from “low” to “high”. In the current policy context, more widespread adoption of low-carbon behaviours increases the energy savings by 12-14 p.p. in 2050; while the corresponding savings in the decarbonisation context are relatively smaller at 9-10 p.p., showing the diminishing returns from an increased shift to low-carbon behaviours in a progressively decarbonised system.

3.3.3 CO₂ emissions

Baseline CO₂ emissions in the EU-27&UK residential sector (Figure 3), are projected to decrease in PRIMES-BuiMo by 25% and 51% in 2030 and 2050 respectively, relative to 2015 levels. Conversely, REMIND-Buildings projects a somewhat lower decrease in Base scenario emissions, which amounts to 18% in 2030 and 44% in 2050 below 2015 levels. The less

pronounced reduction in baseline emissions in 2030 can be explained by the smaller change in total energy demand from current levels; while in 2050 this can be traced back to the higher share of remaining coal and liquids compared to the final energy demand of PRIMES.

Similarly in the decarbonisation scenario, PRIMES-BuiMo projects CO₂ emissions from households to reduce in 2030 by 52%, while the corresponding reduction in REMIND-Buildings is lower at 36%. Nevertheless, emissions in both models virtually reach zero by 2050, as strong decarbonisation policies drive the significant electrification of the sector and massive displacement of fossil fuels combined with the uptake of zero-carbon options, such as heat pumps and district heating.

Emission reductions increase in the lifestyle change variants with emissions in the low(high)-ambition LC baseline scenario dropping further by 4 p.p. (10 p.p.) in 2030 and 7-8 p.p. (16-17 p.p.) in 2050 compared to the core baseline case. In agreement with final energy demand results, the impact of lifestyle change on emissions is less significant in a decarbonisation setting, as the maximum additional emission reduction in the two models is 6 p.p. in 2030 and almost negligible by 2050 as net zero emissions are already achieved in the region. CO₂ emissions in both models display greater variation between the core decarbonisation and baseline case, compared to the variation observed between the core scenario and its lifestyle change variants.

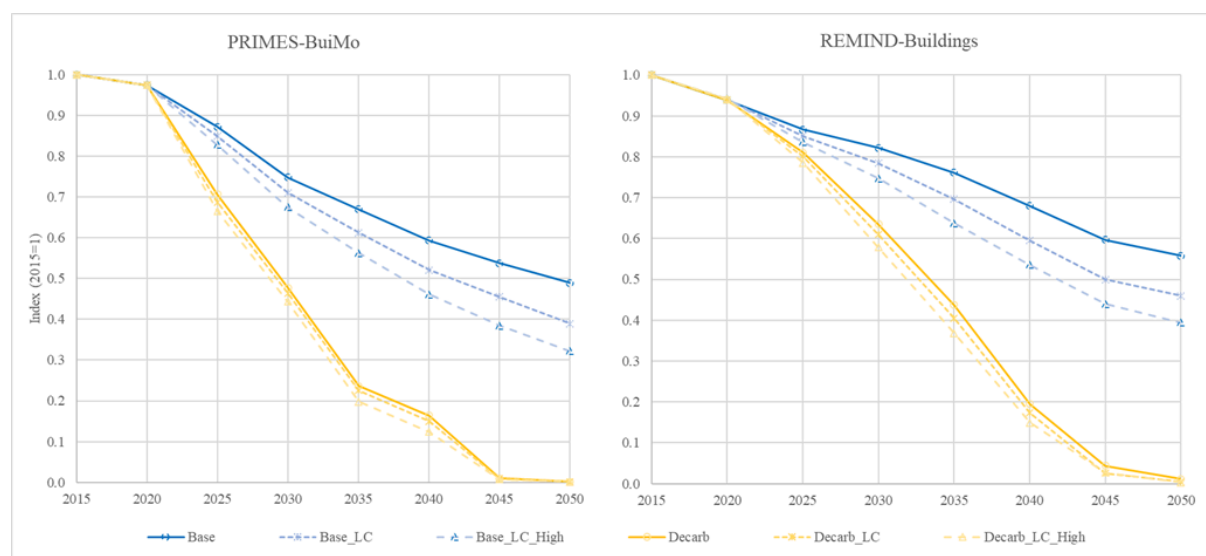


Figure 3 Evolution of residential CO₂ emissions at the EU-27&UK level as projected by the PRIMES-BuiMo (left) and REMIND-Buildings (right).

3.3.4 Costs

This section compares the costs incurred by consumers in the residential sector under the various scenarios, based on PRIMES-BuiMo results (Figure 4). The cost indicators selected are annual fuel expenses and capital costs, which comprises payments for direct energy efficiency measures (renovation and new building constructions) and for new energy equipment (e.g. heating equipment, electric and electronic appliances etc).

Fuel purchasing expenses reduce in the decarbonisation scenario relative to the baseline, around 1% when cumulated over the period 2021-2050. Factors like the introduction of carbon price in non-ETS sectors from 2030 onwards which increases fossil fuel prices, mitigate the reduction in fuel expenses due to lower energy demand. Lifestyle changes reduce even more the cumulative fuel expenses over the period 2021-2050 by 6-7% and 13-14% in the low- and high- ambition LC scenarios respectively, compared to the Base and Decarb scenarios without lifestyle changes. In this way, lifestyle changes are effective in reducing energy expenditure[8].

Compared to the baseline case, capital costs in the decarbonisation scenario increase by about 20% over the 2021-2050 period. This is influenced by policies enabling additional capital investments in energy efficiency, based on a higher rate and depth of buildings' renovation and the accelerated uptake of capital-intensive low-carbon technologies, including heat pumps, as well as energy efficient equipment and appliances. As a result, capital costs in 2050 for the Base and Decarb case are respectively 80% and 120% higher than the corresponding 2020 level.

In the lifestyle change variants, changes in capital costs are driven by two opposite effects, namely the increased spending on renovation measures assumed in the LC variants counterbalanced by the reduced investments in energy-using equipment as thermal needs are lower (lower household space, lower temperature set-point). As the latter is a larger cost element, cumulative capital costs under the LC variants are lower than the cases without lifestyle changes both in the baseline and decarbonisation context. Over the 2021-2050 period, capital costs reduce in the LC (LC_High) case by 1% (3%) in the baseline, and 1% (4%) in the decarbonisation scenario, relative to the no lifestyle change cases. Cumulative total energy-related costs (comprising capital costs and energy purchases) are therefore reduced by 4% and 8% under the low and high-ambition lifestyle change case respectively, for both the baseline and decarbonisation scenario. The share of cumulative operating to total costs drops from 49% in the baseline scenario to 41% in the Decarb_LC_High case while the share of capital costs increases due to the investment in buildings' renovation and the purchase of more capital-intensive (and energy efficient) technologies and appliances.

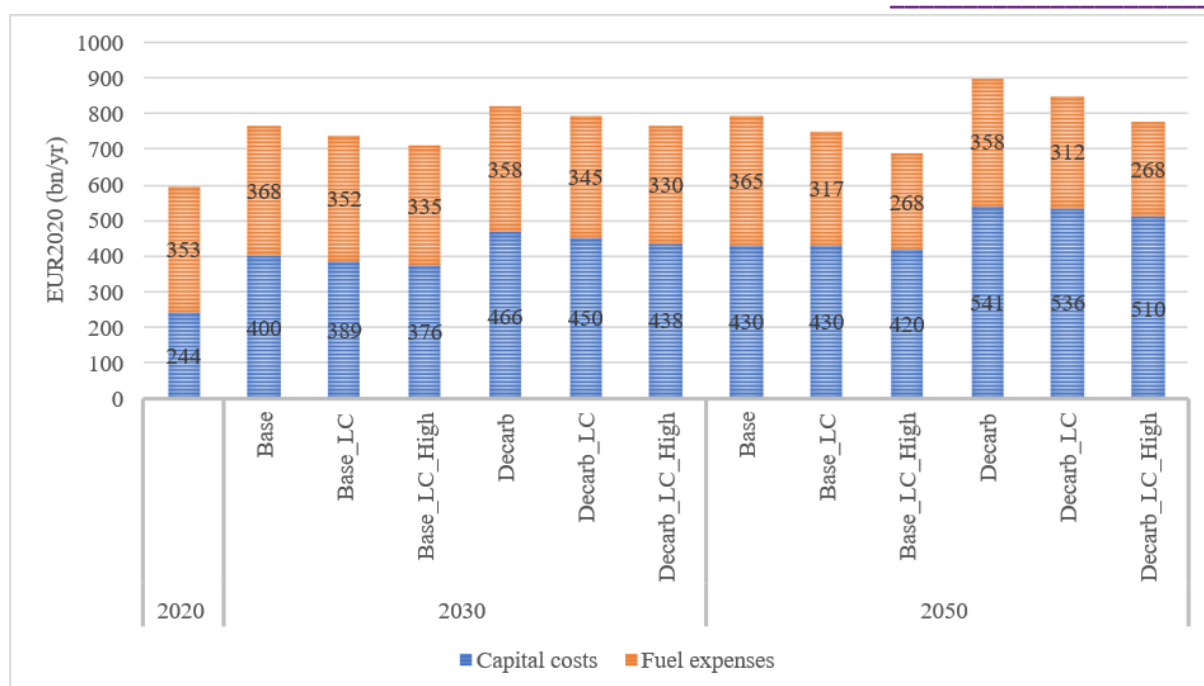


Figure 4 Annual fuel expenses and costs for capital based on PRIMES-BuiMo results.

3.3.5 Decomposition analysis

This section elaborates on the results of the decomposition analysis of energy savings achieved in the decarbonisation scenarios incorporating individual high-ambition behavioural changes compared to the Decarb case without lifestyle changes. Amongst the assessed measures/lifestyle changes, the one having the strongest impact on final energy use for both PRIMES and REMIND is the reduction of average household space, with cumulative savings of 12-14 EJ in the 2021-2050 period relative to the Decarb case (Figure 5). The second most effective measure is thermostat set-point adjustments according to PRIMES, with cumulative energy savings of around 7 EJ. Conversely in REMIND, increased renovation has the second largest effect (11 EJ savings), followed by thermostat adjustments (8 EJ savings).

In PRIMES, intensification of renovation measures has a much less pronounced contribution to overall energy savings, as in the basic Decarb scenario the modelled energy efficiency policies already lead to an increased rate and depth of renovation leaving a smaller room for further energy demand reductions in the LC cases. The decreasing effect on useful energy demand via increased building renovation under the basic Decarb case is represented more coarsely in REMIND such that the effect of an additional increase of the renovation rate has to be calibrated to results from models including explicit renovation activity. Appliance use has a moderate impact on energy savings in both models (~6EJ savings), while hot water conservation measures has the lowest impact (~3EJ savings).

Adding together the energy savings resulting from individual behavioural measures leads to a level of total savings that is higher than the ones achieved under the Decarb_LC_High scenario (plotted in Figure 5). This could be explained by the potential (but moderate) trade-offs between lifestyle changes targeting demand for space heating and cooling, namely the interplay between building renovation choices and exogenous assumptions about changing thermostat temperature set-points and dwelling size. In the scenarios where renovation rates are unconstrained, the introduction of individual exogenous measures on top of the Decarb scenario leads to energy savings according to the mitigation potential (in % terms) of each action. Enforcing higher renovation rates and depth in the Decarb_LC_High case results in a lower useful energy demand for space heating relative to the Decarb case, thereby limiting the room for additional savings from other behavioural measures.

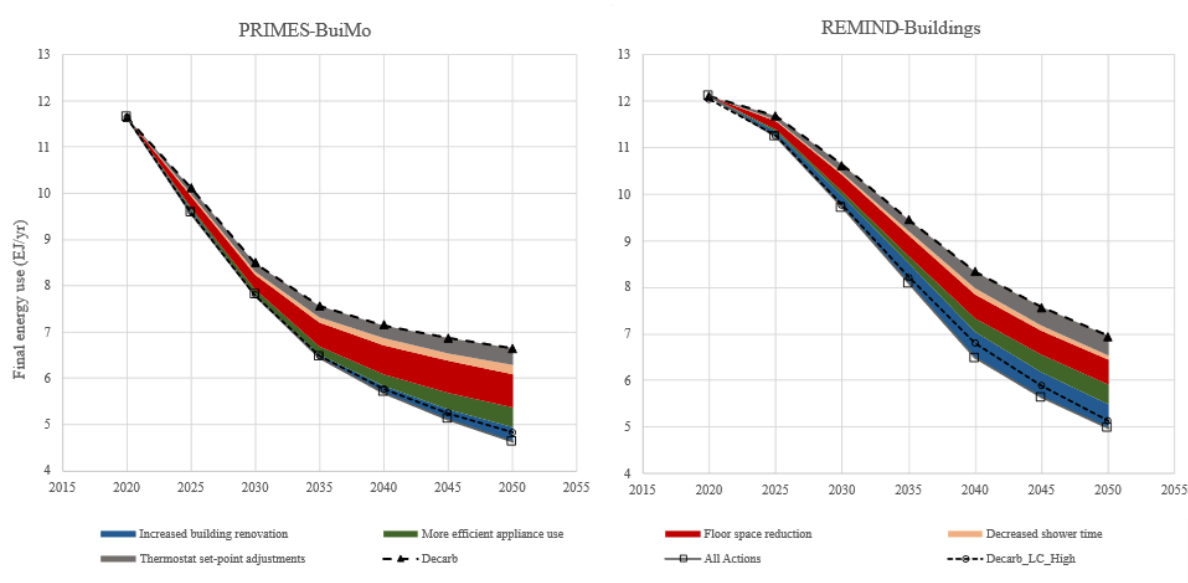


Figure 5 Decomposition of the effects of individual behavioural measures on final energy use for PRIMES-BuiMo (left) and REMIND-Buildings (right).

3.4. Discussion

3.4.1 Impact of lifestyle changes and policy implications

The critical role of behavioural shifts in shaping future energy consumption patterns in the residential sector is emphasised in both models' results, especially in the long-term when the uptake of lifestyle changes is maximised. This is particularly evident under the baseline scenario's specifications where lifestyle shifts result in substantial reductions in energy demand and CO₂ emissions from the residential sector. This showcases the significant contribution of radical demand-side transitions and lifestyle changes in achieving energy efficiency and CO₂ reduction goals.

Savings from lifestyle changes in the baseline context for the low-ambition scenario variant are broadly consistent but on the high end of the range of estimates from previous similar studies. EU-level residential emissions in the Low Ambition scenario decrease by 18-20% from their baseline level in 2050, which compares well with the 16% and 12% emissions reduction estimates in the global and European lifestyle case of van Sluisveld *et al.* (2016) and Costa *et al.* (2021)[9] respectively. The impact on CO₂ emissions in 2050 is somewhat larger compared to the 9% reduction estimate derived from the “Pocket Lifestyles” scenario in van den Berg *et al.* (2024). The smaller impact can be explained by the lower saturation rate of various lifestyle changes in 2050 compared to the 100% rate adopted in our study and the non inclusion of building renovation in the list of behavioural measures. Furthermore, comparison with previous studies demonstrates the optimistic nature of our High Ambition lifestyle change case, which requires a radical up-scaling of behaviours and social norms in the residential sector. In the baseline high-ambition scenario variant, our models project CO₂ emissions to reduce by 61-68% between 2015 and 2050. This is still within the 40-70% range of the technical potential for emissions reduction in 2050 through demand-side actions in all end-use sectors, as estimated by the Intergovernmental Panel on Climate Change (IPCC) (Creutzig, Roy, *et al.*, 2022).

Lifestyle change impacts on energy efficiency and decarbonisation goals are smaller under a climate-neutrality policy framework (in agreement with van Sluisveld *et al.*, (2016)). This suggests that the effectiveness of lifestyle changes depends also on broader climate action. While most of the emission reduction effort is attributed to the overall decarbonisation measures, lifestyle changes could still have a complementary role and support medium-term goals in case of weaker implementation of decarbonisation policies. Results suggest that lifestyle changes, such as reducing average dwelling size and thermostat set-point adjustments, can act as a substantial complementary driver to climate policies in a decarbonisation setting to accelerate the EU’s transition.

Moving to economic considerations, scenario results highlight that lifestyle changes can lower energy expenditure for residential consumers as they lead to reduced fuel expenses, irrespective of the policy context. Moreover, under the decarbonisation context where ambitious policies drive additional investments in energy efficiency, lifestyle changes can be effective in mitigating the increases in capital expenditure incurred by consumers. Overall, this provides evidence that the role of lifestyle changes in the policy agenda could be two-fold, one for the contribution to decarbonisation goals and another for reducing energy costs for consumers. Lower expenditures due to lifestyle changes could potentially aid in the reduction of the risk of energy poverty for low-income European households, and support broader SDGs with clear co-benefits in terms of reduced air pollution, improved health and enhanced sustainability.

The overall findings of this study underline the need for designing mitigation strategies tailored to the residential sector’s challenges and potentials, with a strong representation of

radical demand-side transitions and lifestyle changes. However, caution is needed in the promotion of lifestyle changes to the extent to which they do not compromise well-being and hinder progress towards achieving decent living standards (Millward-Hopkins *et al.*, 2020). Currently, these elements lack significant representation in most of the current EU-wide policies and national climate strategies (Salem, Lenzen and Hotta, 2021). Some exceptions exist for EU countries, such as in the long-term strategies of Austria and Portugal (Federal Ministry Republic of Austria, 2019; Republica Portuguesa, 2019), which incorporate some behavioural changes for buildings, however mostly focusing on building renovation measures.

3.4.2 Limitations and future work

The robust integration of diverse lifestyle changes and behavioural shifts into leading IAMs and ESMs, an aspect which is often overlooked in traditional modelling approaches, allows for a better understanding of their potential contribution to a low-carbon transition. This study has focused on modelling lifestyle changes and their impacts on the EU-27&UK residential sector, through improving two leading sectoral energy models. The performed analysis informs policy makers about the potential contribution and added value of environmentally sustainable lifestyle changes of increased intensity and adoptability for the net-zero transition goals.

Despite the rich representation of lifestyle change impacts in the modelled scenarios, our approach has some limitations. First, with the exception of building renovation in PRIMES-BuiMo, lifestyle changes are represented in our models in an exogenous manner; a common feature of ESM/IAM-based approaches (Andreou *et al.*, 2022; Krumm, Süsser and Blechinger, 2022). As a result, a comprehensive analysis of the implementation barriers, enabling factors and policy costs incurred by lifestyle transitions was not performed. Second, due to the unavailability of information on heterogeneous energy preferences, the scenarios have applied a uniform change in lifestyles across household groups. Not comprehensively representing actor heterogeneity does not allow studying the varying responses of consumer types to policies targeting lifestyle changes (Keppo *et al.*, 2021). Third, despite our effort to validate our scenario assumptions about lifestyle changes through reviews and expert insights, the real extent to which such demand-side transitions can happen has remained outside the scope of this study.

Future work could focus in endogenising lifestyles in large-scale IAM/ESM models and representing the heterogeneity of energy preferences between diverse consumer groups. For buildings, research could focus on the drivers and more importantly the psychological and infrastructural barriers of behavioural shifts with a high mitigation potential, such as reducing average living space size (Huebner and Shipworth, 2017) or changing the thermostat set-point. A promising approach is the linking of IAMs/ESMs with tools grounded on rich empirical data on energy use behaviours, such as statistical lifestyle modules (Pettifor *et al.*,

2024) and agent-based models (Niamir, Ivanova and Filatova, 2020; Niamir, Mastrucci and van Ruijven, 2024). A linkage with an agent-based model can in particular aid in capturing complex social dynamics, such as lifestyle changes, as they have rich representation of heterogeneous actor characteristics and can simulate social interaction and learning effectively.

Moreover, the scope could be broadened to include other domains with a large carbon footprint and high sensitivity to behavioural change such as mobility, diet and consumer goods (Grubler *et al.*, 2018; Ivanova *et al.*, 2020). Systemic analysis -using full-system IAMs- can also provide a more holistic representation of lifestyle change impacts on the energy system, including energy supply, but also in land-uses and in the broader economy and society. Testing the generalisation of findings could involve expanding the geographical scope to encompass other regions, including other developed or less-developed economies (van den Berg *et al.*, 2021).

3.5. Conclusions

Achieving the ambitious decarbonisation targets set by the PA requires significant efforts on the supply and demand side of energy-economy systems. Unlike supply-side solutions, demand-side actions have not been explored extensively in ESM- and IAM-based studies, thus less is known about the drivers, impacts and mitigation potential of lifestyle changes in end-use sectors. This study aims to improve the representation of behavioural change in the mathematical framework of two sectoral models for buildings (PRIMES-BuiMo and EDGE-Buildings), by focusing on a more accurate split of residential energy demand to specific end-uses and disaggregation of the behavioural and non-behavioural factors driving useful energy demand. The improved sectoral models are used to devise scenarios for the evolution of energy use, CO₂ emissions and consumer expenditure in the European residential sector, under varying assumptions about the strength of climate policy targets and the adoption of lifestyle changes. The multi-model analysis of lifestyle change impacts showcases the level of uncertainty governing the development of low energy demand pathways and the need for employing diverse modelling tools to perform similar assessments capturing a range of the associated uncertainty.

Our study, building on improved methodologies in sectoral models, demonstrates the important role of lifestyle changes as a potential complementary driver to climate policies for achieving low-carbon transitions, by contributing not only to additional energy and CO₂ savings but also to important cost reductions for residential consumers. This highlights that policies need to incorporate characteristics of low energy demand transitions, while addressing the drivers, costs, and barriers of ambitious lifestyle changes. Future work could focus on internalising some of these elements in the modelling frameworks of ESMs and IAMs.

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[1] https://ec.europa.eu/eurostat/databrowser/view/PROJ_STP22/default/table?lang=en&category=proj_proj_19n

[2] <https://www.climate-campaigners.com/>

[3] Avoid actions involve a reduction in the overall level of an energy service, while shift ones require a transition to a more environmentally-friendly behaviour. Improve actions mainly consist of opting for more efficient technological options.

[4] <https://www.navigate-h2020.eu/>

[5] <https://multifutures.eu/>

[6] <https://www.net0prisma.eu/>

[7] PRIMES-Builmo categorises appliances based on their efficiency as ordinary, improved, advanced and future, where learning by doing factors apply on technological development.

[8] In this study reduced fuel expenses are only the result of lower energy demand due to lifestyle changes in the residential sector. Potential secondary impacts on end-use fuel prices or private consumption of households from declining energy demand are not considered here, as this would require the use of full energy-system and economy-wide modelling tools.

[9] This estimate covers all GHG emissions instead.



4. Feasibility of short-term methane mitigation

Research report

Authors: Mathijs Harmsen (PBL), Mark Roelfsema (PBL)

More than a third of present-day global warming is caused by methane emissions (Smith and Gasser, 2022), both directly, through methane-induced radiative forcing, and indirectly, through additional forming of tropospheric ozone, another potent greenhouse gas. Ambitious short-term mitigation can also rapidly limit near-term warming, due to its short atmospheric lifetime (+/- 12 years), meaning that atmospheric concentrations strongly depend on emissions, rather than cumulative emissions (as in the case of CO₂). This adds importance to the accuracy of the short-term representation of methane emissions. Anthropogenic methane emissions have been steadily increasing in the last decades to 320-366 Mt CH₄ / year in 2022 (Crippa et al., 2024; Hoesly et al., 2025), and by 3.5 % between 2020 and 2023. These emissions are expected to continuously rise with current existing national policies (Dafnomilis et al., 2023; Roelfsema et al., in prep.). Atmospheric concentrations have followed suit, with a 17% increase over the past four decades (NOAA, 2025), further increased by positive feedbacks of global warming on the atmospheric lifetime of methane and wetland methane emissions (Yuan et al., 2024), implying that additional mitigation is needed to achieve a certain low methane concentration (and radiative forcing) target.

The main effort to curb global methane emissions is the Global Methane Pledge (GMP), which has been launched in November 2021 at COP26. The initiative is aimed at reducing global emissions by 30% in 2030, compared to 2020. Currently (May 2025), 160 countries have signed the GMP, covering 57 percent of global human emissions. Notably, China, Russia and India, the largest emitters, have not joined the GMP. As the GMP is framed as a global goal, this implies that participating countries (i.e. signatories) must go beyond a 30% reduction. China, Russia and India also lack quantitative methane emission targets in any federal policy, although China has pledged to increase its policy ambitions in the short term (presumably 5-10 years), as part of their methane action plan (MAP)⁶.

The GMP target can be considered highly ambitious, to the point of being hypothetical, for several reasons. 1) Model-based studies show it is difficult to reach even despite maximized policy efforts. 2) The target is set five years from now, while emissions have actually increased since 2020 (by an estimated 6%), instead of decreased and, most importantly, 3) there is no effective policy backing up the GMP.

⁶ See: <https://www.ccacoalition.org/resources/national-methane-action-plans>

In an analysis with the IMAGE (3.2) model, as part of the NAVIGATE project, it was found that the GMP can only just be reached in a low emissions scenario (SSP1), with additional lowered meat-based human diets, full global participation, optimistic technical potential and maximum reduction in all sectors (NAVIGATE, 2023). All of these preconditions are currently not in place. In a current study, also using the IMAGE model (the most recent 3.4 version) (Roelfsema et al., in prep.), a similar conclusion is reached. Here, methane reduction from a successfully executed GMP is compared to a current policies reference case, and 1.5° and 2° climate policy scenarios (see Figure 4.1). Reductions in the GMP are shown to go far below the reductions in the highly ambitious 1.5 ° scenario. In this study, scenarios exclude reductions achieved by a shift to more plant-based diets. In that situation, the GMP target can only be reached by assuming faster than normal developments in (“end-of-pipe” or emission intensity lowering) mitigation measures, with mitigation potentials normally assumed in 2040 already being achieved in 2030. This is in line with Malley et al. (2023) who argue that mitigation actions as pledged in the nationally determined contributions (NDCs) could achieve the global GMP goal, but only if measures go far beyond their current technical potential.

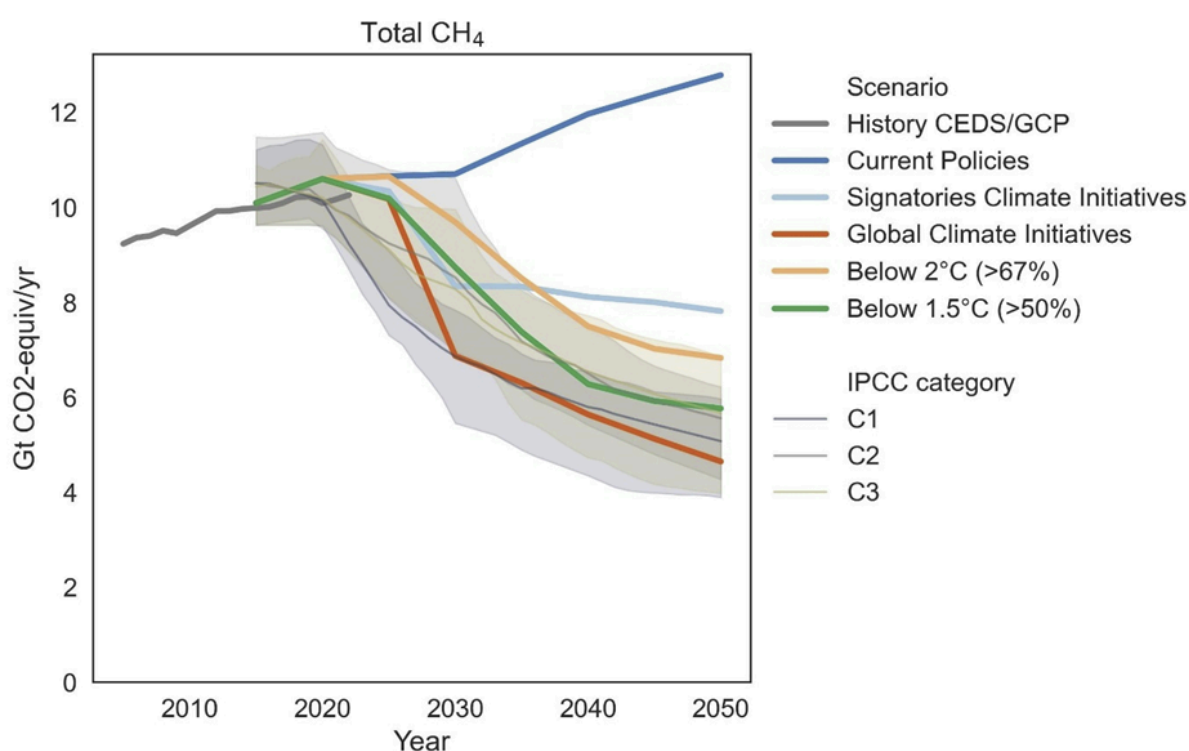


Figure 4.1 Methane mitigation in the global methane pledge. “Global climate initiatives” represents the GMP, “Signatories climate initiatives” represents a scenario where a 30% emission reduction is only realized in the participating countries. Methane reductions are compared to the IMAGE 3.4 default 1.5-degree and 2-degree scenarios (From: Roelfsema et al., (in prep))

However, with no substantial policy currently in place to support the GMP, the global goal can only be considered motivational. National MAPs and NDCs are found to have very few quantitative targets or timelines; an estimated 3%-7%-points of the GMP's 30% reduction target is backed in national plans. There is little (<30%) focus on agriculture, which generally forms the largest bottleneck. Moreover, NDCs and MAPs almost universally lack any mentioning of regulatory frameworks or financial incentives, making it unlikely that the combined global reduction following from the quantitative targets is achieved. For IAMs, this implies that any scenario that goes beyond the 2030 GMP target should be deemed highly unlikely, and only highly ambitious scenarios should come close. In addition, emission source-specific projections should not go beyond what is technically possible. Harmsen et al. (2023) have systematically assessed the reduction potential of non-CO₂ GHGs by source, based on a comprehensive literature study of mitigation case and meta studies. They provided a range in mitigation potentials and costs, in the form of "optimistic, default and pessimistic" marginal abatement cost (MAC) curves. Table 4.1 shows maximum reductions in 2030, 2050 and 2100 (as relative reductions in emission intensities compared to the global average in 2015). The optimistic values can be considered the technical limit and should not be exceeded, especially not in a lower ambition scenario. Relative reductions of methane emissions can in some cases be larger, when the emitting activities are also lowered (e.g. when fossil fuels meat products are reduced).

Table 4.1 Source-specific CH₄ maximum reduction potentials (MRP) in 2030, 2050 and 2100. Derived from Harmsen et al. (2023). Values represent the maximum relative reductions in emission intensities compared to source-specific global mean averages in 2015. Coal, oil and gas mitigation is based on Höglund-Isaksson et al., 2020, without mitigation ranges. Values represent the average across IMAGE regions.

Emission source	MRP in 2030 (%)			MRP in 2050 (%)			MRP in 2100 (%)		
	Pessimistic	Default	Optimistic	Pessimistic	Default	Optimistic	Pessimistic	Default	Optimistic
Coal	-	42	-	-	57	-	54	79	84
Oil	-	65	-	-	85	-	82	90	95
Gas	-	48	-	-	66	-	54	80	85
Landfills	51	58	63	51	61	66	69	79	90
Wastewater	18	24	30	30	50	67	49	59	90
Rice	15	44	55	41	59	78	58	71	83
Enteric fermentation	4	9	29	11	22	47	21	32	56
Manure	6	18	32	17	33	50	54	79	84

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5. Economic structural change and sector transition – the case of implementation of CCS in Poland

Research report

Authors: Maciej Bukowski (WiseEuropa)

Introduction

Climate change represents one of the most pressing global challenges of the 21st century, necessitating a coordinated international response. The cornerstone of current global climate governance is the 2015 Paris Agreement, in which signatory nations committed to limiting the increase in global average temperature to well below 2°C above pre-industrial levels, with efforts to cap the rise at 1.5°C. Achieving these targets requires a rapid and comprehensive reduction of greenhouse gas emissions across all sectors and regions of the world economy—not only in the power generation sector, but also in transport, agriculture, and industrial processing.

In this context, carbon capture, utilization, and storage (CCUS) technologies are increasingly recognized as critical instruments for enabling deep decarbonization, particularly in hard-to-abate sectors. The Intergovernmental Panel on Climate Change (IPCC) has identified CCUS as one of the essential mitigation tools for industries that are difficult to electrify, such as cement, steel, and chemical manufacturing.

Forecasts by the International Energy Agency (IEA) underscore the indispensability of CCUS technologies in the transition to global net zero emissions. Specifically, CCUS is projected to contribute up to 60% of the necessary emission reductions in cement production and approximately one-third in the steel and chemical sectors. The IEA emphasizes that, in these sectors, CCUS represents the only currently viable technological pathway to achieving substantial emission reductions at scale. Furthermore, CCUS remains the primary technological route to generating negative emissions—whether through direct air capture (DAC) or bioenergy with carbon capture and storage (BECCUS)—given the limited absorption potential of nature-based solutions such as afforestation. CCUS technologies are also instrumental in enabling low-carbon hydrogen production; notably, "blue hydrogen" (derived from steam methane reforming of natural gas with CO₂ capture) is expected to remain the most cost-effective production method by 2050, accounting for an estimated 40% of global hydrogen output.

At the European level, the strategic importance of CCUS for decarbonizing emissions-intensive sectors has been explicitly acknowledged. In 2023, the European



Commission released its "Industrial Carbon Management" communication—informally referred to as the EU CCUS Strategy—which sets an objective of achieving at least 50 million tonnes of annual CO₂ injection capacity within the EU by 2030. This initiative is underpinned by regulatory frameworks such as the Net-Zero Industry Act, which mandates member states to streamline permitting processes and obliges designated stakeholders to participate in infrastructure development. A key advantage of CCUS lies in the potential for economies of scale: shared infrastructure, including pipelines and storage hubs, can serve multiple emitters. Moreover, CCUS facilitates the reuse of captured CO₂ as an industrial input for producing fuels, chemicals, and construction materials, thus integrating circular economy principles into decarbonization strategies.

For Poland, one of the European Union's most coal-dependent economies, the transition to a low-carbon development path presents particular challenges. National energy strategies over the past decade have predominantly focused on the power sector, where the deployment of CCUS is not strictly necessary due to the availability of cost-effective zero-emission alternatives such as wind, solar, and nuclear energy. However, recent policy shifts indicate a growing recognition of the role of CCUS in Poland's decarbonization portfolio. In 2023, amendments to the Geological and Mining Law simplified licensing procedures and allowed CO₂ storage from industrial facilities emitting more than 100,000 tonnes annually. Furthermore, CCUS has been incorporated into strategic planning documents such as the Polish Energy Policy to 2040 and the National Recovery and Resilience Plan, which allocates funding for CCUS cluster development.

Nevertheless, while Poland's energy transition planning has increasingly accommodated CCUS in the energy sector, it remains comparatively underdeveloped in addressing industrial decarbonization. Policy documents such as the National Energy and Climate Plan and the Polish Energy Policy offer limited detail on reducing process emissions from mineral processing, iron and steel production, and the oil and gas sectors. In particular, current analyses have largely avoided quantifying the marginal abatement costs or broader macroeconomic implications associated with CCUS deployment in these industries. As such, a rigorous economic assessment of CCUS in non-energy sectors remains a critical gap in Poland's climate policy framework.

This article addresses these limitations by presenting a quantitative analysis of three scenarios for CO₂ capture and storage in Poland. In the following sections, we discuss: 1) the adopted modeling strategy, 2) the assumptions of the analyzed CCS scenarios, 3) the assumptions behind the reference scenario to which we compare the results, 4) the simulation results (analysis of the impact of CCS introduction on the economy), and 5) Summary and conclusions.



Modeling Approach

The analytical framework employed in this study integrates two complementary modeling tools: the ESM_PL energy system model and the VESPA macroeconomic model. ESM_PL belongs to the TIMES family of partial equilibrium energy models, while VESPA is a large-scale dynamic stochastic general equilibrium (DSGE) model tailored to the Polish economy.

The ESM_PL model includes a portfolio of carbon capture and storage (CCS) technologies applicable in the electricity generation, industrial, and fuel production sectors. The model architecture allows for the specification of annual and cumulative CO₂ storage capacity constraints, enabling flexible scenario design. In addition to storage, the model accommodates pathways for CO₂ utilization—such as synthetic fuel production, including methanol and diesel—offering insight into the techno-economic potential of carbon valorization. Outputs from ESM_PL, following appropriate aggregation and harmonization, serve as inputs into the VESPA model. VESPA features a detailed sectoral decomposition of the economy, including an explicitly modeled energy sector and, for the purpose of this study, an endogenously integrated CCS sector. This sector is conceptualized as a distinct industry engaged in the provision of carbon capture, transport, and storage services. Firms in other sectors—particularly energy and industry—can reduce their expenditure on emission allowances by selling CO₂ to CCS providers at negative prices. In turn, CCS firms invest in physical capital and labor to deliver these services. The CCS module in VESPA is calibrated based on technology cost and deployment data from the ESM_PL model, ensuring internal consistency across the two modeling layers. The combined system is solved under four distinct scenarios: a business-as-usual (BAU) reference scenario, and three policy scenarios with varying levels of CCS technology diffusion—CCS_MIN, CCS_MED, and CCS_MAX.

The scenarios are differentiated by the extent of CCS availability to domestic actors. In the BAU scenario, CCS technologies are assumed to be entirely unavailable, prompting the energy system to optimize using only non-CCS mitigation options—such as renewable energy sources, improvements in energy efficiency, nuclear deployment, or demand-side adjustments in response to carbon pricing. The BAU case thus serves as a counterfactual benchmark, simulating a path in which Poland diverges from broader European CCS development trajectories while remaining subject to the same EU-wide carbon pricing regime. This scenario captures the economic costs associated with such divergence, particularly in sectors with limited abatement alternatives. By contrast, the CCS_MIN, CCS_MED, and CCS_MAX scenarios allow for progressively greater deployment of CCS technologies, subject to sector-specific limitations on capture and storage capacity. These scenarios explore the macroeconomic and structural implications of various degrees of CCS integration, including potential effects on industrial competitiveness, investment patterns, and carbon cost exposure.

Scenarios for CO₂ Capture and Sequestration in Poland

Poland possesses some of the most favorable geological conditions for carbon dioxide (CO₂) sequestration within the European Union. These conditions are primarily due to the widespread availability of deep saline aquifers across the country, supplemented by the presence of depleted hydrocarbon reservoirs. According to current assessments, Poland's total theoretical CO₂ storage capacity is estimated at approximately 10 to 15 gigatonnes (Gt), with the Polish Lowland Basin alone accounting for an estimated 6 to 7 Gt. A more conservative estimate of *practical* storage capacity—accounting for technological, regulatory, and economic constraints—suggests a range of 7 to 9 Gt. Additionally, the Baltic Sea region represents a potentially significant but largely untapped resource, with its utilization constrained by environmental, legal, political, and logistical factors.

For the purpose of the present simulation exercise, the modeling framework assumes that annual CO₂ capture in Poland does not exceed 70 million tonnes (Mt) over the forecast horizon. Attaining this capture rate is projected to take approximately 15 years, reflecting the lead time required to mobilize the necessary capital investments and develop supporting infrastructure. At this maximum annual capture rate, Poland could theoretically deploy CCS technologies for 150 years, sufficient to abate the entirety of current industrial emissions and roughly 20% of emissions from the power sector.

In the short to medium term, offshore storage in Norwegian formations offers a viable complementary pathway. The *ECO2CEE* project—developed jointly by PKN Orlen, Lafarge, and Air Liquide—aims to construct a CO₂ import-export terminal in Gdańsk, along with a dedicated transport network capable of handling up to 9 Mt of CO₂ annually. Lithuania has also expressed interest in utilizing this infrastructure, further reinforcing its regional significance.

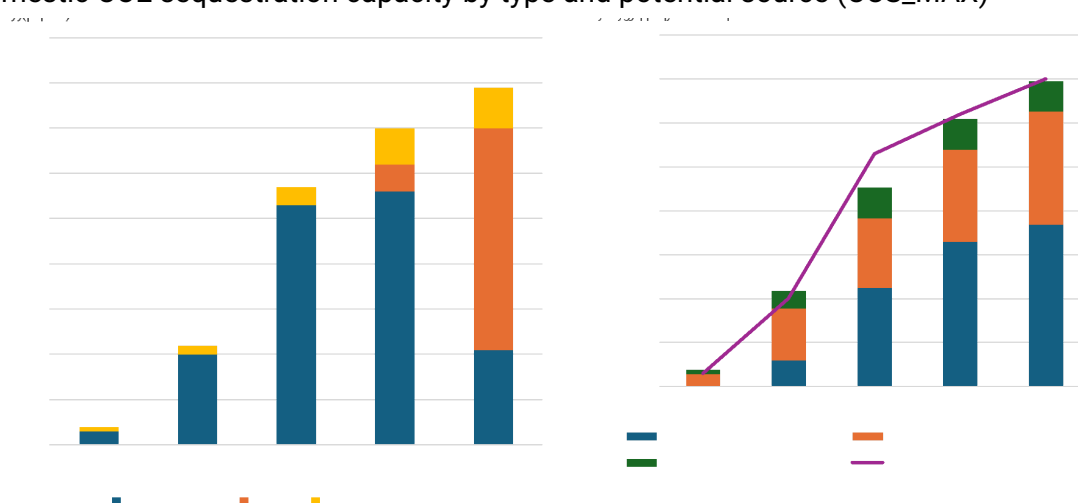
An important transitional advantage for Poland lies in the ability to rely on depleted hydrocarbon deposits for domestic CO₂ storage until approximately 2045. These formations entail significantly lower infrastructure costs relative to saline aquifers, which require more complex site development and regulatory clearance. The phased development strategy envisioned in the model reflects this reality: early-stage storage leverages hydrocarbon deposits, with brine formations gradually taking over as the primary storage medium after the mid-2040s.

From an economic standpoint, domestic storage offers the additional benefit of retaining value creation within national borders, reducing reliance on foreign sequestration services and potentially fostering the growth of a domestic CCS service industry. While CO₂ export to Norway remains a cost-effective option in the near term, its role is expected to diminish over

time, serving mainly as a strategic buffer or interim solution during the domestic infrastructure build-out phase.

Simulation results for the maximum CCS deployment scenario (CCS_MAX) indicate a sectoral concentration of installations in power and combined heat and power (CHP) plants, as well as in the cement and fuel refining industries. These sectors collectively represent the largest point sources of emissions in the Polish economy and are thus natural candidates for early CCS deployment. Investment outlays for developing successive storage formations are modeled as phased expenditures, aligned with the gradual transition from hydrocarbon-based to saline-based sequestration systems.

Domestic CO₂ sequestration capacity by type and potential source (CCS_MAX)



CCS Capture Scenarios

The modeling framework incorporates three distinct carbon capture and storage (CCS) deployment scenarios, differentiated endogenously by the interaction of carbon pricing signals and sector-specific availability constraints. These scenarios reflect varying levels of technological diffusion and regulatory ambition, allowing for the analysis of heterogeneous policy pathways and their economic implications.

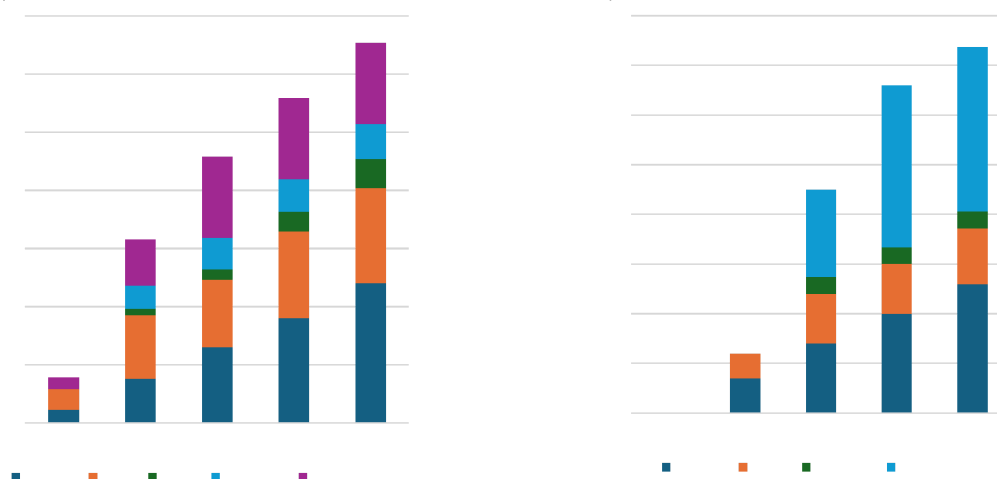
1. **Maximum CCS Deployment (CCS_MAX):** In this scenario, CO₂ capture technologies are made available across a broad range of sectors, encompassing both industry—including cement, steel, chemical processing, glass manufacturing, and hydrogen production—and the energy sector, specifically coal-fired power plants, natural gas units, and combined heat and power (CHP) installations. The carbon price is calibrated to incentivize widespread adoption of CCS technologies, resulting in a

high degree of sectoral coverage. Notably, this scenario allows for the retrofitting of several coal-fired units commissioned around 2010, thereby reflecting a policy trajectory that maintains these relatively modern assets within the power system. This aligns with the 2021 *Social Agreement on the Transformation of the Hard Coal Mining and Power Sector*, which envisions the phaseout of coal generation by 2049.

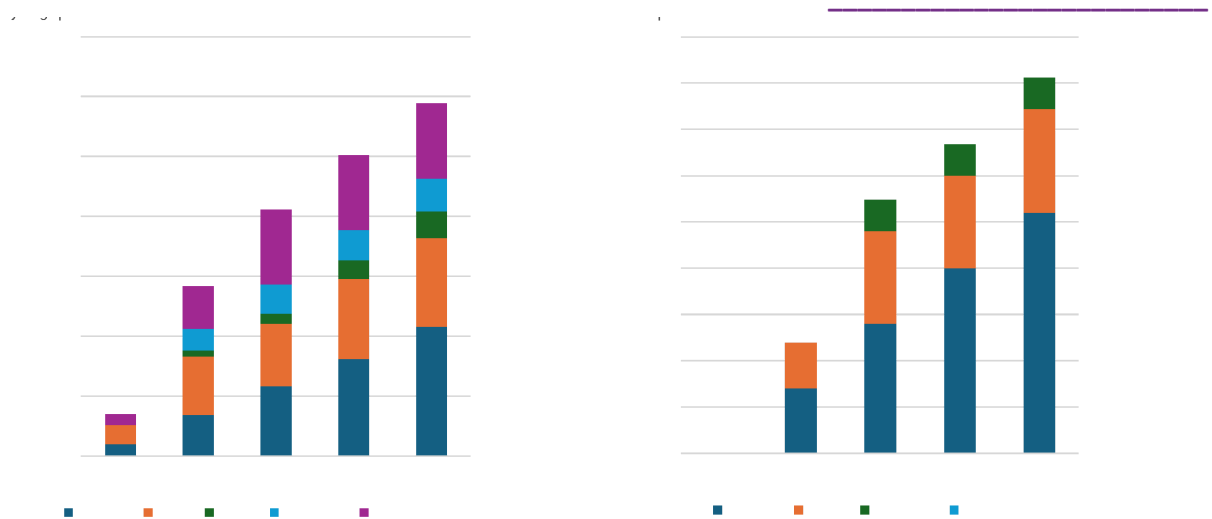
2. **Intermediate CCS Deployment (CCS_MED):** The medium scenario permits CO₂ capture in industrial sectors similarly to CCS_MAX, but constrains CCS deployment in the energy sector to natural gas-fired facilities. Specifically, this includes both professional and industrial CHP plants, as well as combined cycle gas turbines (CCGTs). This scenario reflects a transitional strategy that limits investment in long-lived CCS infrastructure for coal assets, potentially in response to political or financial risk associated with coal phaseout commitments.
3. **Minimal CCS Deployment (CCS_MIN):** The minimum deployment scenario restricts CCS technologies to gas-fired CHP plants and selected processing industry segments, excluding iron and steel. In these excluded sectors, electrification or the deployment of hydrogen-based furnaces is assumed to substitute for CCS, consistent with decarbonization pathways emphasizing fuel switching over post-combustion capture. This scenario reflects a highly constrained view of CCS potential, either due to cost barriers, public acceptance, or institutional inertia.

A detailed sector-by-sector breakdown of CO₂ capture across the industrial and energy domains is provided in the following section. This disaggregation enables a more nuanced interpretation of technology adoption patterns, investment dynamics, and sector-specific mitigation costs under each scenario.

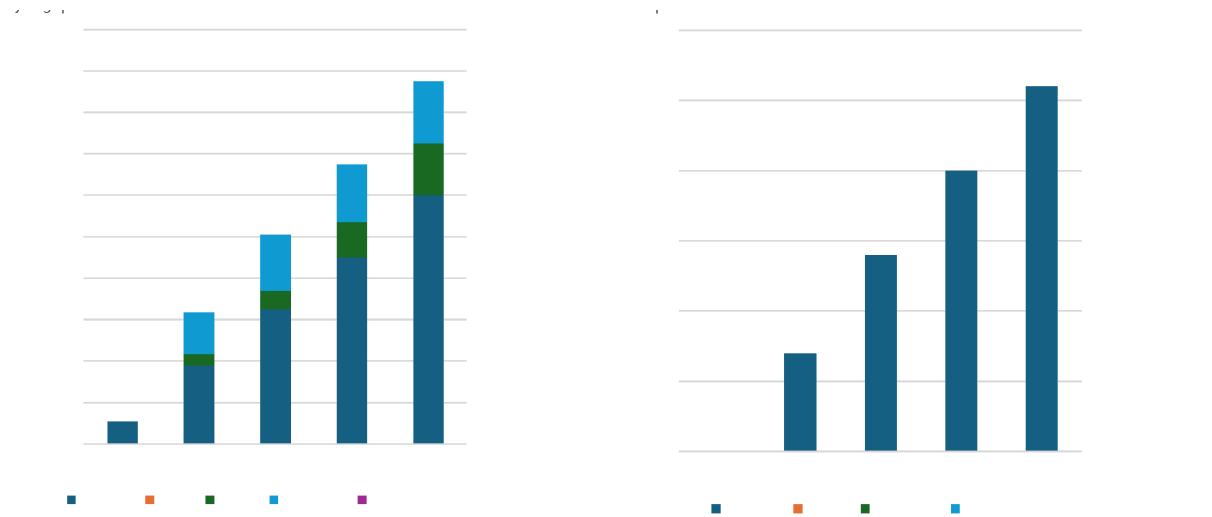
CO₂ captured by industrial and Energy subsector (CCS MAX)



CO₂ captured by industrial and Energy subsector (CCS MED)



CO2 captured by industrial and Energy subsector (CCS MIN)



Reference Scenario and CCS Counterfactuals

The analysis contrasts three CCS deployment scenarios with a reference (business-as-usual, BAU) scenario, constructed to align as closely as possible with the assumptions and trajectories outlined in the most recent draft of Poland's *National Energy and Climate Plan* (*Krajowy Plan na rzecz Energii i Klimatu*, KPEiK 2025).

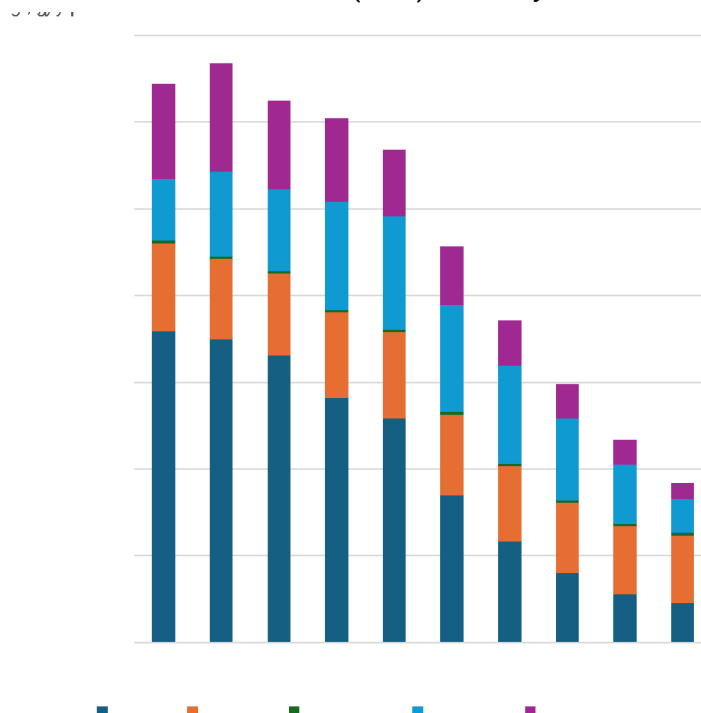
In line with the KPEiK framework, the BAU scenario assumes a significant acceleration in the pace of decarbonization after 2025, driven by an economy-wide electrification process encompassing residential and district heating, transportation, and industrial energy use. As a result, total electricity production is assumed to approximately double by mid-century. The decarbonization of the power sector proceeds through a substantial structural transformation, with hard coal and lignite gradually phased out and replaced by renewable energy sources—primarily wind, solar, and biomass. After 2035, nuclear power and grid-scale energy storage technologies are introduced to ensure system stability and meet peak demand.

Importantly, the BAU scenario does not permit the deployment of carbon capture and storage (CCS) technologies in any sector. Consequently, process-related emissions in industry must be reduced either through low-carbon substitutes (where feasible) or via contraction of economic activity. In sectors where alternative abatement pathways are limited or prohibitively expensive, this results in constrained production potential.

By 2050, the BAU scenario forecasts an approximately 80% reduction in national CO₂ emissions relative to current levels. The bulk of these reductions originate in the energy sector, where Poland's historically carbon-intensive generation mix presents substantial mitigation opportunities. Significant emissions abatement also occurs in transport, primarily due to the post-2030 replacement of internal combustion engine vehicles with electric alternatives. Emissions in the heating sector decline as fossil-fuel-based systems are replaced with electric or renewable heat sources.

However, in the industrial sector, emissions remain comparatively persistent. In the absence of CCS technologies, few cost-effective decarbonization options are available for process emissions in cement, chemicals, and other heavy industries. As a result, industry achieves the smallest relative reduction in emissions among all sectors, underscoring the strategic role of CCS in enabling deeper and more balanced economy-wide decarbonization.

Reference scenario (BAU) –CO₂ by sector.



In the reference (BAU) scenario, the long-term configuration of Poland's power system evolves toward near-complete reliance on zero-emission generation technologies. Renewable energy sources (RES) constitute the backbone of the future energy mix, with total installed capacity projected to increase by more than 250% between 2025 and 2050. The dominant generation technologies include onshore and offshore wind farms as well as photovoltaic systems. In parallel, nuclear power plants are anticipated to be commissioned before 2050, providing an estimated 20–25% of national electricity demand and offering dispatchable baseload capacity to complement variable RES.

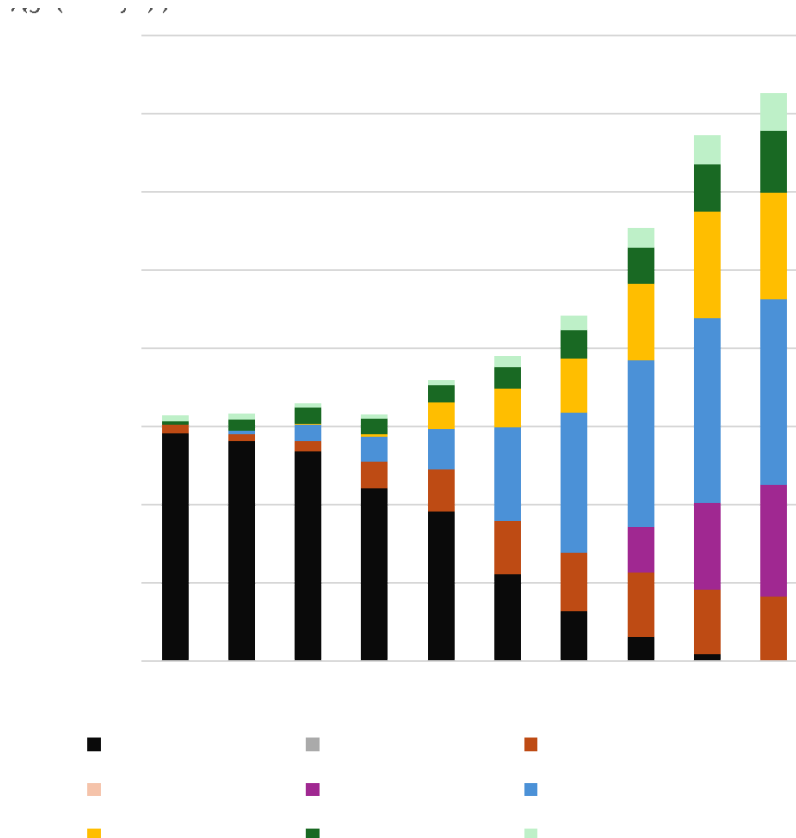
A core structural shift occurs in the progressive phaseout of coal from the electricity sector. Lignite-fired power generation is projected to decline from several tens of terawatt-hours (TWh) in 2025 to zero by 2040. The withdrawal from hard coal proceeds more gradually, with residual generation of approximately 15 TWh expected in 2040, primarily from a diminishing fleet of existing coal-fired units.

To support system flexibility and ensure reliable supply amid the growing share of intermittent renewables, the model incorporates natural gas-fired generation. Gas turbines are deployed for both peak balancing and combined heat and power (CHP) applications. In particular, gas-fired CHP remains integral to urban energy systems, especially in large and medium-sized cities with extensive district heating infrastructure. These areas are assumed

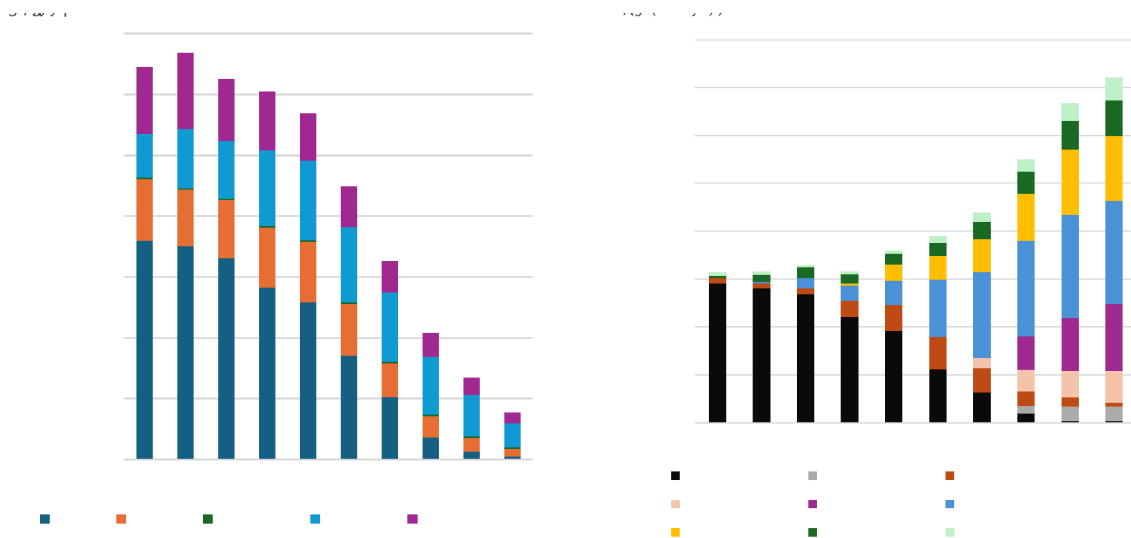
to continue receiving policy support for high-efficiency cogeneration investments well into the 2050 horizon. In contrast, smaller district heating networks are primarily supplied by biomass-fueled systems, while larger networks are served by gas-based cogeneration.

To mitigate the variability of renewable generation and reduce dependence on fossil-fueled backup capacity, energy storage systems play an expanding role. The installed capacity of storage technologies—including battery storage and pumped-storage hydropower—is projected to increase from 5.5 GW in 2030 to several gigawatts by 2050, enabling better load shifting and peak shaving. This scaling up of storage infrastructure reduces the system’s reliance on maintaining large reserves of flexible gas capacity and contributes to overall system decarbonization.

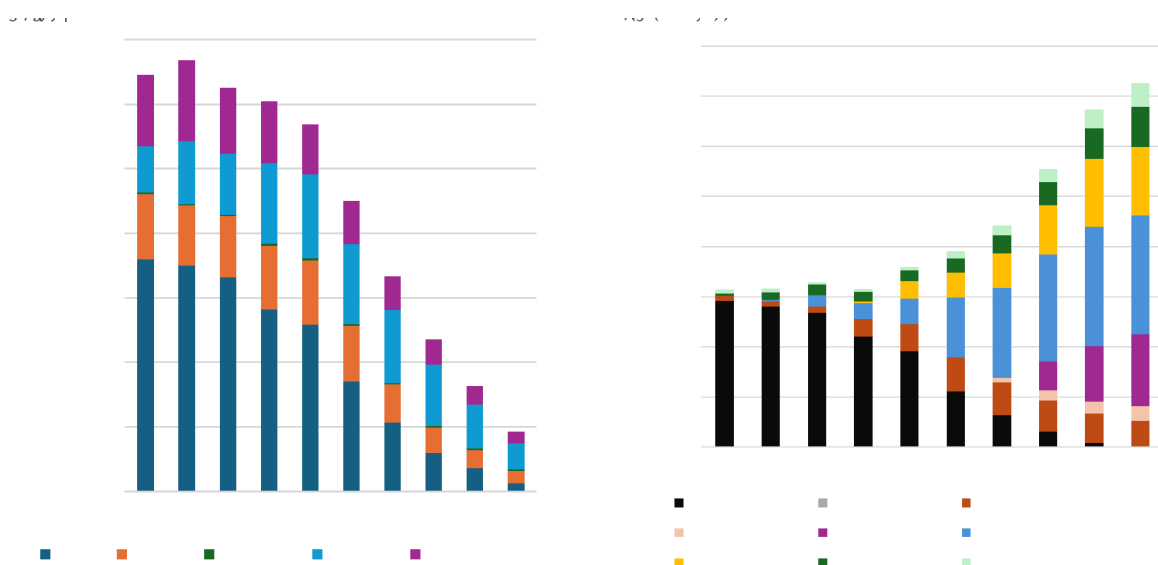
Reference scenario (BAU) – electricity generation by technology type



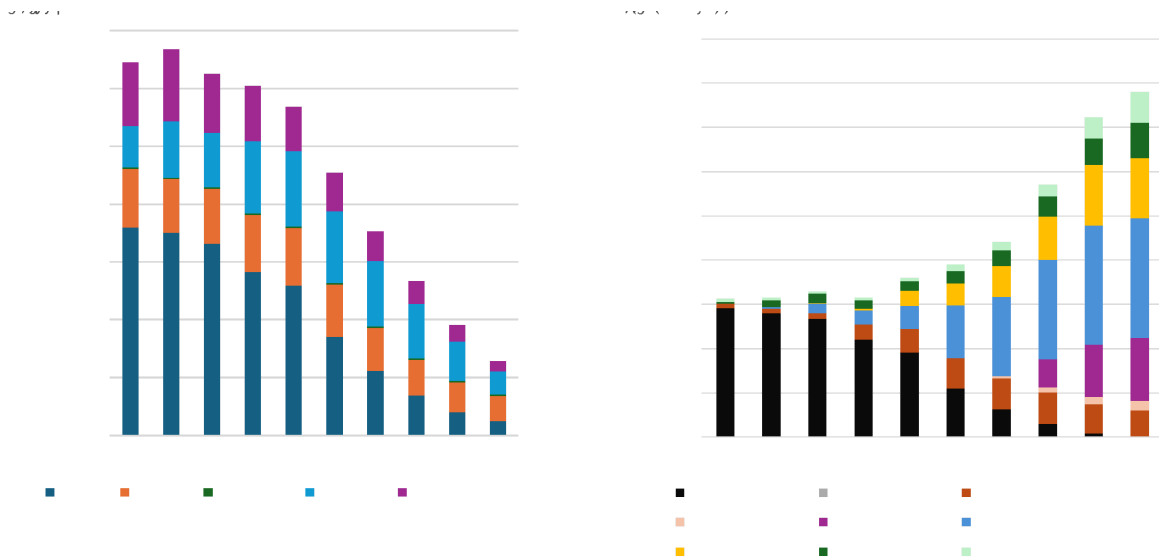
CO2 and electricity generation by sector and technology (CCS MAX)



CO2 and electricity generation by sector and technology (CCS MED)



CO2 and electricity generation by sector and technology (CCS MIN)



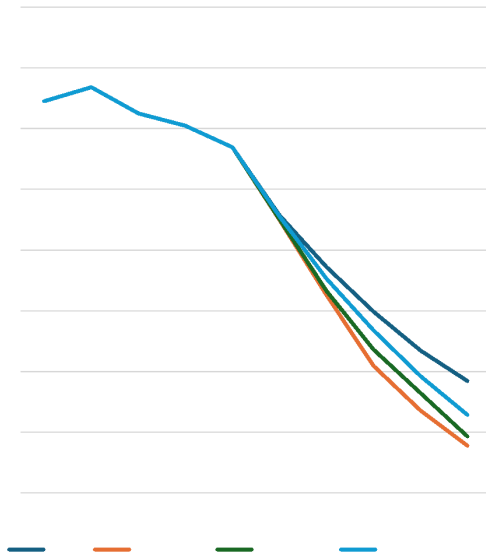
Macroeconomic Impacts of CCS Deployment

All modeled CCS deployment scenarios yield a positive macroeconomic impact relative to the reference (BAU) scenario, while simultaneously enhancing climate mitigation outcomes. By 2050, annual CO₂ emissions are further reduced by approximately 25 to 50 million tonnes (Mt) beyond the reductions achieved under BAU. This enables the CCS_MAX and CCS_MED scenarios to reach an emissions reduction of around 90% relative to 1990 levels, albeit with a roughly 10-year delay compared to the EU-wide net-zero strategy. This delay is consistent with Poland's relatively unfavorable baseline conditions in 2025, characterized by a carbon-intensive energy system and high industrial emissions.

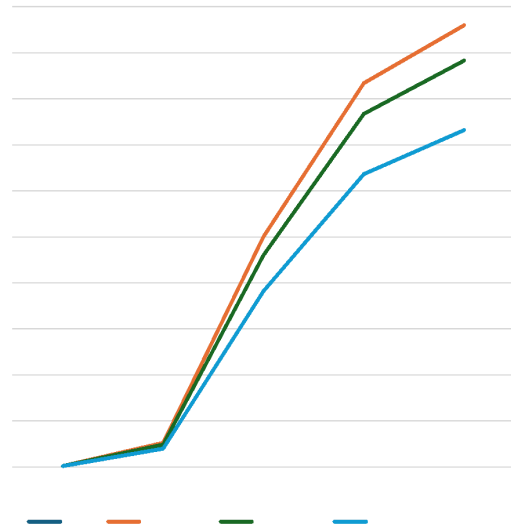
Importantly, the depth of additional emission reductions is negatively correlated with GDP impact—a result stemming from the role of CCS in preserving industrial activity. In the BAU scenario, many energy- and emissions-intensive production processes become economically non-viable due to high carbon prices and the absence of technological alternatives. By contrast, CCS deployment allows these sectors to maintain output, mitigating the contractionary effects associated with unaddressed process emissions.

In scenarios where CCS is more widely available (especially CCS_MAX), CO₂ prices required to meet climate targets are lower, which further reduces compliance costs across the economy and stimulates broad-based economic activity. As a result, GDP, consumption, exports, employment, and wages all exhibit higher trajectories relative to the BAU path. In the long term, value added growth is driven on the demand side by rising investment and export volumes, and on the supply side by increased employment and, more gradually, capital accumulation induced by sustained investment activity.

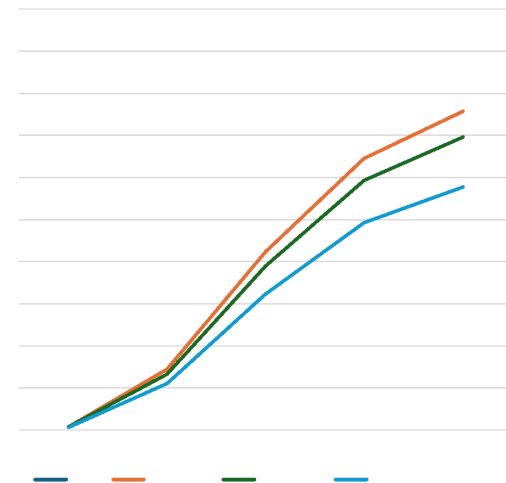
CO2



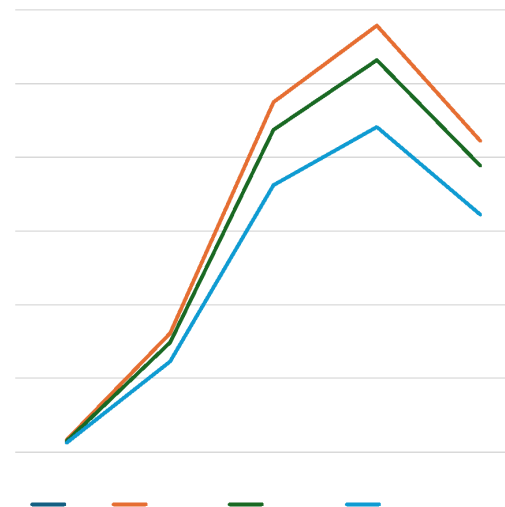
GDP



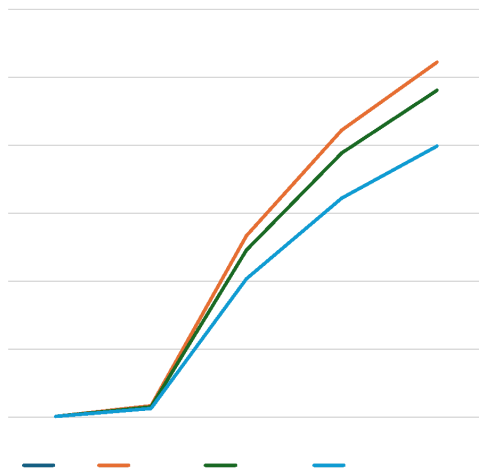
Consumption



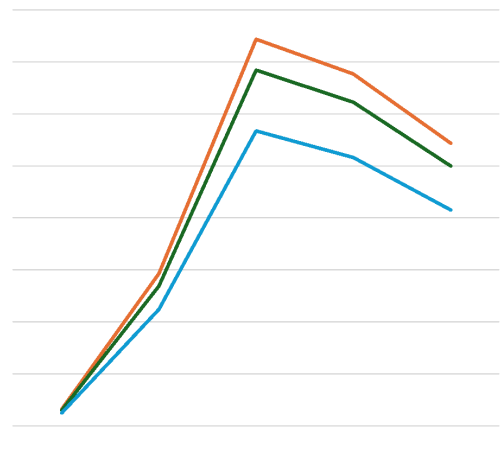
Investment



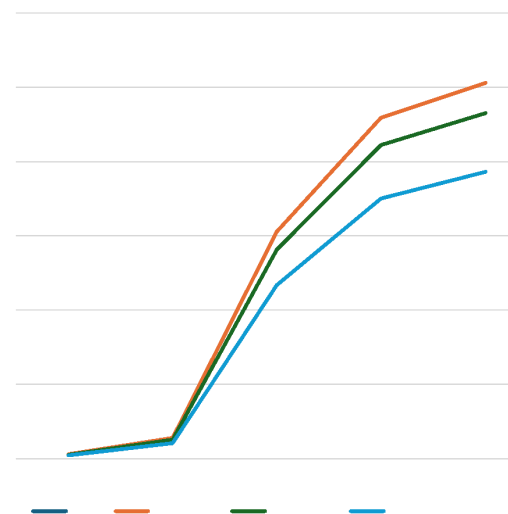
Export



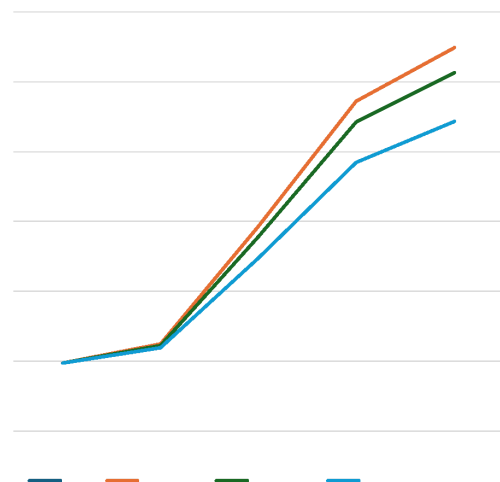
Import



Employment



Wage



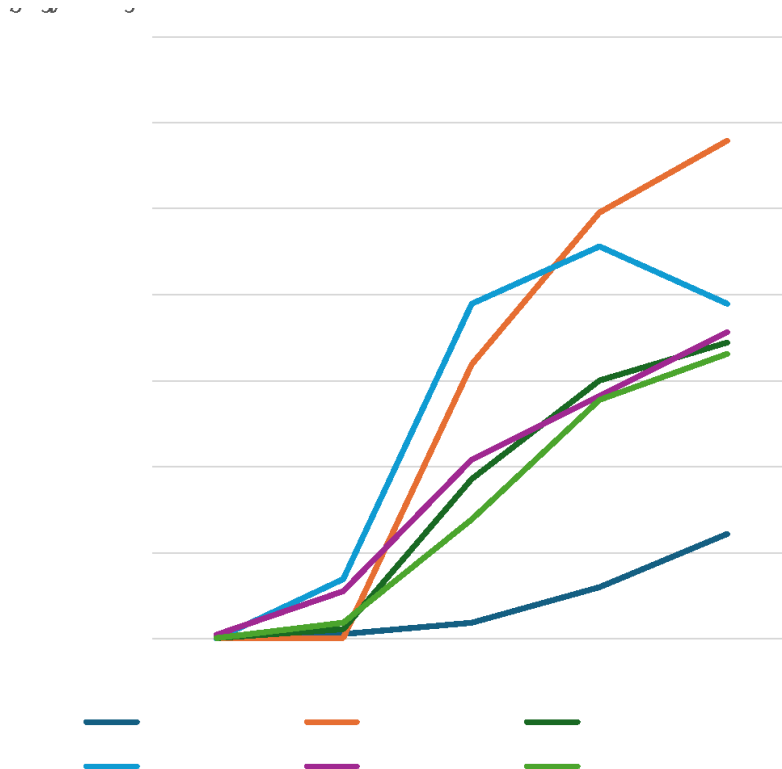
Export performance is particularly strong under CCS scenarios, reflecting improved terms of trade relative to BAU. These gains are attributed to multiple channels: (i) higher productivity, (ii) lower product prices due to reduced or eliminated costs from emission allowance pass-through, and (iii) avoidance of production offshoring. In CCS-covered industries, the ability to decouple production from CO₂ emissions stabilizes cost structures and improves international competitiveness. At the same time, imports increase significantly in the early years, driven by the high import intensity of CCS-related investment. Poland's industrial expansion—while robust in terms of domestic output—remains reliant on imported equipment, machinery, and construction materials. Over time, however, the import share declines, as initial capital expenditures taper and domestic value-added rises in response to increased capacity utilization and endogenous supply chain development.

Modeling results indicate that the deployment of carbon capture and storage (CCS) in the energy sector is economically viable and yields net positive effects for the national economy. This conclusion holds for both the CCS_MAX scenario, which permits the continued operation of recently built coal-fired power plants with retrofitted capture technologies, and the CCS_MED scenario, in which CCS is restricted to gas-fired power plants and CHP installations. While the CCS_MAX scenario performs marginally better in macroeconomic terms, the differences between the two are relatively small. This suggests that the decision regarding the pace of coal phase-out, including whether to retain relatively modern coal units, may be more appropriately guided by social and political considerations rather than strictly economic ones.

In contrast, the industrial sector emerges as the primary long-term beneficiary of CCS deployment. This is especially evident in the cement industry, where output in 2050 under the CCS_MAX scenario is projected to be several percentage points higher than in the reference (BAU) scenario. These results align with expert consensus that cement production, due to the inherent difficulty of reducing process-related emissions, is a strong candidate for early and extensive CCS adoption. The steel sector also displays favorable investment signals under CCS scenarios, pointing to the viability of combining CCS with traditional production routes where electrification is less feasible. Additionally, the model highlights a notable role for CCS in supporting hydrogen market development. In particular, CCS enables the production of low-emission hydrogen from fossil fuels—so-called “blue hydrogen”—which can act as a transitional vector toward a green hydrogen economy. By lowering the carbon intensity of fossil-based hydrogen, CCS provides a pathway to stimulate demand, build market infrastructure, and smooth the eventual transition to electrolytic hydrogen produced from renewable electricity.

In sum, CCS offers differentiated benefits across sectors. While its role in the energy sector may be partly substitutable with other low-carbon technologies, in emissions-intensive industrial processes, CCS is not only cost-effective but often technologically irreplaceable in the medium term.

Impact of CCS on value added in selected sectors (CCS_MAX scenario)



Conclusions

This study presents a comprehensive quantitative assessment of the macroeconomic, energy system, and sectoral implications of carbon capture and storage (CCS) deployment in Poland, using a dual-model approach that links the ESM_PL energy model with the VESPA macroeconomic DSGE model. The analysis demonstrates that CCS technologies—when deployed in a targeted and phased manner—can play a pivotal role in Poland’s transition to a climate-neutral economy while delivering positive macroeconomic outcomes.

Across all CCS scenarios examined, we observe a significant reduction in CO₂ emissions beyond the reference (BAU) trajectory, with additional annual abatement of up to 50 Mt CO₂ by 2050. In the more ambitious CCS_MAX and CCS_MED scenarios, total emission reductions reach approximately 90% compared to 1990 levels—close to EU climate neutrality goals—albeit with a lag of about one decade due to Poland’s challenging initial conditions.

The macroeconomic benefits of CCS deployment are equally noteworthy. Unlike the BAU scenario, where high carbon prices force output contraction in emissions-intensive sectors, CCS enables these industries—particularly cement, steel, and chemicals—to remain economically viable while reducing their emissions intensity. This preservation of industrial activity results in higher GDP, employment, investment, and export growth relative to the no-CCS baseline. Moreover, by lowering the marginal CO₂ price required for compliance, CCS creates broader system-wide efficiency gains and enhances Poland’s terms of trade.

From a sectoral perspective, the analysis underscores the differentiated but complementary role of CCS. In the energy sector, CCS offers a transitional mechanism that can be rationally deployed on coal and gas infrastructure, although its long-term competitiveness may be challenged by renewables and nuclear energy. In contrast, in the industrial sector, CCS emerges as a uniquely viable decarbonization pathway for hard-to-abate process emissions, especially in cement and hydrogen production. These findings are consistent with broader international assessments emphasizing CCS as a critical enabler of deep decarbonization in heavy industry.

Importantly, the study highlights that the economic rationale for retaining modern coal-fired assets under CCS_MAX is only marginally stronger than that for shifting to gas-based CCS configurations in CCS_MED. This suggests that the choice between these paths should be primarily guided by political economy considerations, including regional employment impacts and public acceptance, rather than by strict efficiency criteria.

Finally, the results reinforce the strategic importance of domestic CO₂ storage infrastructure. With an estimated 7–9 Gt of practical storage capacity, Poland is well-positioned to internalize much of the CCS value chain, reduce dependency on foreign storage solutions,

and stimulate domestic technological development. However, realizing this potential will require sustained investment, regulatory clarity, and coordination across sectors and borders.

In conclusion, CCS is not a panacea, but it is an essential pillar of a credible, cost-effective, and socially balanced decarbonization strategy for Poland. Its integration into national planning should be guided by rigorous economic analysis, aligned with industrial and innovation policy, and embedded within a broader vision for climate resilience and technological sovereignty.



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