IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

D5.7 – Behaviour, social and disruptive innovation – Update

WP5 – Expanding – Resilient, inclusive, and sustainable recovery and development

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EC Summary Requirements

1. Changes with respect to the DoA

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

2. Dissemination and uptake

This report contributes to the project's evaluation of how various policy objectives influence mitigation pathways, in line with Task 5.4 – Disruptive Innovation in Models and Off-Model/Qualitative Socio-Technical Analyses and Task 5.5 – The Role of Behavioural Change and Social Innovation in the Transition, as outlined in the Grant Agreement. It also addresses key research questions identified during the second cycle of IAM COMPACT's Policy Response Mechanism that are of relevance to these two tasks. The findings aim to support stakeholders, including technical policymakers, industry representatives, and civil society actors, as well as researchers, by providing insights on policy-relevant issues. Parts of this work are intended for submission to peer-reviewed journals.

3. Short summary of results

Intended to reflect the IAM COMPACT project's research efforts in issues relating to behavioural, societal, and disruptive innovation, this deliverable first applies hindcasting using the D-EXPANSE model across 31 European countries, revealing that real-world electricity transitions deviate from cost-optimal scenarios by 44–60%, far exceeding the commonly assumed 10–20% slack in Modelling to Generate Alternatives, highlighting the need for empirically grounded, country-specific slack values. It then shows that incorporating geopolitical risks into the D-EXPANSE electricity system model improved hindcasting accuracy of the technology mix for many European countries—especially larger ones—by better reflecting real-world diversification toward renewables, though disentangling geopolitical effects from broader societal factors remains a key challenge for future research. The deliverable then shows that, while climate finance has reached record levels, it remains vastly insufficient, inequitably distributed, and skewed toward mitigation over adaptation, with persistent gaps in transparency, definitions, and governance. Without structural reforms to align finance with local priorities, enhance access, and ensure accountability, global climate goals risk being undermined by continued political inertia and systemic inequities. Finally, it investigates the impact of lifestyle changes in the EU-27, particularly in mobility, housing, and diets, finding that these can reduce emissions by 10–25%, offering significant mitigation potential even under ambitious policy scenarios, with generally beneficial cost impacts, though future implementation depends on addressing social acceptance and harmonising data inconsistencies across models.

4. Evidence of accomplishment

This report.

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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Executive Summary

This deliverable concludes the IAM COMPACT project's work on disruptive innovation, socio-technical transitions, behaviour change, and social innovation, focusing on how these dynamics can be represented in integrated and energy system models. It presents findings from six studies that advance empirical, conceptual, and methodological insights to better capture complex transition processes in climate and energy policy modelling.

Section 2 investigates how Modelling to Generate Alternatives (MGA) can more accurately reflect socio-technical complexities by empirically grounding its key parameter—slack, or the permissible deviation from cost-optimality. Using the D-EXPANSE electricity system model in a retrospective analysis of 31 European countries (1990–2019), the study finds that historically observed transitions deviate from model-optimal costs by 44–60%, far exceeding commonly assumed slack values (10–20%). This finding calls for modellers to use higher, context-specific slack values, improving the realism of MGA scenarios.

Section 3 explores the influence of geopolitical risks on energy transition modelling. By integrating five geopolitical risk indices using six modelling approaches into the D-EXPANSE model, the study shows that including geopolitical constraints improves hindcasting accuracy in many countries. While results vary by method and context, models that promote greater renewable deployment under risk scenarios perform best. The study demonstrates how embedding geopolitical considerations can enhance model credibility and highlights the need to better integrate broader societal risks in future modelling.

Section 4 presents a comprehensive analysis of climate finance, examining global financial flows, the communication of needs, and the governance mechanisms that shape allocation and access. It highlights persistent issues with transparency, definition, and equity in climate finance, and concludes with structural reform proposals to align finance with Paris Agreement goals. Key recommendations include the need for harmonised reporting, improved accountability, and more inclusive governance structures to ensure scale and justice in climate finance delivery.

Section 5 quantifies the mitigation potential of lifestyle change in the EU-27 under both no-policy and long-term transition scenarios. Using three integrated assessment models—PROMETHEUS, GCAM, and WILIAM—it shows that lifestyle changes could reduce emissions by 10–25%, with mobility offering the highest potential. While model agreement is strong for emissions, results vary for expenditure and land use. Causal loop diagrams further illuminate the socio-political dynamics influencing lifestyle shifts, reinforcing the importance of context-specific and policy-aware modelling.

Section 6 evaluates pathways for electrifying the global buildings sector by 2050 using a hybrid model ensemble and stakeholder-informed scenarios. The study connects macroeconomic and sectoral models to assess electrification progress at global, EU, and national levels, with case studies for India and Greece. Results show that successful decarbonisation hinges on regions achieving their electrification potential, with significant variation driven by policy ambition, structural limitations, and socioeconomic conditions.

Collectively, these six studies reinforce the importance of embedding real-world complexity into models that inform climate policy. By integrating empirical evidence, stakeholder perspectives, and broader social, political, and economic dynamics, IAM COMPACT contributes to more credible, relevant, and actionable transition pathways.

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1 Introduction to the deliverable

This deliverable concludes IAM COMPACT work on disruptive innovation, socio-technical transitions, behaviour change and social innovation and their representation in models. Six studies are reported. First, Section 2 provides empirical evidence to inform the choice of slack in Modelling to Generate Alternatives (MGA) applications within energy system optimisation models. While MGA has become a widely used method to represent socio-technical complexities by allowing deviations from cost-optimisation rationale, the selection of slack—a key parameter defining acceptable cost deviations from the optimal solution—remains largely subjective and inconsistent across studies. Using the D-EXPANSE electricity system model, the authors retrospectively analyse 31 European countries from 1990 to 2019 to assess the cost gap between real-world transitions and model-derived cost-optimal solutions. By applying both multi-year and single-year model versions, the study identifies empirical ranges of cost deviations, helping to ground the selection of slack values in historical data rather than arbitrary assumptions.

Section 3 explores how incorporating geopolitical risks into energy system modelling can enhance the realism of energy transition projections. While geopolitical instability—ranging from regional wars to resource competition—poses challenges for climate mitigation, its impacts on the energy transition are complex and understudied. Through a literature review and a novel modelling experiment, the authors integrate five geopolitical risk indices using six different methods into cost optimisation models of 31 European electricity systems. Using hindcasting from 1990 to 2019, the study evaluates which approaches improve model alignment with historical developments. The study offers empirical insights into how and when integrating geopolitical factors may enhance the credibility of forward-looking energy models and discusses broader implications for modelling other societal dimensions.

Section 4 begins by exploring the composition and evolving patterns of climate finance flows, followed by an assessment of how financial needs are defined and conveyed, and concludes with an evaluation of the governance frameworks that shape access and allocation. It closes by proposing structural reforms to improve both the scale and fairness of climate finance, ensuring its effectiveness in this critical decade for climate action.

Section 5 explores the mitigation achievable in a lifestyle change in the Europe of the 27 Member States. A new lifestyle consistent with the existing social inertia to clarify the potential role of households' activities in two contexts with and without technological transition in the energy sector. We analyse the impacts of this lifestyle change in two levels, moderate and high, as social change is uncertain by 2050 through three integrated assessment models: PROMETHEUS, GCAM, and WILIAM. The scenario creation is based on the literature and similar projects. The results presented in section 5 include emissions, households' expenditures, and land use changes, revealing agreement across models for emissions while disagreement in expenditures. Mobility is found as the activity with higher mitigation potential for a lifestyle change. Additionally, causal loop diagrams have been conceptualised to highlight the inherent internal complexity of lifestyle shifts over time. These diagrams offer a picture of positive and negative causal relations of real policy to provide policy context to the results of our simulations.

Section 6 evaluates the decarbonisation of the global buildings sector (residential and commercial) by 2050, with a focus on electrification. Using a hybrid modelling ensemble that combines integrated assessment, energy system, and sectoral models, and informed by stakeholder input, it links top-down macroeconomic and systemic perspectives with bottom-up technological and sector-specific detail. The analysis spans global, EU, and national scales, including case studies for India and Greece. Results show that electrification of buildings increases worldwide by 2050, but with large regional differences reflecting policy ambition, structural constraints, and socioeconomic contexts. Regions unable to expand electricity's share in final energy consumption fail to decarbonise, while those falling short of their electrification potential fail to achieve deep decarbonisation. Overall, electrification trajectories are context-dependent and vary across scales.

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2 Empirical evidence for slack in Modelling to Generate Alternatives

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This section will be submitted to a peer-reviewed journal.

2.1 Introduction

Energy system optimisation models have become essential tools for exploring possible long-term energy transition options to achieve net-zero emissions from regional to global levels (DeCarolis et al., 2017; Pfenninger et al., 2014). By identifying the least-cost capacity expansion and system operation options in single-year or multi-year model versions, these models combine technological, economic, environmental, and policy considerations. As long as they have been used though, these optimisation models have also been criticised for oversimplifying the complexities of the dynamic, uncertain, and socially embedded nature of the real-world transitions (DeCarolis, 2011; Trutnevyte et al., 2019). The rationale of using cost optimisation has been particularly questioned (Trutnevyte, 2016). While costs are surely important in shaping the energy transition and it is likely that the real-world transitions do not diverge far from the cheapest options, it is also unrealistic to believe that societies can steer the real-world systems to a single cost-optimal point.

Modelling to Generate Alternatives (MGA) technique has hence emerged as a common tool to overcome the limitations of pure cost optimisation since MGA identifies a range of cost-optimal and near-optimal model solutions. The MGA approach was introduced in 1979 by Brill E. (1979) for various infrastructure planning case studies. In the 2010s, it was adopted in the energy modelling community starting with the pioneering work by DeCarolis and Trutnevyte (DeCarolis, 2011), and by now MGA has become a popular approach in both multi-year and single-year models (Lau et al., 2024; Trutnevyte, 2013; Trutnevyte et al., 2011). In addition to its simple implementation, the advantages of MGA are numerous. Once the near-optimal space of model solutions is systematically considered, more technologically diverse scenarios are extracted and these scenarios vary with respect to the non-modeled objectives, e.g. resilience or acceptance (Brill, 1979). MGA can also be considered as a type of uncertainty analysis, partly covering both parametric and structural uncertainties (DeCarolis, 2011). Finally, by providing a range of cost-optimal and near-optimal scenarios, MGA has a higher chance to encapsulate the real-world energy transition (Trutnevyte, 2016).

MGA results are, however, contingent on the subjectively assumed value of slack: slack defines the maximum allowed deviation in total system costs of MGA scenarios as compared to the costs of the cost-optimal scenario. In other words, slack is the constraint that defines which scenarios will still fall in the acceptable range of near-optimal scenarios. This subjective choice of the modeler has profound implications on the outcomes: a slack of 1 will provide much less technological diversity than a slack of 20%. Typical values of slack in existing literature compiled by Lau et al. (2024) range enormously, from 1% to 30% (see Table 1), while sometimes this fundamental assumption is not even reported. Only few studies conduct a sensitivity analysis on slack (Trutnevyte, 2013; Weerd, 2023). Although DeCarolis et al. (2017) provide best-practice advice on choosing the value of slack, it is crucial to gather empirical evidence to allow a more objective choice. Hindcasting (Wen et al., 2023), also referred to as retrospective or ex-post modelling (Fujimori et al., 2016; Trutnevyte et al., 2016; Wen et al., 2022), provides a unique opportunity as it evaluates model performance against historical data of the real-world transition. In fact, using the multi-year model of the United Kingdom's electricity system in 1990 - 2014, Trutnevyte already showed that the meaningful slack values could be 9% to 23%. However, this empirical evidence is for now limited to a multi-year transition model of one country (Trutnevyte et al., 2016).

Table 1: Slack values from the studies cited in (Lau et al., 2024) for which the slack amount was identifiable.

Slack	Multi-year transition models	Single-year models

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< 10%	Luo et al (2023); Sinha et al (2024)	Neumann, Brown (2023); Grochowicz et al (2023); Sasse, Trutnevyte (2023a); van deer Weerd (2023); Andersen et al (2024)
10%	De Carolis et al (2016); Price, Keppo (2017); Eshraghi (2020); Afolabi (2022); Moultak et al (2021)	Neumann, Brown (2021); Jing et al (2019); Pedersen et al (2023, 2021a); Patankar et al (2023); Dubois, Ernst (2023); van Greevenbroek (2023); Lombardi et al (2023, 2020); Pickering et al (2022a)
20%		Sasse, Trutnevyte (2023b, 2020, 2019); Esser et al (2024); Schwaeppe et al (2024)
> 20%	Trutnevyte et al (2016)	De Carolis (2011); Pedersen et al (2021b); Trutnevyte et al (2013)

In this paper, we seek to provide first-of-the-kind empirical evidence to inform the choice of slack in MGA applications in single-year and multi-year transition models. We calculate the cost deviations – the percentage differences between total system costs of the cost-optimal model solution and the costs of the real-world transition enforced in the same model – for 31 European countries during the period 1990-2019. These 31 countries include 27 EU countries, Iceland, Norway, Switzerland, and the United Kingdom. We use the D-EXPANSE cost optimisation model of the electricity system (Wen et al., 2023, 2022). We conduct this analysis for various time horizons for two model versions to represent the most common MGA applications: a multi-year perfect-foresight transition model and a single-year model.

2.2 Methods

2.2.1 Measuring cost deviations as evidence for slack

To gather empirical evidence for slack in MGA, we use hindcasting to measure retrospective (discounted) cost deviations in the electricity system models in 31 European countries. The term "cost deviations" (with a discount rate of 3.5%) – or *d* – here refers to the difference in percentage between total system costs of the cost-optimal model solution C_0 and the total system costs of the real-world transition enforced in the same model C_r:

$$d = \frac{C_r - C_0}{C_0} \cdot 100\% \qquad \text{(Eq. 2-1)}$$

Therefore, this cost deviation *d* corresponds directly to the definition of slack used by the modelers in MGA. In both single-year and multi-year models, this deviation depends on the length of the time horizon considered. In single-year models, the further ahead the year modeled, the higher is the degree of freedom due to cumulative technology build rates, and the higher the slack needs to be. In addition to that, in multi-year models, the total system costs are also estimated as cumulative. For this reason, we calculate historical cost deviations for the range of time horizons: 10 to 30 years ahead for a multi-year model, and 10, 15, 20, and 25 years ahead in a single-year model. As compared to today (2025), these horizons correspond to the currently most analysed horizons in prospective analyses, such as 2035, 2040 and 2050.

2.2.2 Historical data

We use an existing database (Jaxa-Rozen et al., 2022) that has been created for hindcasting purposes (e.g. (Fisch-Romito et al., 2025; Wen et al., 2023)) for national electricity systems of 31 European countries, including the EU27, Switzerland, Iceland, Norway, and the United Kingdom. The covered period is 1990-2019 and the original data is extracted from open-access sources and harmonised so that it is ready to use as input parameters in a cost-optimisation model. For each country, the data package provides (i) a country file documenting nationally aggregated variables, such as annual time series of electricity demand, transmission and distribution losses, and peak and base load; (ii) a technology file describing techno-economic variables for each major generation technology in the country's electricity mix, such as annual time series of investment costs, historical installed capacities and generation, as well as technology retirements; (iii) resource files describing intensities of carbon emissions and annual time series of costs for fuels; and (iv) load profile describing two representative days (48 hours) for each year by K-means clustering based on daily load profiles during the year. Compared to some other hindcasting studies (Shen et al., 2025; Wen et al., 2025), the modelling here is conducted without explicitly representing historical energy and climate policies as most MGA studies do not represent policies either.

2.2.3 Multi-year and single-year D-EXPANSE models

D-EXPANSE, which stands for the Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios, is a cost-optimisation electricity system model (Trutnevyte, 2016; Wen et al., 2022), which in its basic version has bottom-up structure, rich representation of technologies, perfect foresight, and it models the expansion of capacity and hourly dispatch each year. D-EXPANSE's structure is thus similar to other popular cost optimisation models, such as MARKAL/TIMES (Loulou and Goldstein, 2005), OSeMOSYS (Howells et al., 2011), MESSAGE (Messner and Strubegger, 1995) and PRIMES (E3Modelling, 2018). There exist a handful of variants of D-EXPANSE, including model versions with endogenous technology learning, endogenous electricity demand (Wen et al., 2023), myopic foresight (Shen et al., 2025), and integration of non-technical considerations (Jaxa-Rozen et al., 2025; Wen et al., 2025, Gavrikov et al., 2025). In this study, we use the basic version with exogenously given electricity demand, costs of all technologies and fuels, initial installed capacity and its retirement as per historical data (Section 2.2.2). By means of deterministic hindcasting, we generate the cost-optimal scenario that shows the transition pathway containing installed capacities and annual generation of 15 generation technologies and interconnection transmission line, as well as total system costs. Meanwhile, we also generate the equivalent of the real-world transition by enforcing the historical installed capacities and annual generation values in the model to calculate the total system costs. By doing so, the cost deviation can be calculated (Section 2.2.1).

In order to measure cost deviations to inform the choice of slack in single-year electricity models, such as EXPANSE (Sasse and Trutnevyte, 2023a, 2020), PyPSA (Neumann and Brown, 2023, 2021), or Calliope (Pickering et al., 2022b), we develop a single-year EXPANSE model from D-EXPANSE. This model has a lower resolution and simpler formulation than the typical single-year EXPANSE (Sasse and Trutnevyte, 2023b, 2020), but the benefit is that it is populated with the same historical data from D-EXPANSE. While keeping the same basic model structure, the new single-year model represents only one year in the future and skips the other years. Some model parameters are updated accordingly to the specific year of interest, such as the accumulation of build rates and retired capacity from the initial year to the year of interest.

2.2.4 Monte Carlo simulations for uncertainty analysis

Monte Carlo sampling is typically combined with D-EXPANSE to deal with the parameter uncertainty (Li and Trutnevyte, 2017; Trutnevyte, 2016). In this study, as fully accurate national-level historical cost data since 1990 are very challenging to find (Jaxa-Rozen et al., 2022), parametric uncertainty is calculated around the estimated slack values using Monte Carlo simulations. In particular, we apply 1.000 Monte Carlo runs by varying the most important cost inputs: (i) investment costs and operation and maintenance costs of fossil fuel-based plants, nuclear, hydropower, and new renewable power plants, (ii) fuel costs of hard coal, brown coal, gas, and oil, (iii) heat revenue from combined heat and power plants, and (iv) import costs and export profits.

Each one of the 1.000 Monte Carlo simulations affects the whole 30-year time period. The same 1.000 scenarios are used for the 31 countries and the two different models. Note that, for each Monte Carlo scenario, the real cost for each country is re-calculated using the modified variable values. This means that we apply the costs of the Monte-Carlo scenario to the real data energy trajectories of each country. In each Monte-Carlo simulation, every variable is independently and randomly modified yearly (both optimisation models use yearly values for each variable). The modification, for each variable, is done according to the following process: first, we randomly choose an error between -20% to 20% with uniform probability, that we are going to apply to the initial value (the value of the variable at year 0) of the corresponding variable. Then, for each year (from year 1 to year 30), a yearly error between -5% and 5% is chosen (again with uniform probability) and, if the total is still between -20% and 20%, the obtained variation is applied to the corresponding variable value for the corresponding year. If the result is below (respectively above) -20% (20%), a -20% (20%) variation is applied to the corresponding variable for the corresponding year. In the ANNEX A, the first Monte Carlo simulation is shown in detail.

2.3 Results

2.3.1 Cost deviations in deterministic multi-year model

In a deterministic multi-year model (Figure 2-1), the cost deviations increase for most countries over time, with stabilisation or lower growth rate during the last five years of the modeled period. Although descending, the trajectories of Switzerland and Denmark also stabilise in the 30-year period as illustrated in ANNEX A. The median cost deviation across countries increases from 12% in 10 years (2000) to 46% in 30 years (2020). The minimum cost deviations follow a similar trajectory, growing from -12% in 10 years to 6% in 30 years. The negative values of the cost deviations (where the costs of the cost-optimal solution are higher than the costs of the modeled real-world transition) are possible since D-EXPANSE is run with perfect foresight, possibly leading to cost-optimal solutions over 30 years that are costly in the initial years. The maximum cost deviations have their lowest value of 70% in 15 years ahead and end at 93% in 30 years.

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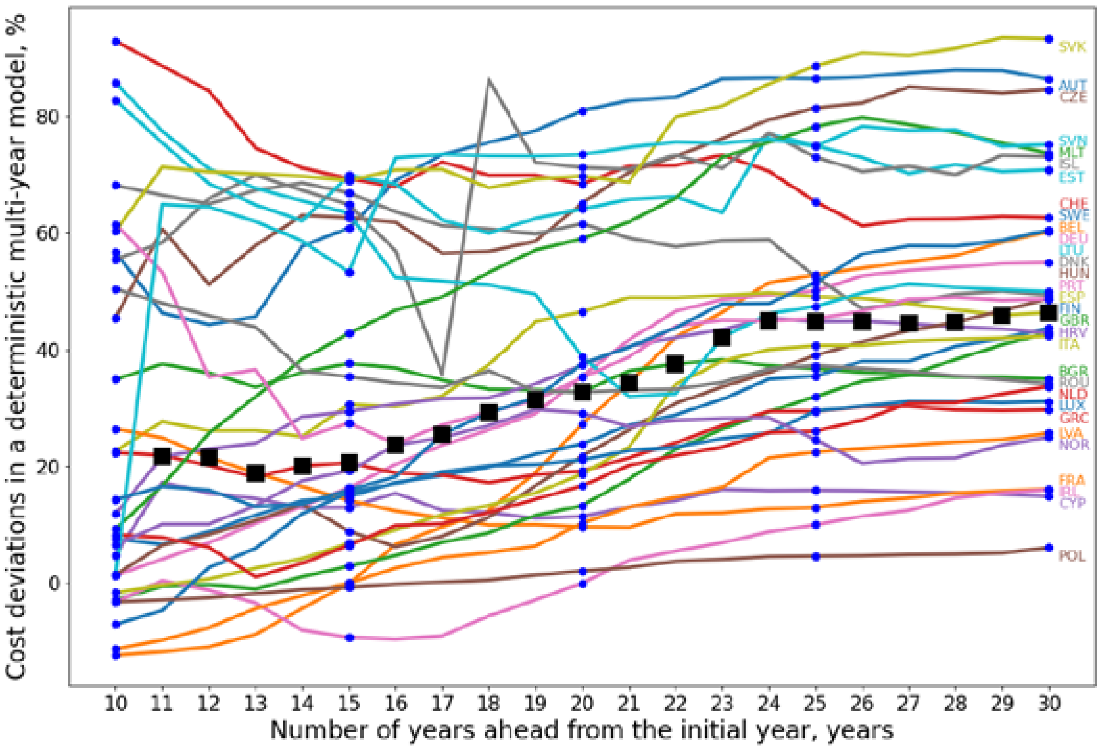

Figure 1: Evolution of cost deviations for 31 European countries in a deterministic multi-year model. The yearly median across the countries is depicted in black squares and black line. In blue circles, the country-specific cost deviations are depicted from 10 years ahead (2000) to 30 years ahead (2020). Countries are indicated in different colors that are consistent with the colors of country names.

As indicated by the dispersion of country-specific deviations (blue dots in Figure 1), the difference between the lowest and highest deviations is enormous, but stable at approximately 85% for the last 18 years. However, the lowest or the highest values have not always been achieved by the same country. It is also worth noting that the range between the lowest and highest country-specific values is not uniformly filled by the 31 countries: Two-thirds of the countries accumulate in the lower half (with a higher density in the upper half of this half), while the last third accumulates in the upper quarter of the corresponding vertical segment. In fact, the deviation trajectories of the two different groups appear well established for the last decade of the modelling period as cost deviations of one group do not intersect with the other group (except for Denmark's descending trajectory).

By the end of modelling 30 years ahead (2020), not a single country in our study has a cost deviation under 5%. Only Poland, with 6% cost deviation, stays under 10%, followed by Cyprus (d = 15%), Ireland and France (d = 16%). Those are the four over 31 countries to have a cost deviation below 20%. Seven countries (Norway, Latvia, Greece, Luxembourg, Netherlands, Romania and Bulgaria) have cost deviations between 25% and 35%, and nine (Italy, Croatia, United Kingdom, Finland, Spain, Portugal, Hungary, Denmark and Lithuania) have cost deviations between 42% and 50%. Germany has a cost deviation of 55%, followed by Belgium, Sweden and Switzerland (all with deviation between 60% and 63%). Estonia, Island, Malta and Slovenia have cost deviations between 70% and 75%, Czechia and Austria - around 85%, and Slovakia tops at 93%. It is worth noticing that the countries with the highest deviations are all relatively small, where even one new larger power plant can substantially reshape the electricity mix. Further country-specific results are provided in the ANNEX A.

2.3.2 Uncertainty in a multi-year model

Once Monte Carlo simulation of uncertainty is added (Figure 2), the overall picture of the median cost deviations

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remains the same. Median cost deviations per country across the Monte Carlo scenarios are slightly higher than the deterministic values for the same countries (Figure 2-2). The median overall value of the deviation cost across the countries remains very high: 44%. The bulk of the cost deviation distributions per country is quite symmetric, with both a tendency of the distribution to accumulate near the median value and a dissymmetry in the tails, with the upper tail being longer than the lower tail. The interval between maximum and minimum deviation values rises with a growing median, albeit with some exceptions. Smaller countries tend to have larger deviation ranges. The country with the highest Monte Carlo variability is Lithuania, which holds both the maximum (at over 303%) and the minimum cost deviation values.

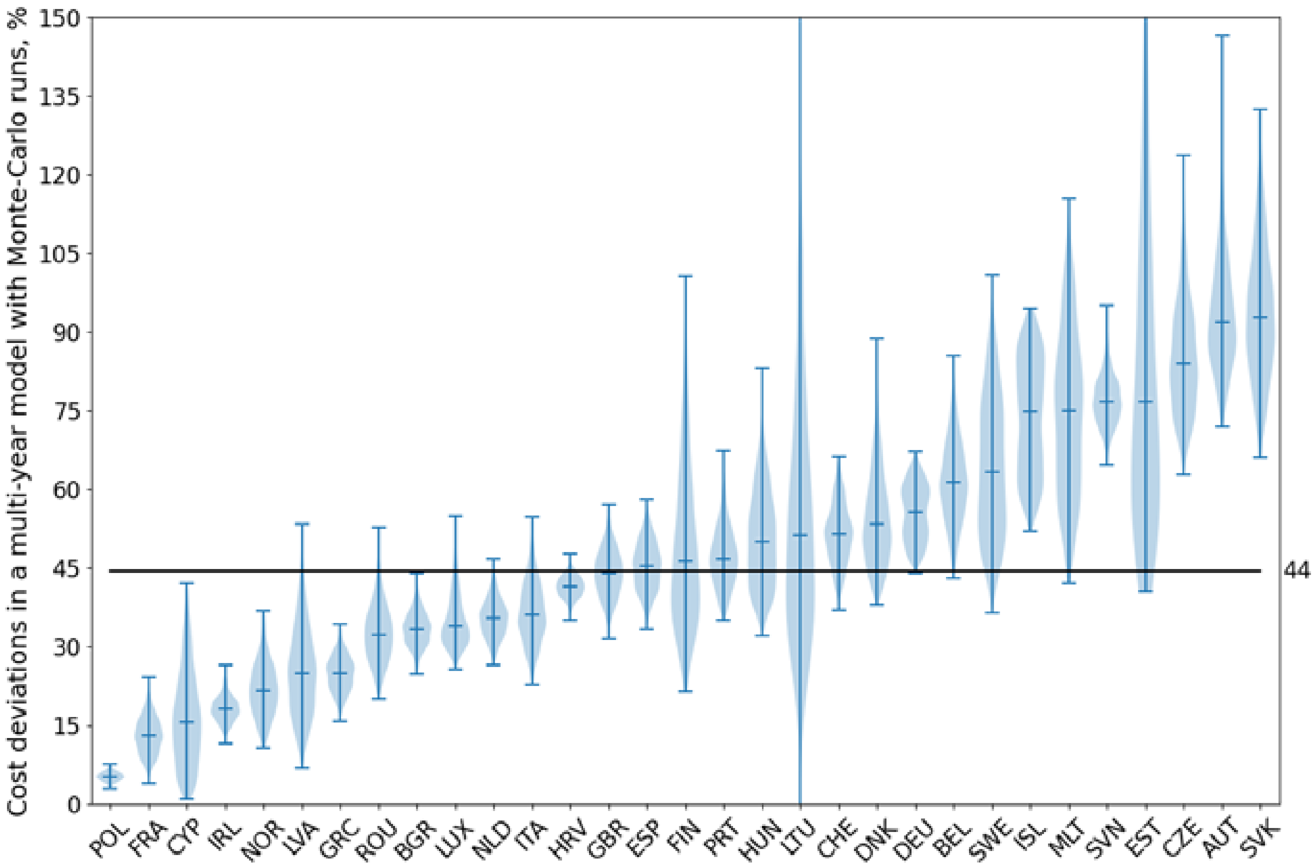

Figure 2: Distribution of cost deviations 30 years ahead (2020) for the 1.000 Monte Carlo runs for each of the 31 European countries. For each country, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution. Countries are sorted from lowest to highest median cost deviation. The black horizontal line shows the median value of 44% over all Monte Carlo runs and the 31 European countries. The extreme values for Lithuania and Estonia are missing here, but can be found in ANNEX A.

As shown in Figure 2, the impact of the Monte Carlo uncertainty highly depends on the country. Seven countries have the whole range of cost deviations below the overall median of 44%: Poland, France, Cyprus, Ireland, Norway, Greece and Bulgaria. On the other extreme, five countries have a whole range of cost deviations above 44%: Slovakia, Austria, Czechia, Slovenia and Island, with Belgium, Germany and Malta having only a few values lower than the general median. The median country difference between the maximum and the minimum cost deviations is slightly above 32%. The cost deviation is below 5% for only 541 over 31.000 Monte Carlo simulations, which is less than 2%. Of those 541 simulations, 430 correspond to Poland, 106 to Cyprus and 2 to Lithuania, but the uncertainty in the case of the latter two countries is very large and Poland overall has very low deviation. The cost deviation is between 5% and 10% in 1.509 over 31.000 Monte Carlo simulations (less than 5%): 1.000 correspond to Poland, 12 to Latvia, 5 to Lithuania, 219 to France and 167 correspond to Cyprus. The cost deviation is between 10% and 20% 2.762 times (less than 9%): 290 correspond to Latvia, 28 to Lithuania, 810 to Ireland, 88 to Greece, 746 to France, 408 to Cyprus and 392 correspond to Norway. Adding all up, there are 4.812 over 31.000 cases where the cost deviation is below 20%, which corresponds to 16% of the simulations. Further

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country-specific results are provided in ANNEX A.

The time dynamics of the Monte Carlo runs (see ANNEX A) follows the same general growing trend as in the deterministic case (Figure 1). The stabilisation time of the Monte Carlo cost trajectories is longer than the stabilisation time in the deterministic case: it takes 15 years for the first decile of the overall trajectories to have a positive cost deviation, followed by 15 years of steady growth, compared to eight years for the deterministic case. Similarly, the ninth decile of the overall cost deviations reaches its lowest value, 65%, at half of the modelling period, followed by 10 years of steady growth and some stabilisation during the last 5 years. The median cost deviation increases from 20% to 44% during the last 20 years of the modelling period.

2.3.3 Cost deviations in deterministic single-year model

As was the case for the multi-year model, the further ahead is the modelled year in the single-year model, the higher generally is the cost deviation (Figure 3). Distributions of deviations for all countries combined have higher median values, higher minimum values and longer upper tails, both for the deterministic and the Monte Carlo versions. The single-year model for 10 years ahead (2020) has a median cost deviation of 17%, for 15 years ahead - 27%, for 20 years ahead - 44% (which is close to the median cost deviation for the multi-year model 30 years ahead), and finally the median cost deviation is 61% for the single-year model 25 years ahead (2015). The minimum cost deviations in the deterministic version are remarkably low for 10 (2%), 15 (4%) and 20 years ahead (5%), but reach the minimum of 20% for the single-year model 25 years ahead.

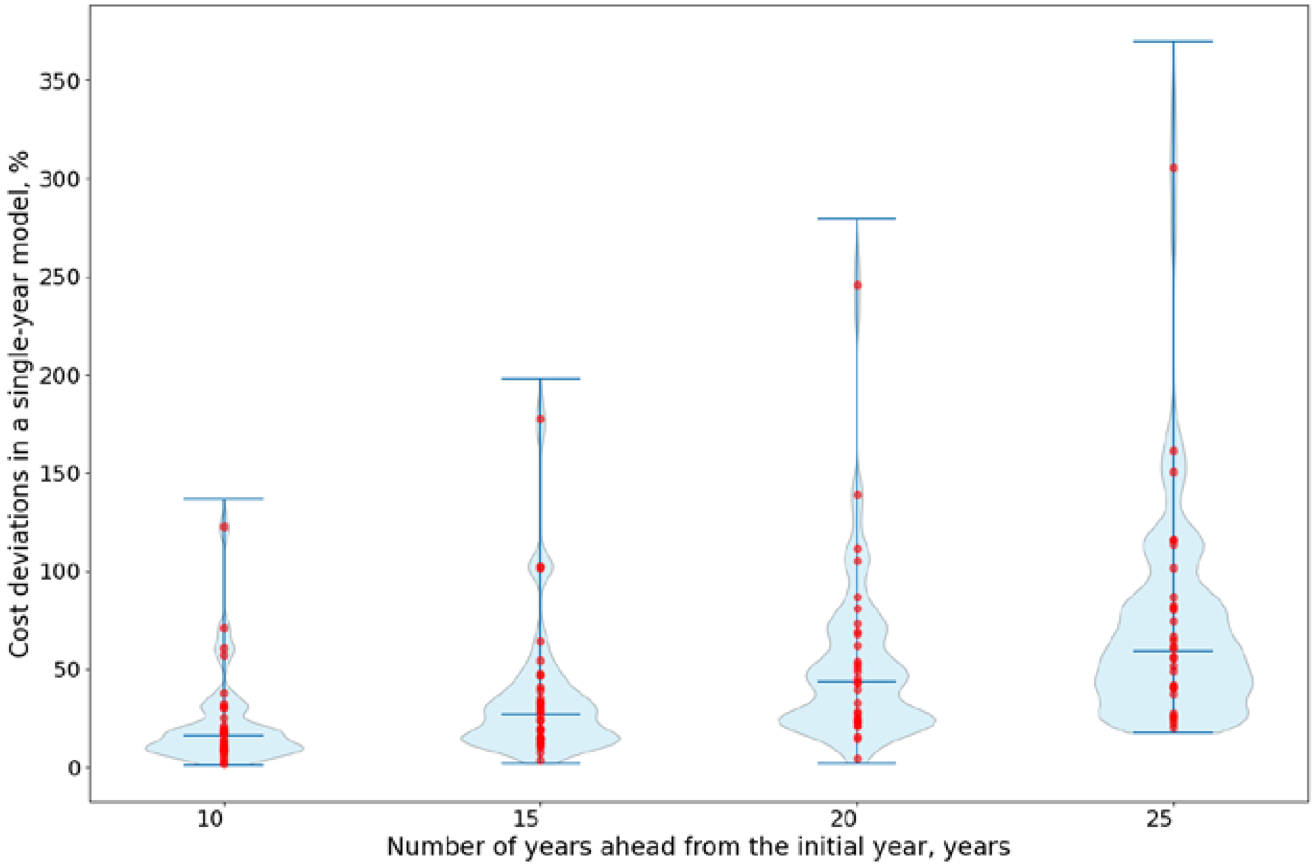

Figure 3: Distribution of cost deviations in a single-year model across 31.000 model runs, combining 1.000 Monte-Carlo draws and 31 countries. Columns represent deviations for models 10 (2000), 15 (2005), 20 (2010) and 25 years ahead (2015) compared to the start yea 1990. Red dots represent the country-specific values of the deterministic model runs. For each time horizon, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution.

A closer look at the country-specific cost deviations (red dots in Figure 3) indicates that the huge dispersion gap between the maximum and minimum values is mainly driven by a single outlier, Denmark, with 122% deviation cost 10 years ahead, 177% 15 years ahead, 245% 20 years ahead and 305% 25 years ahead. Following this

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outlier, we identify another group of countries with high cost deviations detached from the bulk of the distributions: Cyprus (57%), Slovenia (60%) and Slovakia (70%) 10 years ahead; Slovakia (101%) and Slovenia (102%) 15 years ahead; Bulgaria (111%, 150%) and Slovakia (138%, 161%) respectively 20 and 25 years ahead. On the other side of the spectrum, Malta is the single country with cost deviation under 5% for all time horizons up to 20 years ahead, and together with Latvia, Croatia, Sweden, and Norway, they form the single group of countries that are among the ten best performing countries in all time horizons.

The cost deviations for the single-year model 25 years ahead are in the range of 20-30% for six countries: Switzerland, Latvia, Malta, Norway, France, and Croatia. Six countries have deviation costs between 35-50%: Sweden, Poland, Hungary, Luxembourg, Finland, and Romania. Eight countries have cost deviations between 50-75%: Austria, Estonia, Spain, Belgium, Iceland, Italy, Greece, and Ireland. Four countries have cost deviations in the range 80-90%: the United Kingdom, Lithuania, Czechia, and Portugal. Followed by four countries with costs deviations between 100-118%: Cyprus, the Netherlands, Germany and Slovenia. At the end of the spectrum, we find the three outliers cited above: Bulgaria, Slovakia and Denmark. It is worth mentioning that the proportion of the distribution part containing the lower half of the results (the interval between the median and the minimum values) is quite stable going from 14% to 21% of the total interval range of the distribution from 10 years ahead to 25 years head.

2.3.4 Uncertainty in a single-year model

On the one hand, the maximum cost deviation among the 31.000 Monte-Carlo simulations (Figure 4) are 15% higher than the deterministic maximum 10 years ahead and more than 65% higher 25 years ahead, reflecting the long upper tails of the probability distributions in Figure 3. On the other hand, other significant statistics are more coherent between the deterministic and the Monte-Carlo versions: the median values across the countries of the deterministic and the Monte Carlo versions are quite close, with a difference of less than 0.5%, except for the single-year deterministic model for 20 years ahead with a median cost deviation 1% higher than its Monte Carlo counterpart. Similarly, the Monte-Carlo minimum cost values are between 1-2% lower than their deterministic counterparts. Furthermore, these minimum values are not completely isolated among the 31.000 Monte Carlo simulations. For the single-year model 10 years ahead, there are 555 among 31.000 simulations with a cost deviation under 2%. There are, respectively, 2.574, 948 and 508 simulations with a cost deviation under 5%, corresponding to models 10, 15 and 20 years ahead. Finally, there are 447 simulations over 31.000 with cost deviation under 20% for the single-year model for 25 years ahead.

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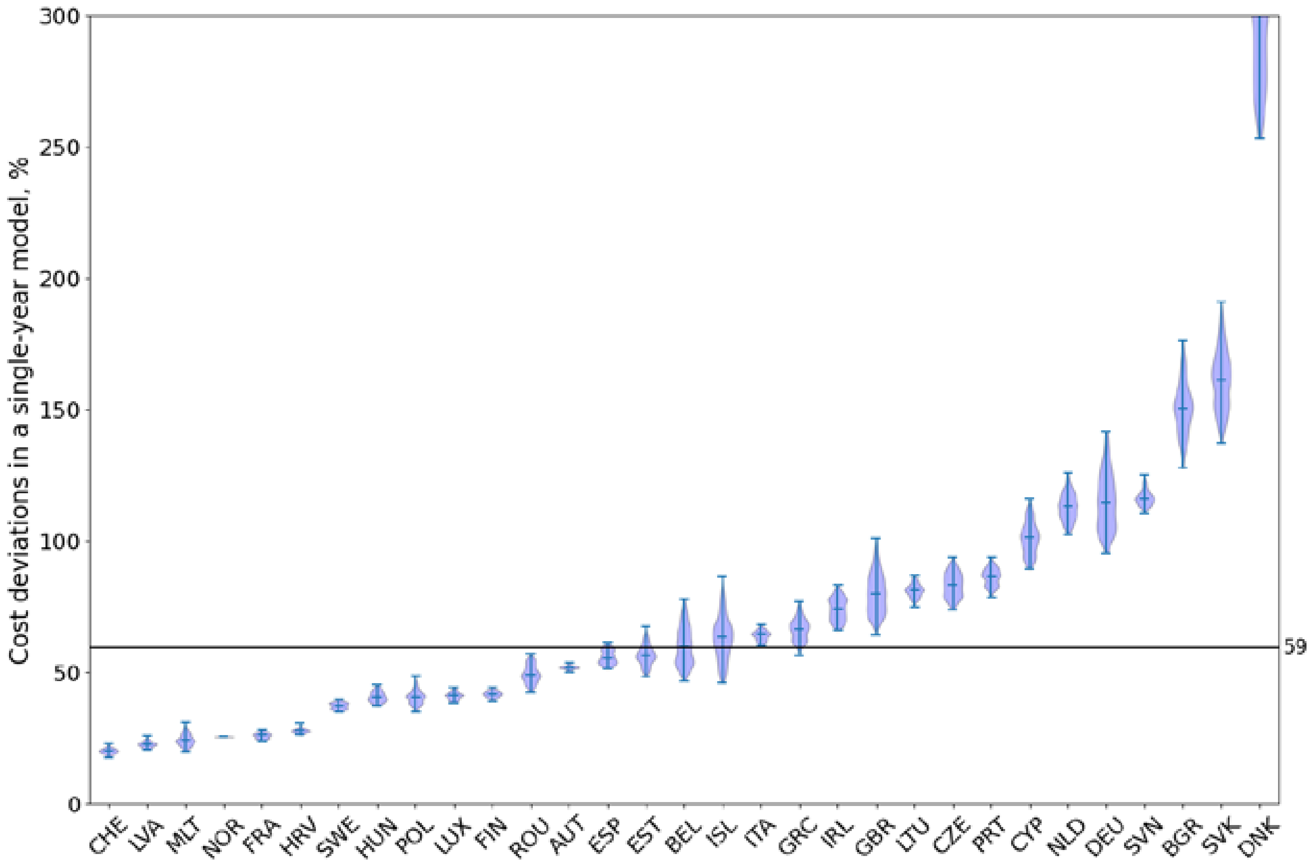

Figure 4: Distribution of cost deviations per country for 1.000 Monte Carlo runs in a single-year model for 25 years ahead. For each country, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution (except for Denmark). Countries are sorted from lowest to highest median cost deviation. The black horizontal line shows the median value of 59% over all Monte Carlo runs and the 31 European countries.

Inter-country variations of cost deviation induced by the Monte-Carlo scenarios are remarkably low in the single-year model, with interval length growing with an increasing time horizon. Indeed, 10 over 31 countries have less than 2 percentage points between their lowest and highest cost deviations 10 years ahead, with only 8 countries exceeding 5 percentage points of interval length at this time horizon. In the other extreme time horizon, 25 years ahead (see Figure 4), five countries have interval lengths lower than 5 percentage points: Norway, Austria, France, Croatia, and Sweden; with Norway having less than 0.3% difference between its lowest and highest cost deviation. Six countries have interval-lengths between 5 and 10 percentage points: Switzerland, Finland, Latvia, Luxembourg, Italy, and Hungary. Finally, 25 years ahead, ten countries exceed 20 percentage points: Greece, the Netherlands, Cyprus, Belgium, the United Kingdom, Iceland, Germany, Bulgaria, Slovakia, and Denmark. The maximum interval length grows much faster than the minimum with an increasing time horizon, and the outliers coincide with the worst performing countries. The same outliers are those that form the long upper tail of the overall cost deviation distributions in Figure 3. Equivalent graphs for other time horizons can be found in ANNEX A.

2.4 Discussion

According to our results, only one of 31 European countries in a multi-year model for 30 years ahead had a cost deviation lower than 10%. However, 10% is the slack value that was used in more than two-thirds of the models in the existing literature (Table 1). Only four countries over 31 had cost deviations under 20%. Taking into account cost uncertainty, the median value of cost deviations across the countries in our 31.000 Monte Carlo simulations is as high as 44%, but none of the existing literature is as ambitious with its slack values. The cost deviations are even higher in the case of single-year models: at 25 years ahead, no country had a cost deviation under 20%,

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the minimum being at 20%. With respect to the single-year models ten years ahead, a slack of up to 10%, which is quite common among single-year studies in the literature, would have covered a bit less than a third of the 31.000 modelled scenarios; and a slack of up to 20%, would have covered slightly more than two-thirds of them.

The reasons behind such high cost deviations are plentiful and many of them have already been discussed in hindcasting literature for the UK (Trutnevyte et al., 2016) or the European countries (Shen et al., 2025; Wen et al., 2025, 2023). First and foremost, we run multi-year optimisation models with perfect foresight for a long period of time (30 years) using real historical data. Our single-year models also have full foresight into future data. In contrast, energy decision making is based on assumed costs, demands, and technology parameters. Second, a single central planner that would be able to steer the system towards its cost-optimal state does not exist in reality, and transitions emerge from a variety of decisions made by heterogeneous decision makers. Third, some of the decisions to deviate from the cheapest solutions are also made on purpose to advance toward other non-modeled objectives (Trutnevyte et al., 2016), including other policy goals (supply security, climate mitigation, liberalisation, acceptance and others). Finally, real-world socio-technical transitions are characterised by so many other real-world complexities that techno-economic modelling will always fall short in capturing these complexities completely (Trutnevyte et al., 2019).

For energy system optimisation modelers, this study has threefold implications. First, the large values of estimated cost deviations underscore the importance of using MGA to explore near-optimal scenarios of cost-optimisation models. The cost-optimal solution is just too much off the real-world developments to provide an accurate proxy and a good basis for unbiased insights. Second, slack values for MGA with both multi-year and single-year models should be substantially increased from the commonly used values in the current literature. The broad range of estimated slacks across the countries indicates that, where possible, such hindcasting exercises should be done with any optimisation model to more objectively estimate slack. Even if past slack is not necessarily the same as in the future (as seen in Figure 1), it still appears to be a better guide for the future for most countries than a random guess. If such hindcasting is not feasible in terms of resources, country-specific slack values at least for the electricity sector from this study could be adopted (Table 2). Third, such large slack values also open big questions about the overall usability of energy system optimisation models and whether cost optimisation is at all meaningful to use. While it is grounded in some theory and to some extent makes sense intuitively (Trutnevyte, 2016), cost optimisation combined with MGA with such large slack values will give an enormous diversity of technological scenarios. While there are uncertainty methods available to tackle this diversity to some extent (Guivarch et al., 2022), more fundamental solutions of moving away from cost optimisation models to other modelling functions should not be ruled out.

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Table 2: Country-specific cost deviation results (in %) from the deterministic multi-year (30 years) and single-year (10, 15, 20, 25 years) models.

Country	Multi-year models	Single-year models			
	30 years	10 years	15 years	20 years	25 years
Austria	86	14	29	44	52
Belgium	60	17	31	45	61
Bulgaria	35	30	64	111	150
Croatia	43	8	12	21	28
Cyprus	15	57	47	52	102
Czechia	85	25	35	81	83
Denmark	49	123	178	246	305
Estonia	71	2	12	21	56
Finland	44	20	24	29	42
France	16	12	15	23	26
Germany	55	18	55	87	116
Greece	30	18	19	33	67
Hungary	49	19	33	40	41
Iceland	73	32	41	62	62
Ireland	16	9	24	54	75
Italy	42	10	19	49	65
Latvia	26	3	8	14	23
Lithuania	50	21	33	51	81
Luxembourg	31	6	27	27	41
Malta	74	5	4	5	24
Netherlands	34	38	48	69	114
Norway	25	9	13	15	26
Poland	6	10	15	25	41
Portugal	49	31	39	73	87
Romania	34	8	10	25	49
Slovakia	93	71	102	139	161
Slovenia	75	61	103	105	116
Spain	46	19	30	68	56
Sweden	60	9	15	23	38
Switzerland	63	11	14	23	20
United Kingdom	43	14	20	43	81

This study has been a step forward from previous literature (Trutnevyte et al., 2016) in providing empirical evidence for slack values in MGA applications with energy system optimisation models. However, some limitations

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remain that could be addressed in future research. First, the modelling here was done for the electricity sector only and in the future could be extended to the whole energy system modelling. Second, we used the D-EXPANSE model, but such systematic assessment of deviations could also be done with a broader community of optimisation models to elicit more robust slack values. The single-year EXPANSE developed here was a relatively coarse model as compared to the high-resolution models that are used for forward-looking analyses (Grochowicz et al., 2023; Lombardi et al., 2020; Sasse and Trutnevyte, 2023a). Interestingly though, this version of D-EXPANSE had higher cost deviations in the UK than analysis with a simpler, more stylised model (Trutnevyte et al., 2016). Third, while 31 European countries since 1990 provide a good diversity of country contexts, similar research could be replicated in the global South or with global models. Fourth, we assessed a pure techno-economic perfect-foresight optimisation here, but the model from the start could have included non-technical elements, such as policy, myopic foresight, or other quantifiable non-technical considerations (Shen et al., 2025; Wen et al., 2025). While these elements would influence and could potentially even reduce the historically estimated slack, this could also inform at what stage in the broader modelling process MGA should be best used, e.g. before or after policy scenarios.

2.5 Conclusion

Modelling to Generate Alternatives (MGA) has been increasingly used with energy system optimisation models, but MGA results are highly contingent on the subjectively assumed value of slack. Using electricity system hindcasting in 31 European countries, we quantify deviations between costs of the cost-optimal scenario and the real-world transition represented in an optimisation model and hence provide first-of-the-kind empirical evidence for slack. 10% to 20% slack that are commonly used in the MGA applications are strikingly lower than the median cost deviation of 44-60% that we obtained by hindcasting with single-year and multi-year electricity system optimisation model D-EXPANSE. Although this slack value highly varies between countries, time horizons of interest, and historical cost assumptions, it is barely ever around or below 10%. These results underscore the importance of using larger and country-specific slack values, estimated using hindcasting with each particular model or informed by the guiding values from this paper. At the same time, the large diversity of technological model outcomes that will be uncovered by such a large value of slack opens more fundamental questions about the use of cost-optimisation models.

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3 Geopolitical risks in energy system models: hindcasting in 31 European countries

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3.1 Introduction

Recent years have revealed the geopolitical instability of the modern world. Progressing regional wars (unprecedentedly since the Second World War, also on the European continent), global trade wars, political shift to the right, the race for rare minerals and metals, and other geopolitical tensions challenge the mitigation of the full-scale climate change (Calvin et al., 2023). Despite the numerous negative effects of geopolitical rivalries, scholars argue for some potential positive impacts too (Husnain et al., 2022). Transition towards renewable energy sources happens to be one of these areas, controversially affected by elevated geopolitical risks (Hashmi et al., 2022; Lee et al., 2024). As energy system models (Pfenninger et al., 2014) and integrated assessment models (Keppo et al., 2021) are widely used to inform policy making about climate change strategies, it is key that these models provide meaningful energy projections for the future taking into account techno-economic considerations as well as geopolitical and other societal realities (Trutnevyte et al., 2019). To date, as Section 3.2 shows, limited efforts have been made to account for geopolitical factors in models, while the empirical evidence on what the effects are is also scarce and diverging. Even if there have been experiments to incorporate geopolitical considerations into modelling, the merits of such a model upgrade always need to be verified, as integration of societal factors can also reduce the realism of model results (Fisch-Romito et al., 2025a; Wen et al., 2025). One of the best possible options to tackle this challenge is hindcasting (Trutnevyte et al., 2019; Wilson et al., 2021a), also called ex-post or retrospective modelling, which has been successfully demonstrated in previous studies with integrated assessment models (Fujimori et al., 2016; Guivarch et al., 2009) and electricity system models (Trutnevyte, 2016; Wen et al., 2022, Fossas-Tenas et al., 2025). As far as the peer-reviewed literature shows, no systematic experimentation with integrating geopolitical risks into modelling exists, whether evaluated by hindcasting or not.

In this study, we first conduct a literature review on how geopolitics influences the energy transition and how existing literature has implemented geopolitics in energy system models or integrated assessment models. We then incorporate geopolitical considerations into cost optimisation-based models of 31 national European electricity systems, experimenting with five geopolitical risk indices and six different integration methods. We then assess the performance of various model versions using hindcasting from 1990 to 2019 to delineate which geopolitical risk indices and integration methods have a tendency to improve the realism of the model results. We finish with a broader discussion on the implications for forward-looking modelling and the integration of other societal factors into modelling.

3.2 Literature review

Geopolitics is a field of study that examines how geography, particularly the distribution and allocation of resources, influences relations between states (Blondeel et al., 2024). The geopolitical risk is defined as “the threat, realisation, and escalation of adverse events associated with wars, terrorism, and any tensions among states and political actors that affect the peaceful course of international relations” (p. 1195, Caldara and Iacoviello, 2022), Geopolitical events have historically, without doubt, had an impact on energy systems, particularly via fossil fuels (Bradshaw, 2009; Krane and Medlock, 2018; Van de Graaf, 2013). First of all, dependence on fossil fuels from countries with high geopolitical risks was considered a threat to energy security (Hille and Angerpointner, 2025). For example, for China, geopolitical risks have weakened energy security between 2000 and 2021 through reduced security of oil supply (Wang et al., 2025). Europe's dependence on Russian gas has repeatedly threatened energy security for decades (Bradshaw, 2009; Zhang et al., 2024). Second,

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geopolitical events affect the price of oil and other fossil fuels. Based on the Geopolitical Risk Index (GPR) by Caldara and Iacoviello (2022), geopolitical risk tends to increase fossil fuel prices and decrease trade volumes globally (Liu et al., 2021; Zhang et al., 2023). In the US over the last 150 years, oil price fluctuations were observed during major geopolitical events (Noguera-Santaella, 2016). But GPR can also increase the risk of crashes in fossil fuel prices: geopolitical acts (e.g. war beginnings) mainly drive the crash risk for coal, and geopolitical threats (e.g. war risks or terrorism menaces) mainly drive the risk for oil and gas (Apergis and Fahmy, 2024). Third, geopolitical risk also affects fossil fuel production, with heterogeneous effects depending on the country. For example, a study of OPEC countries showed that an increase in GPR decreased gas production in countries with low production capacity, but increased gas and oil production in nations with high production volumes (Islam et al., 2024).

For renewable energy technologies, the price and availability of critical minerals and metals are particularly sensitive to geopolitical risk (Saadaoui et al., 2025). After the war in Ukraine, the geopolitical risk specific to Russia increased the prices of aluminum, copper, lead, zinc, and nickel (Pata et al., 2024). For rare earths, geopolitical tensions have been shown to increase import prices and reduce trading volumes in the case of Japan, with the impact being stronger for rare earths from China (Fan et al., 2023). With regard to nuclear power, an increase in geopolitical risk has been shown to favor its long-term development (Zheng et al., 2025). This tendency, however, has not been observed in five European countries, heavily dependent on Russian gas, where the war in Ukraine had no effect on nuclear production, except for Switzerland, where it increased, and in Romania, where it decreased (Erdogan et al., 2024). Geopolitical risks have little impact on uranium prices (Lyócsa and Todorova, 2024). Also, geopolitical shocks increase overall vulnerability and uncertainty in energy markets (Liu et al., 2025; Yilmazkuday, 2024), including spillover risk between national energy markets (Xie et al., 2025). Finally, in Europe, an increase in geopolitical risk in countries supplying coal, oil, and gas has led to reductions in total energy consumption, while boosting renewable technologies (Erdogan et al., 2024; Hille and Angerpointner, 2025). Geopolitical effects also had a positive impact on energy efficiency in European countries due to higher energy prices, and this effect was further increased by renewable energy progress (Owjimehr et al., 2023). However, the war in Ukraine in some cases slowed down the transition as European countries committed to contracts for liquified natural gas (Kuzemko et al., 2022; Pye et al., 2025).

Previous studies found that the effect of geopolitical risk on transition varies over time: it can be positive or negative depending on the period (Lin and Zhang, 2025; Su et al., 2021). The level of geopolitical risk also matters. According to Lee et al. (2024), for OECD countries, geopolitical risk index has a U-shaped effect on energy security: it inhibits energy security and energy transition up to a certain threshold as countries increase their imports of fossil fuels in response to the shock, and beyond this threshold countries want to increase their energy independence by developing renewable energy capacity. Several studies show that geopolitical risk can favor the energy transition (Ben Cheikh and Ben Zaied, 2023; Blondeel et al., 2024; Cai and Wu, 2021; Sweidan, 2021a, 2021b; Wang et al., 2024b) and can inhibit CO_2 emissions (Feng et al., 2024). In particular, geopolitical risk reduces the reliability of energy supply, encouraging importing countries to increase their energy independence, notably through the development of renewable sources (Wang et al., 2024b). The impact of geopolitical risk on the energy transition has intensified with time due to falling cost of renewable technologies (Cai and Wu, 2021), while strict environmental regulations and green innovations have amplified this effect (Wang et al., 2024a). However, in developing countries, geopolitical risk has a lower impact on the energy transition as the demand for fossil fuels is highly inelastic and these countries have fewer economic resources to support the development of renewable technologies (Ben Cheikh and Ben Zaied, 2023; Li et al., 2024). In addition, some studies indicate a negative correlation between geopolitical risk and the energy transition (Wang et al., 2024b), where geopolitical threats have a more negative effect than geopolitical acts. Geopolitical risk can negatively impact transition by lowering environmental regulations (Shu et al., 2024). Also, in the case of China, geopolitical risk in 2012 – 2024 had a negative effect on renewable energy development due to supply chain disruptions of metals essential to the transition (Lin and Zhang, 2025).

In terms of representing geopolitical considerations in energy system or integrated assessment modelling, qualitative scenarios have been used. Pye et al. (2025) examined the impact of the war in Ukraine on global gas

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markets, using TIAM-UCL and three scenarios of gas trade and import and export capacities. Mi et al. (2025) analysed the impact of trade tensions between the US and China, particularly in terms of Chinese export of clean energy products, using the GATP model and creating scenarios of US and European tariffs on Chinese products. Harmsen et al. (2024) assessed how the war in Ukraine could affect the supply and demand for fossil fuels and renewable energy, using E3ME-FTT, GEM-E3, and IMAGE models with scenarios of a varying degree of impact. Zwickl-Bernhard and Neumann (2024) studied the evolution of liquefied natural gas trade in Europe, using a cost optimisation model of global gas supply and scenarios that combined geopolitics with climate action. Zhang et al. (2024) investigated the impact of updated nationally determined contributions (NDCs) and the EU-Russia energy decoupling on global fossil fuel trade, using GDyn-E model and scenarios of the combined effect of NDCs and Russia-Europe decoupling. Sampedro et al. (2024) examined the implications for the EU of a potential complete cut in Russian gas imports, using GCAM and comparing a current trends scenario with a scenario without Russian gas import. Moskalenko et al. (2024) analyzed the reduction in Russian gas import into Europe too, using GENeSYS-MOD and scenarios defined by an upper limit on gas supply. Chen et al. (2023) simulated short-term changes in global energy trade following energy sanctions and countersanctions between the EU and Russia, using GTAP-E and scenarios varying the degree of sanctions imposed. Flouri et al. (2015) studied the impact of a disruption in natural gas supplies from Algeria to Europe using Monte Carlo simulation as scenarios. Desogus et al. (2023) quantified the risk for crude oil supplies to Italy, modelling the transport routes and assigning a geopolitical risk index to each country crossed by a route, and developing risk scenarios by varying the risk of failure of each route.

This prevalence of qualitative scenarios to represent geopolitical considerations, however, leads to an integration gap. As empirical evidence on the actual energy system impact of geopolitical risks remains mixed and complicated, the qualitative scenarios and their model implementation could be far from the real-world trajectories. All the modelling to date has been forward-looking, which makes it impossible to evaluate the realism of model results except for stylised evaluation methods, such as model inter-comparisons or stylised facts (Wilson et al., 2021b). Another approach to account for geopolitical factors in models would be to integrate them as exogenous parameters and to modify the model structure (Trutnevyte et al., 2019). However, such an approach could not be found in the literature yet. And as argued earlier, hindcasting would become a beneficial evaluation approach for such a model with an enhanced representation of geopolitics.

3.3 Methods

In this study, 31 national electricity system models (27 countries of the EU, plus Iceland, Norway, Switzerland, and the United Kingdom) are used in a hindcasting mode from 1990 to 2019 (Section 3.3.1). The influence of geopolitical risks is incorporated into the model through the construction of six model versions using one of five geopolitical risk indices (Section 3.3.2). By means of hindcasting in 1990 – 2019, the obtained model results in terms of installed capacity for each technology are then compared against the real-world data using two accuracy indicators to evaluate which integration approaches and indices outperform the others in improving model realism (Section 3.3.3).

3.3.1 D-EXPANSE model

D-EXPANSE is a cost optimisation-based model that is characterised by its bottom-up and technology-rich structure with perfect foresight (Jaxa-Rozen et al., 2025; Trutnevyte, 2016; Wen et al., 2022). It calculates transition pathways with both the yearly capacity expansion and hourly generation dispatch. There exists a handful of model versions with various features evaluated through hindcasting, for instance, the model version with endogenous electricity demand and technology learning (Wen et al., 2023), myopic foresight (Shen et al., 2025), or with inclusion of societal factors and policy (Wen et al., 2025). In this study, the Basic model version is used as this model version is most similar to the structure of other widely-used techno-economic models, such as TIMES or Message. To implement the impact of geopolitical risks, we further develop the model by modifying parameter assumptions or model structure (Section 3.2.2). For hindcasting, we use the existing, harmonised historic dataset of national electricity system transitions in 31 European countries in 1990 – 2019 (Jaxa-Rozen et al., 2022), which includes data on electricity demand, technology and fuel costs, technology characteristics, and retirement of initial capacities. From historical data, we generate three representative days (72 hours for winter, spring and autumn, and summer) for each year for each country using K-means clustering method based on the historical electricity load profiles, where data is available. The model outputs are total system costs, CO_2 emissions, installed capacity and annual generation for 15 electricity technologies (including pumped hydropower as storage) and interconnection. As some deviations between the modeled cost-optimal pathways and the real-world pathways in these 31 countries can be attributed to climate policy (Jaxa-Rozen et al., 2025; Wen et al., 2023), we include the emission target for each country as a proxy for climate policy (Shen et al., 2024; Wen et al., 2025).

3.3.2 Incorporation of geopolitical risk

3.3.2.1 Geopolitical risk indices

We use five geopolitical risk indices (GPIs) to quantify the evolution of this risk over time because each index has its distinct profile and average values (see Figure B1 in ANNEX B). The starting point for these indices is the openly available GPI introduced by Caldara and Iacoviello (2022), which is computed as a fraction of newspaper articles related to adverse geopolitical events to the total number of news articles each month. However, this index has multiple drawbacks. It primarily represents the North Atlantic perspective as it is based on leading newspapers published mainly in the US, as well as UK and Canada. The global index covers a broad scope of geopolitical events, including countries outside Europe, and also terrorist acts and threats, which are not particularly relevant for our modelling. The index is also extremely dynamic because it is estimated monthly. Despite its availability for 44 countries, their index's behavior often does not accurately reflect the geopolitical challenges faced by the countries. For instance, two of the three major peaks in the Finnish GPI in 1990 – 2019 correspond to two negotiations in Helsinki between other countries.

Like in a sensitivity analysis, we therefore derive four different GPIs from the aforementioned index by Caldara and Iacoviello, and complement them with an index from another source. We use the maximum annual values instead of averages in order to reflect the shock effects rather than the permanent conditions of crisis events. The five final indices are:

1. European Geopolitical Risk Index (European GPI): We use the maximum yearly values for the 15 European countries with available monthly country-specific geopolitical risk index from Caldara and Iacoviello (2022) and Iacoviello et al. (2024): Belgium, Switzerland, Germany, Denmark, Spain, Finland, France, the United Kingdom, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, and Sweden. The index for a specific year is the average across countries of these values for that year, normalised to 100% over the entire timeframe of 1990 – 2019. Since these 15 countries are among the biggest in Europe and no data exists for the remaining 16 countries, we assume this averaged value to be accurate.
2. Global GPI without terrorism: Monthly values of the global geopolitical risk index from Caldara and Iacoviello (2022) are modified to exclude two of the eight categories of the index based on their share: terrorism acts and threats. Maximum monthly scores for each year from the obtained index are taken and normalised to 100% over the whole studied period.
3. Import GPI: It is calculated based on the geopolitical risk index from Caldara and Iacoviello (2022) and Iacoviello et al. (2024) of fossil fuel exporters to European countries, such as Australia, Canada, Norway, Indonesia, Russia, Saudi Arabia, and the US, inspired by Hille (2023) Using the data from the latter study on import dependence-weighted average GPI in supplier countries and the shares of net import per total energy consumption for gas, oil, and coal, we create the Import GPI, which is adjusted for the fraction of a specific fossil fuel in a country's power system. Missing data from the article for some years for some fuels are filled with averages across the whole timeframe for this fuel and country. The products of the geopolitical risk index and import shares for all studied countries (excluding Switzerland, as no data were available) are averaged to obtain the average European index for each fuel. To account for electricity production only, the resulting values are multiplied by the share of electricity generation in the total

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consumption of this fossil fuel in Europe (IEA, 2024); for the period of 1990-1999, the value for 2000 was used due to a lack of data. Finally, the Import GPI was created as an average between three European indices for each fossil fuel and was also normalised to 100%.

4. Geopolitical Peaks Index: This index is constructed from three prominent peaks of global geopolitical risk (Caldara and Iacoviello, 2022) to better reflect the lasting effects of geopolitical shocks. These peaks correspond to major geopolitical shocks from 1990 to 2019: the Gulf War of 1991, the terrorist attacks of 2001, and the Iraq invasion of 2003. To assess the lasting impact of these events, we construct the Geopolitical Peaks Index, consisting of two plateaus of 100%: one with a 3-year (1991–1993) and the other with a 4-year (2001–2004) duration, corresponding to these events.
5. European Energy Uncertainty Index (EUI): The last index is based on Dang et al. (2023), who calculates the share of words related to energy and uncertainty in the monthly reports of the Economist Intelligence Unit for each country. This index reflects the opinion of experts on the energy perspective of each country, in contrast to the newspaper-based geopolitical risk index used before. To reflect the average European energy uncertainty, the yearly maximum scores of 12 available European countries (Belgium, Greece, Denmark, Croatia, France, Germany, Italy, Sweden, the UK, Ireland, Spain, and the Netherlands) are averaged. The missing pre-1996 values are imputed using average levels across all years. Annual figures are normalised over the whole period to obtain scores of the European EUI.

3.3.2.2 Methods for integration in the model

As described in Section 3.2, geopolitical tensions affect the energy systems in various ways, requiring alternative methods to integrate geopolitical factors in modelling. The core idea of all our methods is that during periods of high geopolitical risk, governments and other actors strive to make the energy systems more resilient by relying more on reliable and locally available sources of electricity. We develop six versions of the implementation of geopolitical considerations in D-EXPANSE by enforcing more renewable or domestic technologies (1 and 2), by changing discount rates to represent investment risk (3 and 4), or by modifying energy security requirements (5 and 6):

1. Version focused on New Renewable Installations: A new constraint is added to require the country's share of newly built renewable energy capacities (solar PV, onshore and offshore wind power, hydropower plants, biomass and biogas power plants, geothermal plants, and municipal waste incineration plants) to be at least equal to the value of the GPI (in %) for every year, starting from 1991.
2. Version focused on New Domestic Installations: For countries that have at least one domestic fossil fuel (gas, oil, hard coal, or brown coal), a new constraint is set so that the country's share of the newly built capacities with domestic sources (renewable sources as before plus domestic fossil fuel technologies) is at least equal or higher to the value of GPI (%) for every year, starting from 1991. Section B2 of the ANNEX B describes how the twelve relevant countries have been identified: Bulgaria, Croatia, Czechia, Denmark, Germany, Greece, Hungary, the Netherlands, Norway, Poland, Romania, Slovenia, and the United Kingdom.
3. Version focused on Discount Rates for Renewables: Here we model the countries' response to elevated geopolitical risk by modifying the discount rate for certain technologies from the default 3.5%. As the risk associated with investments in different power plants changes significantly during periods of geopolitical instability, we adjust the discount rates proportionally to GPI at hand for renewable technologies up to a maximum of a twofold decrease at a 100% index level. To correct the fact that the average values of different GPIs vary substantially, we normalise each of the indices in this model version so that the minimal value equals 0 for all of them.
4. Version focused on Discount Rates for Domestic: here we merge the rationales of the second and third versions, and, if the country possesses domestic fossil fuel resources, we reduce the discount rates proportionally to the geopolitical risk indices for all domestic technologies up to a maximum of a twofold

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decrease. We also normalise each index as described in the third version.

5. Version focused on Capacity Margin Increase: Another way to modify the model to increase energy security during periods of elevated geopolitical risk is to increase the total capacity margin of the country's electricity system (the default value in the model is 20%). Therefore, we create a model version where we require an additional increase in capacity margin proportional to GPI, with a maximum rise of an extra 20% corresponding to a 100% geopolitical index.

6. Version focused on Diversification: This model version reflects the strategy of increased diversification to increase supply security (Cooke et al., 2013; Wu and Rai, 2017). We use the Herndahl–Hirschman index, also known as the Simpson Index, because it is the most suitable index to incorporate into the model in terms of computing:

$$HHI = \Sigma_{i=1}^{n} share\ of\ techno\log y_i^2 \qquad \text{(Eq. 3-1)}$$

   Since this index employs a nonlinear term, we apply piecewise constraints in the model and use the cost-optimal solution as a benchmark to additionally enhance diversification. We ensure that the sum of all installed capacities in this model version each year is greater than or equal to that in the *Basic* model version, thereby preventing a decrease in installed capacities. Additionally, diversification, measured as the reversed HHI, must increase proportionally to GPI in comparison to the *Basic* version, with a maximum increase of 5% corresponding to a 100% level of GPI. This degree of increase is chosen to observe the noticeable effect on the results and to ensure that most countries will have computable solutions, as stricter requirements for diversification often lead to infeasible solutions in the first modelled years. Also, for each country the earliest possible year of applying diversification constraint for the *European GPI* index is found and the constraint is applied starting from this year: 1992 for Greece, Iceland, the Netherlands, Norway and Sweden; 1994 for Czech Republic, 1996 for Spain, 2002 for France and Bulgaria, and 1991 for the rest of the countries. Figure B3 of the ANNEX B provides examples of the diversification parameter evolution over studied period for two countries.

In cases where no feasible solutions are found for certain countries (Poland, Italy, Germany, and the UK) due to excessive restrictions, GPIs were halved for 1990 and 1991.

3.3.3 Model evaluation using hindcasting

To quantitatively assess how integration of geopolitical considerations into D-EXPANSE improves the model realism, we use hindcasting in 1990–2019 to compare modelled cost-optimal transition pathways against real-world data. In particular, we focus on the accuracy of installed capacities of the technology mix of each country because it best reflects the investment decision-making under geopolitical constraints. We use two indicators (Wen et al., 2022): the symmetric mean absolute percentage error (sMAPE) and the Root Mean Squared Logarithmic Error (RMSLE). These two errors are complementary: while sMAPE is suitable for comparing the accuracy of the same model outputs in different countries and indicates the absolute magnitude of the deviations (higher values correspond to less accurate results), the RMSLE indicator shows the logarithmic deviations instead of percentage ones and prevents the exaggeration of the values with small absolute deviations. We compute their average error values across all years for the installed capacities of all technologies to assess the evolution of the technology mix. To compare the overall performance of the model version across countries and versions, we calculate averages across all the technologies.

3.4 Results

3.4.1 Country-specific accuracy of all model versions

Once geopolitical considerations are integrated, ten of the 31 studied countries have a median accuracy across all model versions that outperforms the Basic version in terms of RMSLE, and only sixteen in terms of sMAPE (Figure 5). Eight countries (Denmark, Germany, Spain, Poland, Hungary, Malta, Portugal, and the UK) exhibit median model performance that is closer to the real-world trajectory in terms of both indicators. In contrast, most countries perform worse on average, according to RMSLE. The two indicators do not correlate perfectly, and sometimes they result in opposite signs of change for medians (for example, Luxembourg, the Czech Republic, and Latvia). These discrepancies can be explained by the definition of these errors, where high sMAPE scores are typical for pathways involving capacities of the technologies that are not present in the real world. On the sMAPE plot, some cases of extreme malperformance with an increase of around 50% or more from the Basic version are prominent for Iceland, France, Lithuania, Estonia, and Hungary. As can be seen in Figure S9 of the ANNEX B, the installed capacity mix for these countries is not drastically different from the Basic version, but the presence of new minor technologies that are not in the Basic version substantially increases the sMAPE scores.

However, average and median values across all model versions can lead to incomplete conclusions due to their dependence on poorly performing model versions. For almost every country (29 countries out of 31), there exists at least one model version that performs more than 1% better than the Basic version, and only for Lithuania and Austria, we observe no improvements for both indicators. However, there is no dominance of any particular model version, with the most frequent one being the New Renewable Installations in around a third of countries.

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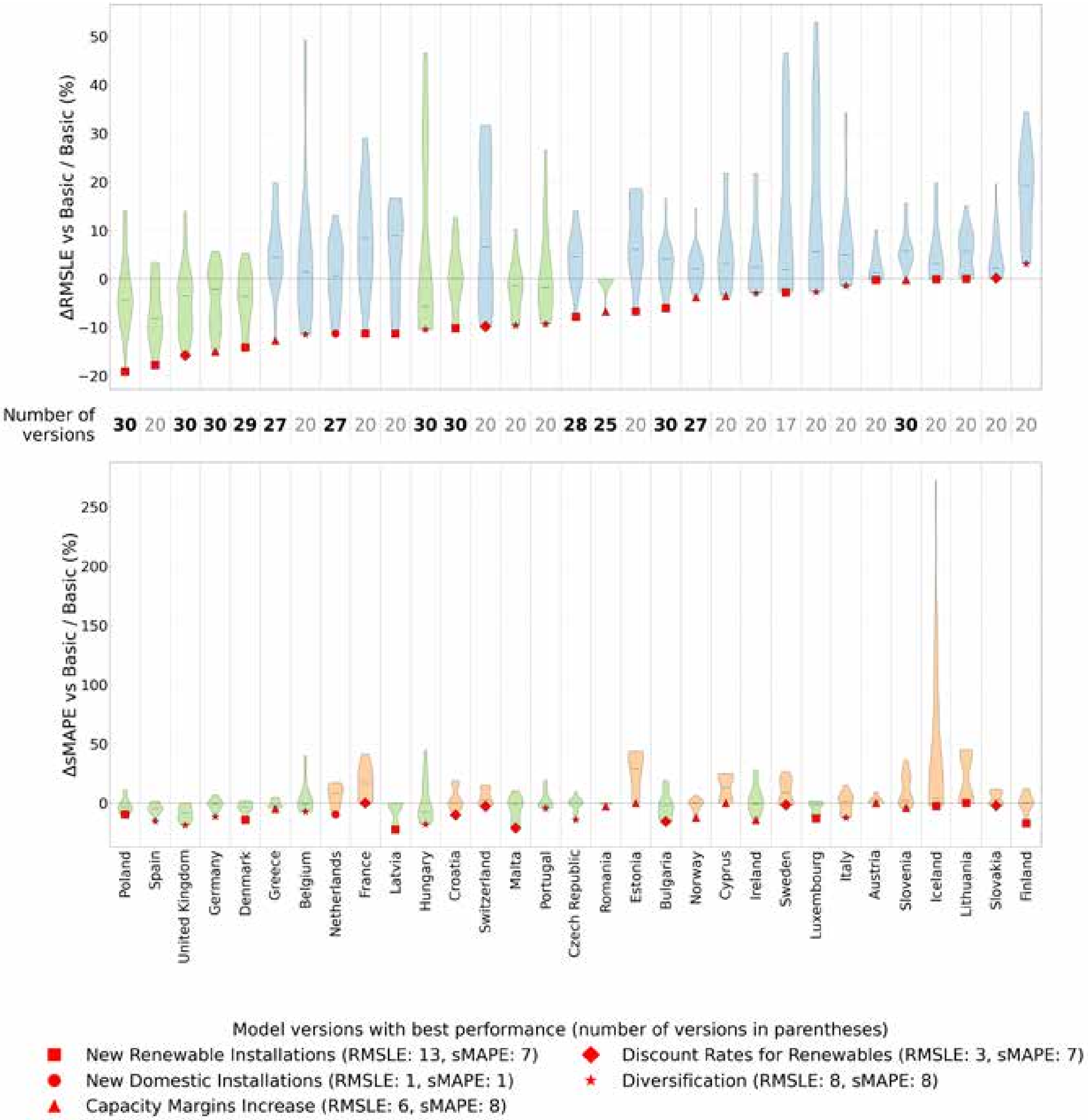

Figure 5: Accuracy of the modelled pathways quantified by RSMLE (top) and sMAPE (bottom) for all different model versions (*New Renewable Installations*, *Discount Rates for Renewables*, *Diversification*, *Capacity Margin Increase,* and *New Domestic Installations* with *Discount Rates for Domestic* for countries with domestic fossil fuels) for each of the five GPIs (in total 30 versions per country at maximum). The error is shown as the ratio to the error of the *Basic* model version; hence, higher values mean lower accuracy. Best-performing model versions are indicated for each country by the shape of the lowest point. The total number of model versions that compute feasible solutions is shown between the plots; numbers for countries with domestic fossil fuels are written in bold. Countries are ordered by the biggest relative improvement of the RMSLE vs**. the *Basic* model version. Countries with median output better than the *Basic* model version are coloured green.**

Nonetheless, for all countries, including the ones with improved hindcasting performance after integration of the geopolitical considerations, the absolute values of the accuracy indicators still remain far from zero, indicating that it is impossible to reach perfect model accuracy (Figure B4 of the ANNEX B). As RMSLE accounts for the absolute and not relative deviations, the average result is sensitive to the size of countries: smaller countries obtain lower scores due to their smaller size. Remarkably, two countries with the highest RMSLE scores of the Basic version and among the largest energy systems, the UK and Germany, obtain substantially improved outputs with the geopolitical risk incorporated, as measured by both indicators. A more detailed analysis of all versions (Figure B5 of the ANNEX B) shows that different model versions differ in terms of accuracy values, with no clear best version across all countries. Among these versions, the most variable results are produced with the New Renewable Installations and Diversification model versions. The Diversification version is usually either the most accurate or the most inaccurate among all individual versions, as indicated by the sMAPE. At the same time, the Discount Rate for Renewables often shows changes in the same direction as the New Renewable Installations version, but on a smaller scale. For 12 countries that extract significant amounts of at least one fossil fuel on their territory, promoting technologies related to these fuels, in addition to renewable generation, in the New Domestic Installations and the Discount Rate for Domestic versions, more frequently leads to worse outcomes than promoting renewable technologies only. Only three of them, Poland, Germany, and the Netherlands, demonstrate better hindcasting accuracy in the New Domestic Installations version with some GPIs. The versions of Discount Rates for Renewables or Discount Rates for Domestic typically perform closely together.

We also observe that for most of the countries, differences in the model versions typically have a greater impact on the hindcasting accuracy than the choice of GPI, despite the very different profiles of the latter (Figure B5 in the ANNEX B). Based on this, the following subsection provides a more detailed analysis of only one of the indices – Global GPI without terrorism – by assessing all model versions for each country, not only through overall scores but also by visually examining the changes in their installed capacity mixes over the years. The choice of the Global GPI without terrorism is due to the absence of diverging results for most of the countries (e. g. Greece or Croatia with Geopolitical Peaks Index, Norway with European GPI, as seen in Figure B5), feasibility of maximal number of versions for all countries, and the relatively high accuracy of the versions that have shown the best performance with this GPI.

3.4.2 Technology-specific hindcasting accuracy

Countries that showed, on average, improved hindcasting performance have some similar features. The UK (Figure 6) is a good example as the energy transition happened there during the whole studied period when hard coal was initially gradually replaced by gas and later by a diverse mix of renewable technologies. The UK was also involved in geopolitical tensions as reflected in the applied GPI, whereas the Basic model version does not accurately account for the transition towards renewable generation, and hence the implementation of geopolitical considerations increases the renewable share in the technology mix and makes model outputs more closely aligned with the real world (Figure 6a). Both accuracy indicators reflect this: sMAPE and RMSLE scores for onshore wind power, biomass, and biogas are lower in all pathways with changes in these technologies, as they replace gas installations, oil, and nuclear capacities that were overbuilt in the Basic version, also decreasing their deviation from the real-world data. The most accurate model outputs, according to the sMAPE indicators in Figure 6b, are those for the model versions of New Renewable Installations and Diversification. However, RMSLE indicates that some renewable technologies (offshore wind power and biomass) become overbuilt, especially during earlier years, for the New Renewable Installations version, resulting in the same overall RMSLE as for the Basic version. Interestingly, in this version, which differs the most from the others, we observe the installation of a small capacity of solar PV in the last year of modelling, which is a rare case for the Basic model version of any country (due to the high PV investment costs in the past). The version that improves average outputs the most, according to both indicators, is the Diversification, as it foresees onshore wind power development without an excess of offshore development, and at the same time maintains a higher oil power plants capacity until 2020, while overbuilding nuclear capacities, especially after 2010.

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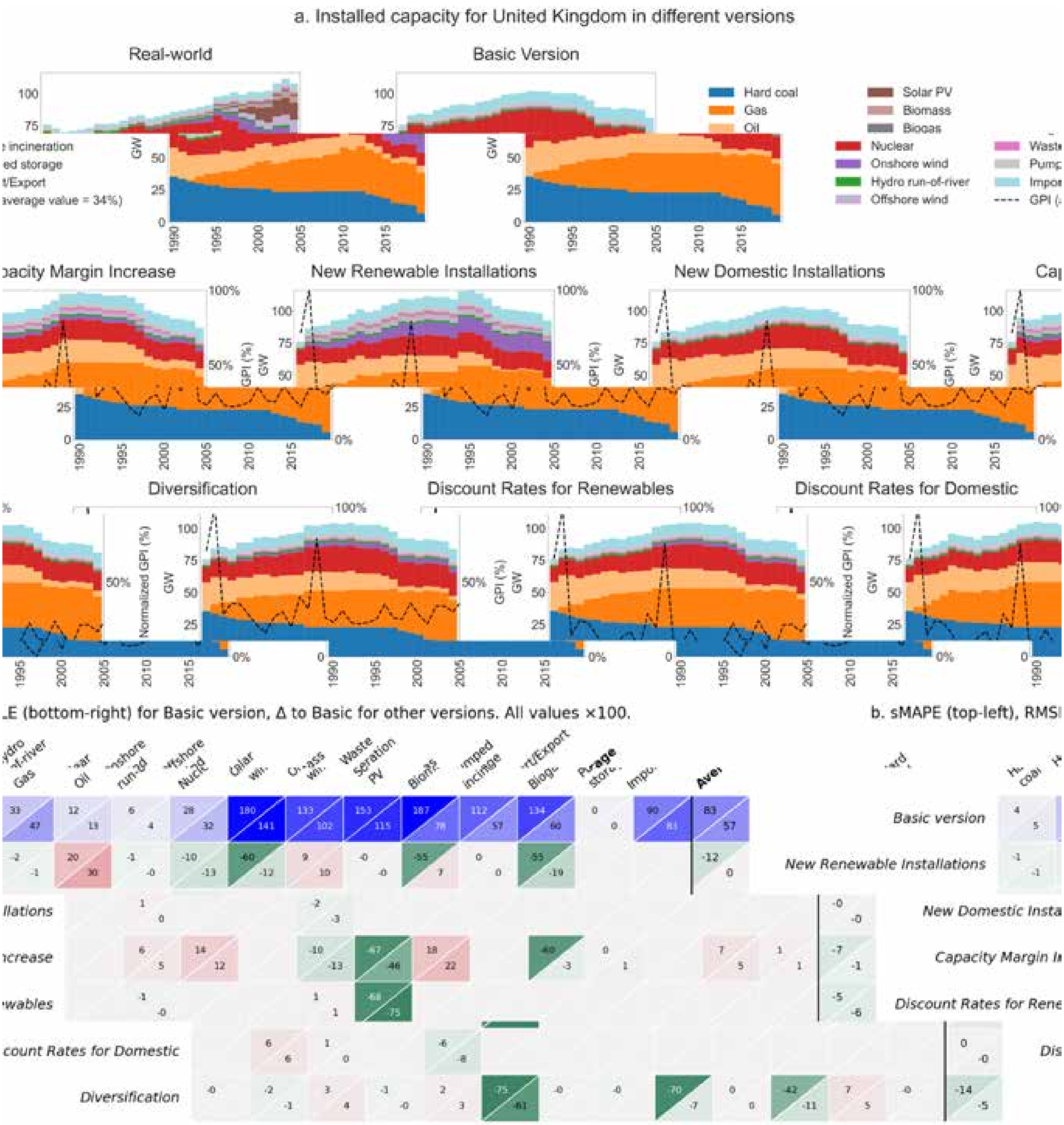

Figure 6: In-depth analysis of the UK case: (a) installed capacities in real-world transition in 1990-2019, Basic model version, and six different model versions, using Global GPI without terrorism as index, and (b) heatmap with computed sMAPE and RSMLE indicators of the Basic model version and error differences in all other model versions with Global GPI without terrorism. For the Basic version, absolute values of indicators are shown; for all other versions, the differences with the Basic version as a ratio are shown. Higher values signify less accurate model outputs; hence more accurate outputs are colored green and less accurate colored red.

Model versions that show minor changes in the UK in comparison with the Basic one are New Domestic Installations and Discount Rate for Domestic, because gas and oil, which are already overbuilt in the Basic version, are domestic fossil fuels for the UK. The additional incentives for these technologies do not produce noteworthy changes in the model results. Although with four other GPIs the Discount Rate for Domestic version is closer to the Discount Rates for Renewables rather than New Domestic Installations version. Hard coal is also almost a domestic fossil fuel for the UK in our definition (Section B2 in the ANNEX B), as it was mined intensively in earlier years, and its production has gradually decreased, as did its use for electricity generation. As it is not promoted

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as domestic fossil fuel in our modelling, we do not observe its overbuilt in none of the modelled versions. The Capacity Margin Increase version is similar to the Diversification version, with increased capacities of oil power plants and offshore wind power, which are overbuilt and replace nuclear power plants' capacity of the Diversification version. As expected, the main deviations from the Basic model version when including geopolitical considerations occur during the peaks of GPI. Significant changes occur either around 1991 (for New Renewable Installations and Capacity Margin Increase versions) or around 2003 (for the Diversification version) (Figure 6). The same observation is true for other GPIs, as demonstrated in Figure B6 in the ANNEX B. Since all used indices have elevated scores because of the Gulf War at the beginning of the 1990s, the changes in the modelled technology mixes mainly occur during that period and are similar across the versions. In cases of European EUI and Import GPI indices with higher average values, we observe a more pronounced buildup of renewable technologies, especially in the New Renewable Installations version (Figure B7 in the ANNEX B). The primary point of improvement for all model versions is the increase in onshore wind capacities, and frequently, the decrease in nuclear and oil capacities.

Very similar results are seen in three other large countries with overall improved outputs: Germany, Denmark, and Spain (Figure B8 in the ANNEX B). The case of Denmark is remarkably similar to the UK, as the New Renewable Installations version better reflects the transition from coal to domestic fossil fuels (gas and oil), which are overbuilt in the Basic version, and later to renewable installations. The main improvement in the New Renewable Installations and Discount Rate for Renewables versions is achieved due to faster buildup of wind power. Similarly, the improvement of Spain's pathways, stipulated by increased wind power capacities and decreased nuclear power compared to the Basic version, is notable, as Spain does not possess any domestic fossil fuels. For Germany, New Renewable Installations and Diversification versions perform better than the Basic version because they tend to predict a more diverse energy mix (similarly to the UK) and decrease nuclear capacities, which is closer to reality due to the political decision to phase out nuclear power. However, one of the observed deteriorations in Germany is specific to the domestic brown coal due to its overutilisation in the New Domestic Installations version. Although the worst prediction is observed for hydropower dams, this case is not special. Around half of the countries experience higher sMAPE due to the overbuilt capacities of hydropower dams in the model versions, with geopolitics, especially when this technology is not present in real-world transitions. For some countries (such as Germany and Finland), this is the primary reason for the poorer hindcasting accuracy. Belgium, Italy, and Finland, which have a medium size, diverse electricity systems and no significant domestic fossil fuel reserves, exhibit similar reactions to GPI incorporation: an increase in renewable capacities and additional diversification during periods of geopolitical risk peaks (Figure B8 in the ANNEX B). However, the modelling does not reach higher accuracy due to the overbuilding of certain renewable technologies (including the hydropower dams), often because they are built too early, during the peaks of GPIs. Countries such as Malta and Romania show that indicators like sMAPE and RMSLE are not always sufficient for understanding the model's performance. Despite the decreased average scores in one or both indicators, visual analysis of their technology mix shows only slight changes, mostly involving minor technologies. At the same time, their main electricity technologies remain unchanged or undergo slight modifications from the Basic version.

Another example of a more moderate response to the incorporation of geopolitical factors in modelling is the case of the Netherlands (Figure 7). Despite the similarity to the already discussed countries (with main variations in the New Renewable Installations and Diversification versions, as well as improvements in outputs of onshore wind capacities and solar PV), only minor changes are observed from the Basic version, especially in the case of Capacity Margin Increase. As the changes in the technology mix are not prominent and occur primarily in the second half of the studied period in the real-world transition, the first spike of GPI has a minimal effect on any of the model versions. The impact of the second peak in 2003 is substantial only for the New Renewable Installations version, which provides relatively good performance. The versions of Discount Rates for Domestic and Discount Rates for Renewables look almost identical, despite gas being a domestic resource. Improved accuracy in other renewable technologies is partially offset by the appearance of hydropower dams (which resulted in higher sMAPE) and overbuilding of offshore wind and nuclear power in some versions. Similar observations of weak response to the GPI introduction, late changes in the real-world transitions that are not represented in any model version,

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and an overall effect around zero, sometimes due to the modelling of dams, appear in many average size and large countries, such as Austria, the Czech Republic, France, Greece, Latvia, Poland, Portugal and Sweden (Figure B8 in the ANNEX B).

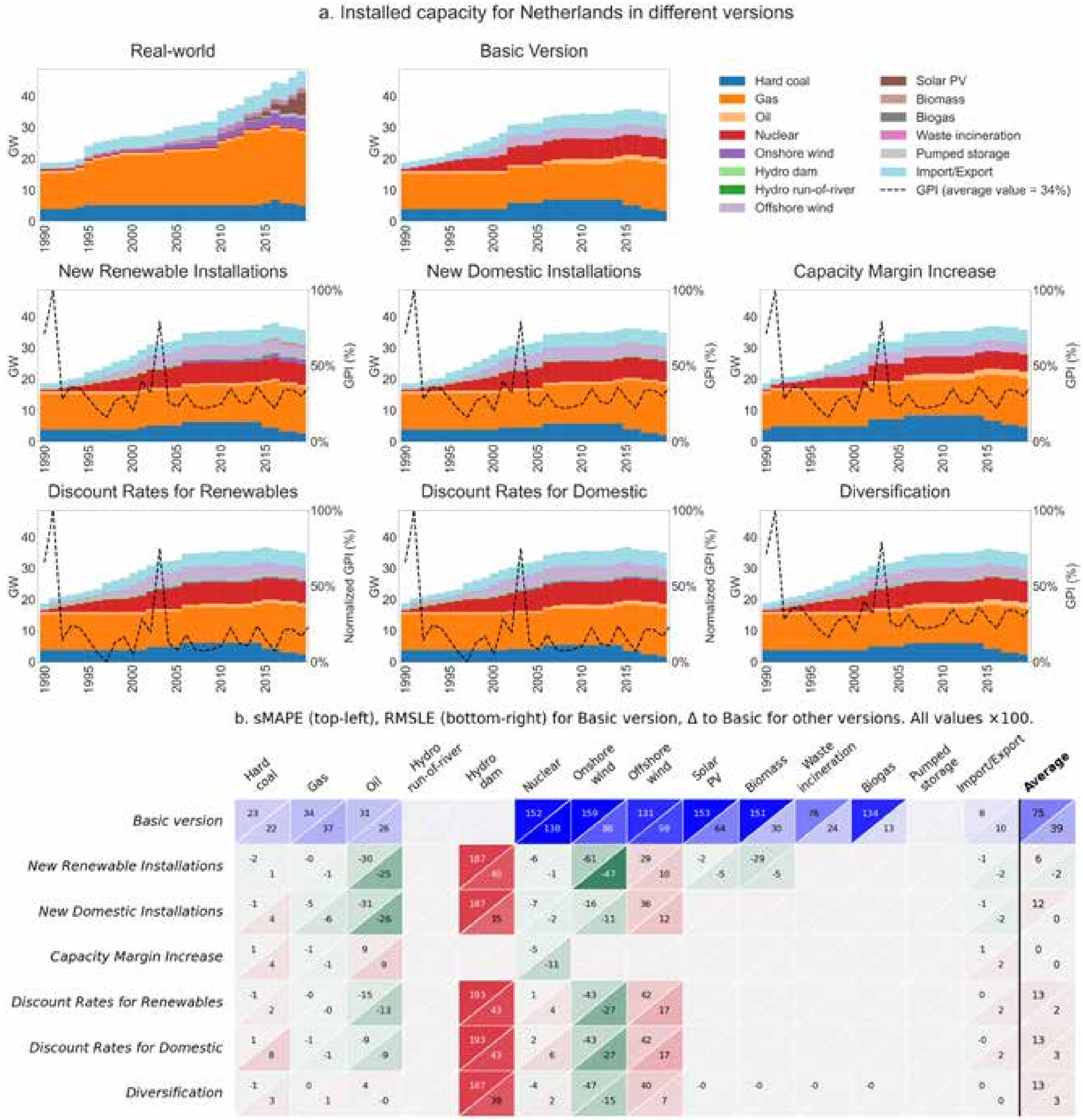

Figure 7: In-depth analysis of the Netherlands case: (a) installed capacities in real-world transition in 1990-2019, Basic model version, and six different model versions, using Global GPI without terrorism as index, and (b) heatmap with computed sMAPE and RSMLE indicators of the Basic model version and error differences in all other model versions with Global GPI without terrorism. For the Basic version, absolute values of indicators are shown; for all other versions, the differences with the Basic version as a ratio are shown. Higher values signify less accurate model outputs; hence more accurate outputs are colored green and less accurate colored red.

As for the rest of the countries (Figure B8 in the ANNEX B), Cyprus and Ireland are rare examples of small countries with a limited set of utilised technologies and already overbuilt renewable capacities in the Basic version of the model (due to the applied CO_2 emissions targets in the Cyprus case). For these countries, additional renewable capacities in model versions with geopolitical considerations only deteriorate model accuracy. The last group of countries with similar changes includes relatively small countries with overbuilt capacities and weak

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changes throughout the studied period: Switzerland, Estonia, Croatia, Lithuania, and Iceland. For these countries, in most model versions, we observe almost no variation in comparison to the Basic version, as there is no need to build new capacities anyway. Additionally, these countries often exhibit poorer performance in Diversification and Capacity Margin Increase versions due to the requirement for excessive capacity that they do not need.

3.5 Discussion

In this study, we attempted, for the first time, to incorporate geopolitical considerations into electricity system modelling by modifying the model itself with six different integration methods and using five different GPIs, instead of adopting a more common scenario approach. By verifying model outputs from 1990 to 2019 against the real-world data in 31 European countries, we found that 80% of countries have at least one version of the model that is 1% or more accurate than the Basic version, based on each of the two indicators used. However, if looking at all model versions, then on average, they frequently do not yield an improvement, as only eight countries show a stable improvement in their average outputs according to both accuracy indicators. We further find that the specific profile of GPI does not play a significant role for the model outputs. The best model version for output varies by country, and the New Renewable Installations version is the most common version to appear in terms of improved accuracy in around a third of countries. There are some similarities among the countries too. For large countries, like Germany and the UK, modelling with the GPI enforces a higher share of renewable generation, thereby improving the output. This logic does not apply to all countries with relatively large electricity systems, though, as for some, the real-world transition occurred later than the major peaks of GPIs (Poland, Belgium), and for others, there is a mismatch between the modeled and really built renewable technologies (France). For smaller countries, countries with prevailing technologies or those with less dynamic systems in the studied period, GPI incorporation often yields less accurate results, particularly as measured by the sMAPE, like in the cases of Switzerland, Estonia, Luxembourg, and Iceland.

The limited improvement in outputs when incorporating geopolitical considerations into cost optimisation-based modelling can be explained by several factors. First, the response of policymakers and investors to increased risks can vary depending on the specific economic and geographic situation of a country and the time (Erdogan et al., 2024). Motivation behind some decisions in energy generation is not always straightforward, and frequently, the response to geopolitical risk is intertwined with climate protection, affordability, and supply security (Crowley-Vigneau et al., 2023). In fact, there is currently no consensus in the literature on the empirical evidence for the impact of geopolitical risks on countries' energy transitions (Anser et al., 2021; Zhao et al., 2023). We employ the hypothesis from the literature that, during the studied period for European countries, increased GPR had a positive effect on the energy transition (e.g. Sweidan, 2021a, 2021b), but we cannot claim that this assumption is always valid based on our results. Second, investment decisions and construction of the power plants can, in some cases, take a long time, leading to a certain time lag, which has not been modelled. Third, we employ a perfect foresight model, which differs from real-world decision making where the onset and resolution of geopolitical instability often occur unexpectedly (e.g., the 9/11 terrorist attack). This means the model may predict the ideal time to install new capacities in the long term, even if that does not accurately reflect real-world situations with shorter time horizons for decision-making. Forth, the range of geopolitical events – from terrorist attacks to nuclear war threats – is too broad and may require a case-by-case approach to integrate them into energy system models (Cai and Wu, 2021). Generalising and simplifying these different types of events can result in less accurate outputs.

This study has several limitations that could be addressed in future research. All the GPI integration methods target future development of the electricity system (specifically, new capacity installations) rather than its current state and immediate responses to unexpected events, which may be the case in the real world. Some common response decisions are also not modelled in D-EXPANSE or other optimisation-based models, such as lifetime prolongation of certain power plants, demand reduction requirements, or restrictions on electricity trade (Kuzemko et al., 2022). Geopolitical events also have a significant indirect economic influence on the development of the energy systems through variations in fuel prices, inflation, and changes in energy costs (Iacoviello et al., 2024; Noguera-Santaella, 2016). For hindcasting, we used historical cost data and were hence not able to endogenously

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capture the evolution of costs. In addition to addressing these issues, future research could also apply time lags when incorporating the GPI (Hille and Oelker, 2023), utilising myopic model version (Shen et al., 2024), differentiate versions by incorporating multiple GPIs by type of geopolitical risk (Wang et al., 2024b), explore alternative integration methods to account for the controverse effects of geopolitical risk on energy transition (Luo and Sun, 2024; Pata et al., 2023), experiment with whole system and not only electricity sector modelling, and extend the range of countries covered, including those in the global South.

This study also provides insights and raises fundamental questions for forward-looking modelling and for the integration of other societal factors in energy system models. In terms of forward-looking modelling, the reasons for geopolitical tensions and how they shape energy transitions in the past are not the same as the ones in the future. While conflicts and rivalries from 1990 to 2020 were frequently driven, among other factors, by the control of fossil fuel resources, the current and future situations may be different (Noguera-Santaella, 2016; Overland, 2019). As countries transition to renewable generation, advanced technology and critical minerals and metals are beginning to play an important role in shaping the geopolitical landscape (Lin and Zhang, 2025; Su et al., 2021). However, empirical evidence is by far insufficient to know what kind of strategies the countries may adopt to respond to these geopolitical challenges. In terms of modelling geopolitical considerations, by describing the complex and variable geopolitical landscape with a one-dimensional index, we clearly oversimplified. The possibility of quantitatively estimating the influence of military conflicts in different regions, terrorist attacks and threats, as well as controversial relations with neighboring and fuel-exporting countries, remains questionable. For using such a parametrisation, numerous assumptions are made, which can limit the ability to model energy transition more accurately, as the results are frequently sensitive to these assumptions. However, a similar pattern has been observed for the integration of all kinds of societal factors in modelling (Trutnevyte et al., 2019), such as market liberalisation (Jaxa-Rozen et al., 2025), acceptance (Wen et al., 2024), investment risk (Fisch-Romito et al., 2025b) and even policy (Shen et al., 2025; Wen et al., In preparation). This specific study on geopolitical considerations reiterates how difficult the challenge is to increase the realism of energy models, especially if the results are verified for quality using hindcasting.

3.6 Conclusion

In this study, we incorporated geopolitical factors in the cost optimisation-based D-EXPANSE electricity system model for 31 European countries and verified the accuracy of the obtained results against real-world data over the period of 1990–2019. First, five geopolitical risk indices in Europe were used to represent from slightly different perspectives, and then six different methods to integrate these indices into the model were created and tested. We modelled the possible effects of geopolitical risks by enforcing more renewable or domestic technologies, by changing discount rates to represent investment risk, or by modifying energy security requirements, such as increasing capacity margin or diversifying investments. For most of the countries, there were increases in the hindcasting accuracy of installed capacities of the whole technology mix with selected model versions, but not all versions by far improved accuracy. Most frequently, the best-performing version consisted of constraining for more new renewable installations (even above climate policy). Larger countries' energy systems were modelled more accurately than smaller ones or countries with pre-existing overcapacities, as the model versions with geopolitical considerations better reflected the tendency towards diversification towards renewable installations. However, the core reasons behind the real-world transitions can be attributed to different factors, not only geopolitical ones, making it hard to disentangle effects of different societal realities. We thus conclude future research should further experiment with integration of geopolitical risks and various other societal factors in the models, necessarily followed by hindcasting exercises, to ensure that the models produce realistic transition pathways to be fed into policy making.

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4 Climate finance

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The following study (Study 12) was co-designed with stakeholders as part of IAM COMPACT's Policy Response Mechanism, during a workshop on EU decarbonisation in the global economy. A central focus was the forthcoming New Collective Quantified Goal (NCQG) on climate finance, which is set to replace the $100 billion per year target under the UNFCCC from 2025 onwards. The NCQG is expected to be more ambitious, needs-based, and responsive to evolving climate challenges, encompassing not only mitigation but also adaptation, loss and damage, and just transition priorities. The workshop aimed to (1) explore how the NCQG can be structured to reflect and respond to the specific priorities of vulnerable and developing countries, with particular attention to scaling and targeting adaptation funding; (2) examine reforms to the international climate finance system that would better align financial flows with the scale, pace, and nature of investments required to achieve the goals of the Paris Agreement; and (3) identify concrete policy instruments to overcome fiscal constraints in developing nations and mobilise a sustained surge in climate finance, including innovative debt mechanisms, risk-sharing tools, and revenue-generating approaches.

4.1 Introduction

Climate change poses a large aggregate risk to the economy and the financial system (Litterman et al., 2020). A central challenge in climate policy is that climate protection constitutes a global public good, delivering benefits to all irrespective of who bears the costs. The financial burden of taking action is distributed unevenly across sectors and regions, with developing countries facing greater constraints in mobilising resources for mitigation and adaptation. To enable equitable participation and effective global action, the international community recognised the need for dedicated support from those with greater historical responsibility and financial capacity (Paterson & Grubb, 1992). Hence, the concept of climate finance was formally articulated at the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro in 1992, where Parties agreed that developed countries "shall provide new and additional financial resources" to developing countries to meet the full and incremental costs of addressing climate change (UNFCCC, 1992). Under the UNFCCC framework, only developed country Parties are obligated to provide and mobilise climate finance for developing countries, acting as the primary sources of such funding, and to report on their actions in this regard. At a minimum, this obligation applies to the Parties listed in Annex II of the Convention. This early definition of climate finance described it as local, national or transnational financing, drawn from public, private and alternative sources of financing, that seeks to support mitigation and adaptation actions that will address climate change (Long et al., 2022). In 2009, developed countries committed to mobilising USD 100 billion per year by 2020 to support climate action in developing countries, an annual target intended to extend through to 2025 (Songwe et al., 2022). The Paris Agreement reaffirmed this commitment in Article 9, which states that *"developed country Parties shall provide financial resources to assist developing country Parties"* while Article 2.1c calls for 'making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development', positioning finance as one of the Agreement's three overarching goals (UNFCCC, 2015). This underscores that without aligning finance in both the real economy and the broader financial system with climate objectives, mitigation and resilience goals cannot be achieved (Zamarioli et al., 2021).
Defining climate finance in a universally accepted way remains challenging, as there is still no agreed definition of what constitutes "climate finance" (IPCC, 2023). Currently, Parties and observers face significant inconsistencies in how climate finance is reported as some count gross financial flows, others report net flows, loans and non-concessional instruments are often reported alongside grants without clarity on their grant- equivalent, and there is no universally agreed method to distinguish climate- specific finance from broader development finance.- The operational definition of the UNFCCC Standing Committee on Finance reads "*Climate finance aims at reducing emissions and enhancing sinks of greenhouse gases and aims at reducing vulnerability of, and maintaining and increasing the resilience of, human and ecological systems to negative climate change impacts."* A further challenge lies in inconsistent accounting methodologies which complicates assessments of

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progress or climate consistency and alignment. The mobilisation, allocation, and governance of climate finance is critical for low- and middle-income countries to achieve their Paris Agreement goals (Isah et al., 2025), and directly linked to the implementation of parties' Nationally Determined Contributions (NDCs). While most developing countries make their mitigation and adaptation contributions conditional upon receiving international support, climate finance remains fragmented, inadequately scaled, and often misaligned with the development and adaptation needs of those countries. The costs of implementing all conditional contributions are too high to be covered by previous promises of support from developed countries, even if the entire annual $100 billion of climate finance were earmarked for NDC implementation (Pauw et al., 2020). The US$100 billion goal was not set in relation to needs, nor was it expected to fully meet them – it was the outcome of a political compromise. Given that the goal had no scientific or technical basis, it placed no constraints on what counted towards it.

At COP27, the Independent High-Level Expert Group on Climate Finance (IHLEG) published a report estimating the climate-related investment needs of developing countries (Songwe et al., 2022). Drawing on aggregated findings from multiple studies and national assessments, following the methodology of (Bhattacharya et al., 2022) the report identifies three priority areas: (i) the energy transition, (ii) adaptation and resilience, including loss and damage, and (iii) restoration of natural capital through sustainable agriculture, food and land use practices, and biodiversity conservation. It estimates that, excluding China, developing countries will need to collectively invest about $1 trillion annually by 2025, rising to $2.4 trillion annually by 2030. To meet these needs, the report calls for an additional $1 trillion in external financing per year by 2030. At COP29, an agreement was reached to triple finance to developing countries, from the previous goal of US$100 billion annually, to USD 300 billion annually by 2035. One key element in the design of this New Collective Quantified Goal (NCQG) on climate finance is to resolve persistent accounting and definitional issues surrounding what is counted as "climate finance."

However, these technical issues alone cannot explain the chronic shortfall in funding; the more fundamental barrier lies in the lack of political will among developed countries to deliver on their commitments at the necessary scale and speed. Numerous studies have shown that climate finance pledges have been shaped more by political bargaining than by scientific assessments of needs (Pauw et al., 2020; Weikmans & Roberts, 2019), as these pledges are still not emerging from robust estimations of adaptation and mitigation costs, even though such estimates are readily available (CPI, 2025; IPCC, 2022a; UNEP, 2024). Moreover, while wealthier nations have repeatedly reaffirmed their obligations under the UNFCCC and Paris Agreement, delivery has often been constrained by domestic political considerations, competing fiscal priorities, and reluctance to commit substantial public resources (Roberts & Weikmans, 2017). This political inertia not only undermines trust between developed and developing countries but also risks entrenching structural inequities in the global climate regime, perpetuating a "credibility gap" in international climate governance, and reproducing existing dependency dynamics.

Building on these historical commitments and ongoing challenges, understanding the forms, flows, and governance of climate finance is essential to assessing its adequacy, equity, and effectiveness. Climate finance is delivered through a wide range of instruments, i.e., grants, concessional and non-concessional loans, guarantees, equity investments, and blended finance, each with different implications for debt sustainability, fiscal space, and long-term development trajectories in recipient countries. Global climate finance flows are tracked through both top-down approaches, such as aggregate reporting by multilateral development banks (MDBs) and UNFCCC submissions, and bottom-up needs assessments embedded in national planning processes, including Nationally Determined Contributions (NDCs), National Adaptation Plans (NAPs), and Long-Term Low Emission Development Strategies (LT-LEDS). A persistent governance challenge lies in bridging the gap between these two perspectives: aligning international finance mobilisation with locally defined priorities while ensuring transparency, accountability, and coherence across multiple delivery channels. This analysis proceeds by first examining the composition and trends of climate finance flows, then assessing how needs are quantified and communicated, before evaluating the governance structures that mediate access and distribution. The paper concludes by identifying structural reforms that could help enhance both the scale and the justice of climate finance, ensuring it is fit for purpose in the decisive decade for climate action.

4.2 Forms of finance

Based on the Climate Policy Initiative's (CPI) framework, climate finance consists of three elements (Figure 8): Mitigation finance refers to financial resources directed towards activities that contribute to reducing or avoiding greenhouse gas (GHG) emissions, including those regulated under the Montreal Protocol, or to maintaining and enhancing GHG sinks and reservoirs (CPI, 2025). Adaptation finance encompasses resources allocated to activities aimed at reducing the vulnerability of human or natural systems to climate change impacts and climate-related risks, by maintaining or enhancing adaptive capacity and resilience. Dual benefits finance covers resources directed towards activities that simultaneously contribute to both climate change mitigation and adaptation, meeting the respective criteria for each. Climate finance can be classified according to its origins, actors, instruments, sectoral focus, geographic allocation, and targeted development status. The origins of finance may be international, domestic, or indeterminate, reflecting the transnational nature of capital mobilisation for climate action. Climate finance actors are categorised into public and private entities, each playing distinct roles in mobilisation and delivery. Public actors include development finance institutions, governments and their agencies, national and multilateral climate funds, state-owned enterprises and financial institutions, export credit agencies, and public funds. Private actors comprise corporations, households and individuals, commercial financial institutions, institutional investors, private funds, and third sector organisations. This dual structure reflects the hybrid nature of global climate finance governance, in which public funding often serves a catalytic role in leveraging larger volumes of private capital (Griffith-Jones & Ocampo, 2018). In terms of financial instruments, mitigation and adaptation efforts are supported through a variety of channels, including balance sheet financing (both debt and equity portions) and grants (i.e., non-repayable transfers in cash, goods, or service, often essential for funding public goods and capacity-building initiatives (OECD, 2022)). Debt instruments range from low-cost concessional loans, extended at below-market terms to lower borrowing costs, to market-rate debt such as term loans, credit facilities, or mezzanine financing, typically extended under commercial conditions (Bhattacharya et al., 2022). Project-level debt is serviced directly from the project's cash flows, while project-level equity involves risk-sharing through equity stakes in ventures, with returns dependent on project performance. Balance sheet financing, in contrast, uses the corporate or institutional balance sheet for direct debt or equity investment, potentially enhancing leverage capacity. Innovative mechanisms, such as conditional debt relief, climate-for-debt swaps, and mission-oriented investment funds, are increasingly proposed to alleviate fiscal constraints in the Global South (Volz et al., 2021). While multilateral channels like the Green Climate Fund aim to mobilise large-scale resources, critiques point to slow disbursement, administrative complexity, and limited transformational capacity (Coetzee, 2024). Notably, risk mitigation instruments (e.g., partial risk guarantees, political risk insurance) which could play a significant role in de-risking investments in high-vulnerability contexts, are not yet systematically included in reporting frameworks, representing a gap in tracking and reporting. The sectoral distribution of climate finance spans a broad range of activities, from agriculture, forestry, and other land uses to buildings and infrastructure, energy systems, industry, transport, waste management, water and wastewater, information and communications technology, and cross-sectoral interventions. This diversity underscores the multi-dimensional nature of climate action, integrating both mitigation and adaptation objectives across economic systems (Kreibiehl et al., 2022). Geographically, flows are channelled to regions including Central Asia and Eastern Europe, East Asia and the Pacific, Latin America and the Caribbean, the Middle East and North Africa, Sub-Saharan Africa, South Asia, Western Europe, the United States and Canada, other Oceania, and transregional initiatives. From a development status perspective, finance is distributed among advanced economies, emerging markets and developing economies, and least developed countries (LDCs), with ongoing debates over equity, access, and prioritisation in allocation (Weikmans & Roberts, 2019). This multidimensional mapping of climate finance forms reveals both the breadth of current flows and the structural asymmetries in allocation, accessibility, and instrument design, highlighting the need for enhanced tracking, more inclusive governance, and greater alignment with recipient-defined priorities.

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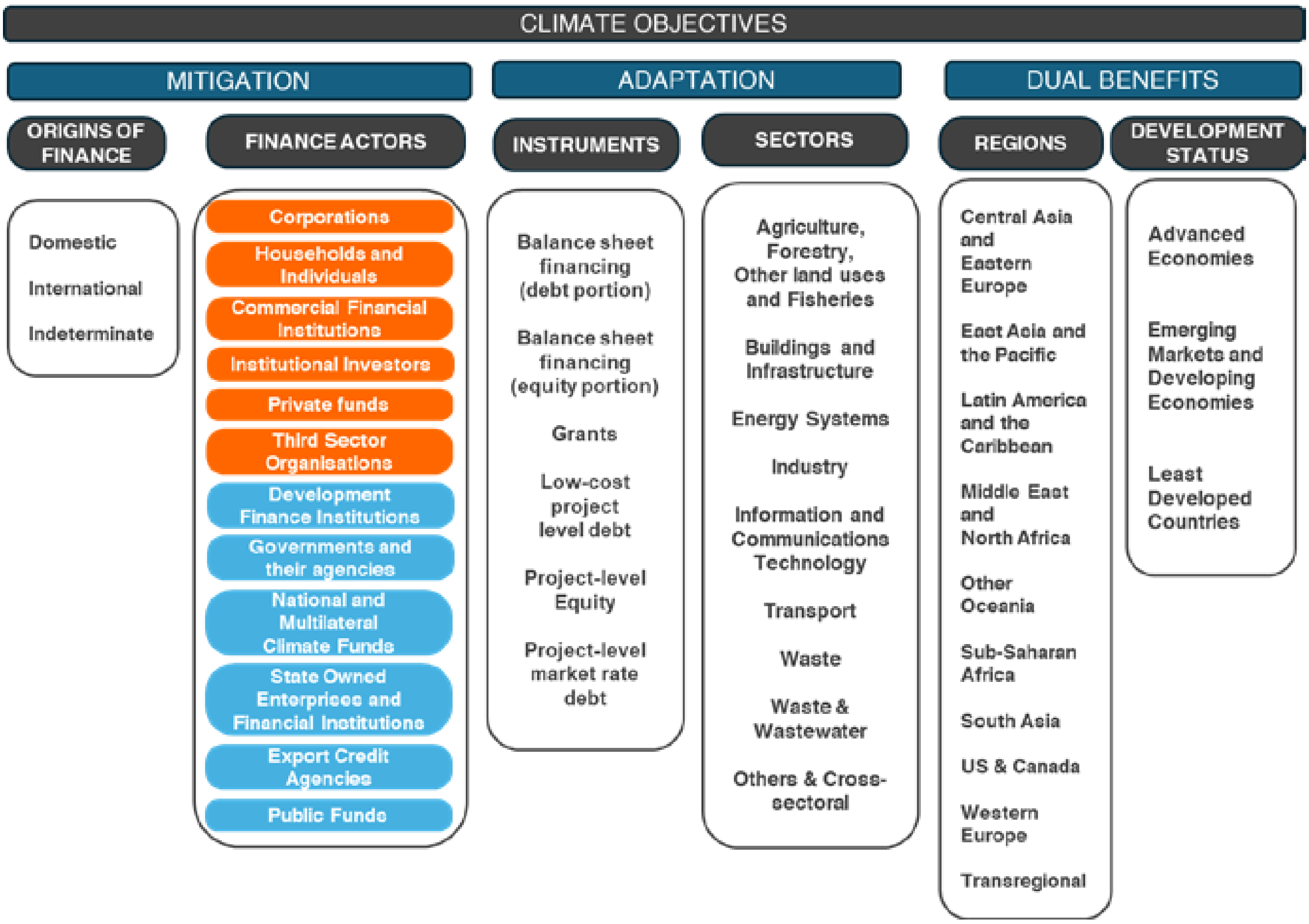

Figure 8: Form of finance; adapted from (CPI, 2025)

4.3 Global finance flows

Transparency in climate finance remains a persistent challenge despite decades of negotiation under the UNFCCC. Disputes endure over how much finance is flowing from developed to developing countries, whether it is “new and additional” to official development assistance (ODA) or instead diverts ODA for socioeconomic development, whether it prioritises mitigation or adaptation, and whether it is delivered as grants or loans. Analysis of self-reported climate finance data from 26 countries between 2014 and 2021 shows that current UNFCCC transparency arrangements have not significantly improved clarity (Bergsvik et al., 2024). Two main factors underpin this outcome: (i) the absence of a multilaterally agreed definition of climate finance, which allows countries to apply heterogeneous accounting approaches; and (ii) political constraints on the scope and depth of international review processes. The effectiveness of UNFCCC transparency arrangements in clarifying contested aspects of climate finance remains in doubt, raising concerns for trust and accountability in the climate regime. The Paris Agreement’s Enhanced Transparency Framework (ETF) largely builds on existing arrangements, extending reporting obligations to all finance providers but without a multilaterally agreed accounting methodology (Weikmans et al., 2020). While developed countries must disclose their assumptions and methodologies, key issues remain unresolved: grant-equivalent loan reporting is voluntary; mitigation–adaptation distinctions lack proportional breakdowns; and rules on “new and additional” finance remain unchanged (UNFCCC, 2018). The ETF allows peer review questions on climate finance provided, but without enforcement or follow-up mechanisms, its impact is uncertain. Loss and damage is not a standalone reporting category and remains an optional subcomponent of adaptation finance, limiting clarity on its scale and additionality (van Deursen & Gupta, 2024). Overall, without substantive methodological harmonisation or mandatory, detailed reporting, the ETF may improve formal structures but is unlikely to resolve long-standing controversies over climate finance transparency.

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In this regard, monitoring and analysing global climate finance flows is essential for assessing progress toward the Paris Agreement's goals and identifying gaps in both scale and allocation. The Global Landscape of Climate Finance Report published periodically by the Climate Policy Initiative (CPI) provides the most comprehensive and methodologically consistent dataset currently available, covering public and private flows for mitigation, adaptation, and dual-benefit activities (CPI, 2025). CPI's approach integrates multiple sources and applies a harmonised definition of climate finance, enabling cross-sectoral and cross-regional comparability despite acknowledged data limitations. According to CPI's latest report, global climate finance in 2023 reached unprecedented levels, hitting USD 1.9 trillion in 2023 (Figure 9) and likely surpassing USD 2 trillion in 2024, with annual flows growing at an average of 26% between 2021 and 2023. Whilst this is an increase compared to previous years, the climate finance gap remains significant. An average of at least USD 6.3 trillion in annual climate finance will be needed from 2024 through to 2030 to avoid the worst impacts of climate change.

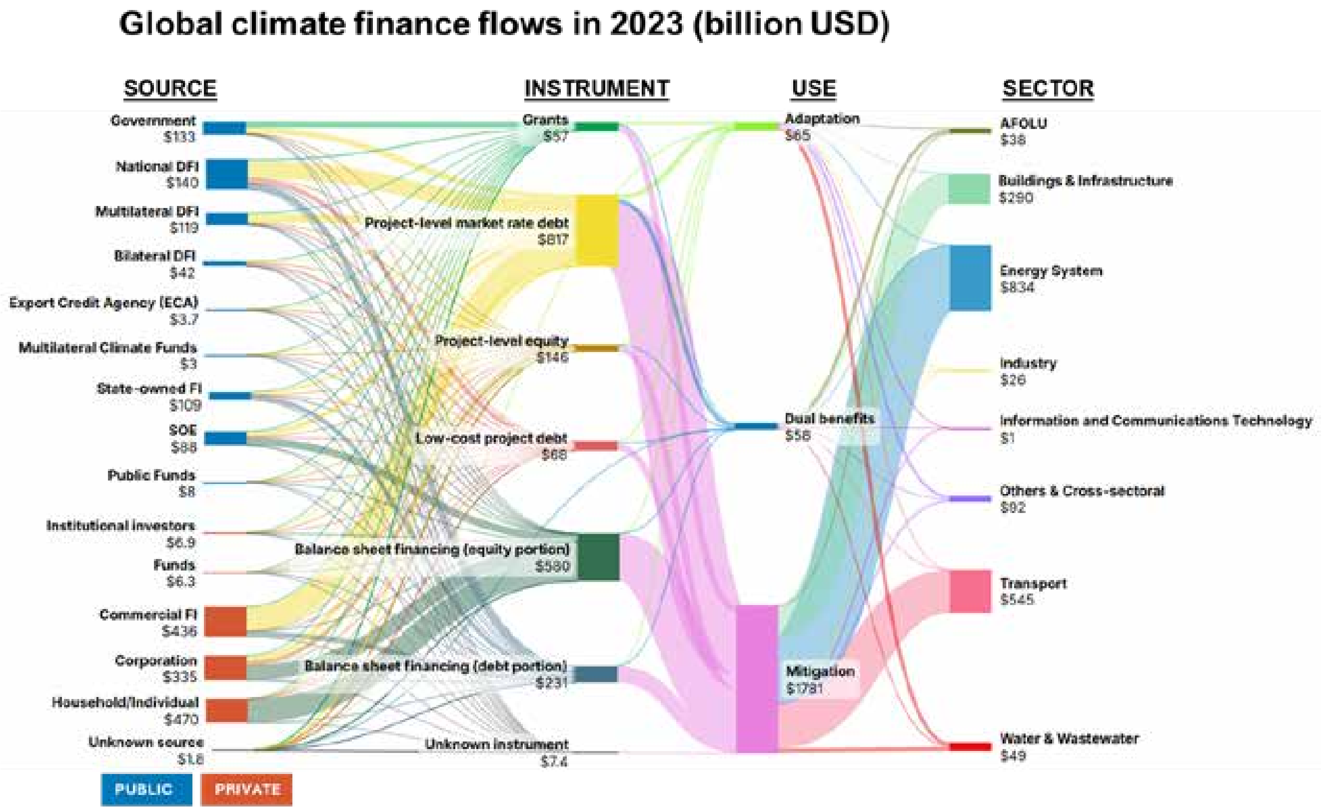

Figure 9: Global climate finance flows by source, financial instrument, use, and sector; data from (CPI, 2025)

Private finance reached an unprecedented USD 1 trillion in 2023, accounting for more than half of global flows. Households were significant contributors, particularly in high-income economies, investing in low-emission vehicles, rooftop solar, and energy-efficient heating and cooling systems. Public climate finance, by contrast, fell by approximately 8% between 2022 and 2023, reflecting fiscal pressures in the wake of the COVID-19 pandemic and cuts to official development assistance. Mitigation finance more than doubled from USD 757 billion in 2018 to USD 1.78 trillion in 2023, led by private investment in renewable energy (notably in advanced economies and China), transport electrification, and energy-efficient buildings. Adaptation finance, by contrast, remained modest. CPI tracks USD 65 billion in 2023, but persistent methodological challenges, especially in capturing private flows and applying consistent definition, suggest this figure likely underestimates the true scale. Other assessments, such as UNEP's Adaptation Gap Report (UNEP, 2024), indicate developing countries alone will require USD 215–387 billion annually this decade, underscoring the magnitude of the shortfall. Dual-benefit activities, integrating mitigation and adaptation outcomes, account for a relatively small but growing share of tracked flows. In terms of sectors, more than three-quarters of climate mitigation finance was channelled into energy systems and transport, with growth driven primarily by solar PV, wind power, and electric vehicles. By contrast, investment in buildings, infrastructure, and industry declined, held back by persistent barriers to energy efficiency, retrofitting,

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and decarbonisation of hard-to-abate sectors. Funding for agriculture, forestry and other land use (AFOLU), fisheries, waste, and cross-sectoral solutions remained relatively modest but continued to grow, largely supported by public finance, reflecting a rising interest in nature-based solutions.

Global climate finance is projected to exceed USD 2 trillion in 2024, growing by 26% annually since 2021. Despite this growth, an annual average of at least USD 6.3 trillion is needed from 2024–2030 to avert the worst climate impacts. When viewed in context, it becomes clear however that the main challenge is not lack of capital, but its persistent misallocation and management (IPCC, 2023). In 2024, estimated fossil fuel investment reached USD 535 billion for oil, 365 billion for natural gas and 248 on coal, totalling USD 1.14 trillion, with more than half concentrated in USA, China, and the Middle East (IEA, 2025). Meanwhile, global public military spending rose to USD 2.7 trillion in 2025 (Liang et al., 2025), amounting to over half of the estimated climate finance gap, an increase driven by escalating geopolitical tensions worldwide (Sarfraz, 2025).

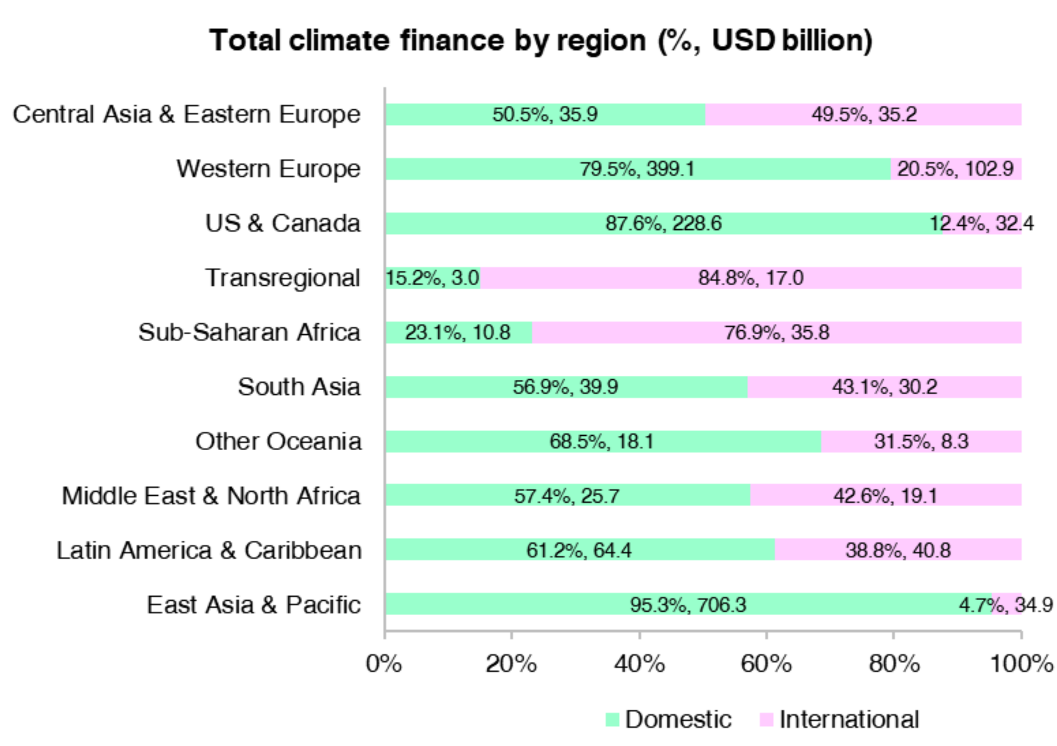

Figure 10: Total climate finance by region raised domestically or internationally in 2023; data from (CPI, 2025)

Geographically, 80% of climate finance in 2023 originated from domestic sources, concentrated in East Asia and the Pacific (dominated by China), North America, Western Europe, and a handful of upper-middle-income emerging markets (Figure 10). Many least developed countries (LDCs) continue to depend heavily on international public finance, often in the form of concessional loans and grants. International climate finance to emerging markets and developing economies (EMDEs) totalled USD 196 billion in 2023, of which 78% was from public actors. Cross-border private flows to EMDEs more than doubled between 2018 and 2023, reaching USD 42 billion, with the largest shares directed toward clean energy investment in Latin America and the Caribbean, the Middle East and North Africa, and Central Asia and Eastern Europe. The distribution of climate finance reflects global inequities. Climate finance flows disproportionately benefit countries with stronger credit ratings or alignment with donor interests, rather than those with the greatest vulnerability or need (Islam, 2022). These patterns reinforce dependency and limit recipient countries' policy autonomy. Prioritising the quality of finance over its quantity is critical, as impact and direction matter more than scale alone (Mazzucato & Macfarlane, 2024). Multilateral and national development banks (MDBs and NDBs), which collectively manage over $22.5 trillion in assets—12 percent of global annual investments—are uniquely positioned to deploy patient, risk-tolerant public finance toward high-risk, high-impact projects. In terms of quantity, however, nearly a tenth of global climate finance could be under

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threat as US president Donald Trump's aid cuts risk wiping out huge swathes of spending overseas (Carbon Brief, 2025).

The NCQG represents an opportunity for stakeholders across the climate finance ecosystem, i.e., sources, channels, intermediaries, recipients, and beneficiaries, to converge around a shared commitment to improving access for developing countries. This requires a comprehensive design that spans the full financing chain. The NCQG must embed specific institutional mandates and frameworks aimed at improving access, not only within the multilateral climate funds (MCFs) under the UNFCCC but across diversified financial sources and mechanisms (Clynes et al., 2024). It is crucial that these mechanisms incorporate robust monitoring, evaluation, and accountability systems to ensure implementation and measure impact, particularly given existing evidence on the effectiveness and inclusivity challenges in climate finance delivery. Without such measures, increases in climate finance volumes risk disproportionately benefiting a select few rather than advancing equitable opportunities for the broader, and often marginalised, recipient base (Robertson, 2024).

4.4 Climate governance

As climate-related challenges grow in complexity and urgency, the efficacy of governance structures and funding mechanisms becomes central to the delivery of fair and transformative climate action. The governance of climate finance has historically mirrored broader geopolitical and economic asymmetries. Institutions such as the World Bank and IMF have faced critique for prioritising conditionalities that reinforce austerity and inhibit transformative development, especially in the Global South (Browne, 2022; Ciplet et al., 2022), which would require a structural rethinking of climate finance governance, away from fragmented, donor-driven approaches, and toward more pluralistic, democratic, and context-sensitive systems. However, climate finance governance cannot be understood in technical terms alone. It is deeply embedded in political, institutional, and epistemic power structures (Marquardt, 2017; Wilkens & Datchoua-Tirvaudey, 2022). Justice considerations must be mainstreamed into the design and delivery of finance, requiring not only fair distribution but also procedural inclusion and recognition of diverse knowledge systems (Pachauri et al., 2022; Zimm et al., 2024). This is particularly relevant for addressing loss and damage, where traditional insurance or adaptation funds have fallen short.

Climate governance increasingly sits at the intersection of legal authority, political will, and enforcement capacity. While international climate agreements, from the UNFCCC to the Paris Agreement, rely heavily on voluntary compliance and peer pressure, no supranational regime has yet imposed specific, binding obligations to reduce greenhouse gas emissions. Realist perspectives emphasise that in the absence of credible enforcement, whether through punitive measures or rewards, states may defect from commitments when compliance becomes costly. This creates a governance gap: the cooperative mechanisms that form the backbone of climate diplomacy risk collapse into more conflictual international relations if they fail to deliver substantive results. If policymakers treat human security as equally important as state security or come to see human insecurity as the greatest threat to state stability, it could fundamentally transform the dynamics of international politics, as climate impacts increasingly threaten livelihoods, stability, and even territorial integrity (Gilley et al., 2013). Strengthening monitoring, enforcement, and dispute settlement mechanisms could help close this gap, but experience suggests they are effective only when backed by powerful states capable of imposing material consequences on violators (Gilley & Kinsella, 2015).

Such a shift would demand a reorientation of priorities in both global and regional governance, including within the European Union. Here, funding allocations illustrate the tension between security paradigms: while the ReArm Europe initiative directs €800 billion towards defence and military readiness (European Commission, 2025a), the Social Climate Fund, intended to support vulnerable households in the green transition, receives €65 billion (European Commission, 2025b), i.e., far away from "shifting the billions" towards human-centred climate security.

Against this backdrop, the recent advisory opinion by the International Court of Justice (ICJ) on climate change represents a potentially transformative development in global climate governance. Although non-binding, the ICJ's interpretation of states' legal obligations to address climate change extends far beyond bilateral disputes between small, vulnerable states and major emitters. It provides an authoritative view of the duty to prevent

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harm, protect human rights, and consider intergenerational equity in climate action. This legal framing may not create immediate coercive force, but it strengthens the normative and political foundations for holding states, and potentially corporations, accountable. In the long run, it could help shift climate governance from a purely cooperative model towards one where international law, public opinion, and economic pressures converge to make non-compliance increasingly costly, moving closer to the kind of enforcement logic realists see as necessary for meaningful compliance (Hadfield, 2025).

4.5 Conclusion

The analysis of climate finance and governance underscores that while global attention and financial flows toward climate action have increased, major gaps persist in terms of adequacy, equity, coherence, and effectiveness. Although global climate finance reached USD 1.9 trillion in 2023 and is projected to exceed USD 2 trillion in 2024, this still falls significantly short of the estimated USD 6.3 trillion annually required through 2030 to limit global warming and build resilience. A disproportionate share of these flows originates domestically in a few high-income and upper-middle-income countries, particularly in East Asia, North America, and Western Europe. By contrast, least developed countries and many developing economies remain heavily reliant on international public finance, which is often delivered through concessional loans and grants, but remains inadequately scaled and poorly aligned with local priorities.

One of the core barriers to more effective climate finance is the persistent lack of a multilaterally agreed definition of what constitutes "climate finance." This definitional ambiguity has enabled heterogeneous accounting methodologies and blurred the lines between development assistance, mitigation, and adaptation finance. Countries differ significantly in their reporting, some count gross financial flows while others report net flows, and many fail to distinguish between grants and loans on a grant-equivalent basis. As a result, transparency remains weak, and trust in international climate finance pledges is undermined. The Paris Agreement's Enhanced Transparency Framework has made some progress in requiring countries to report methodologies and assumptions, but key issues, including the voluntary nature of grant-equivalent loan reporting and the unclear treatment of "new and additional" finance, remain unresolved.

Politically, the failure to meet the USD 100 billion annual climate finance pledge made in 2009 exemplifies the credibility gap that persists in international climate governance. Numerous studies show that climate finance targets have been shaped more by political compromise than by empirical assessments of mitigation and adaptation needs. The 2022 Independent High-Level Expert Group on Climate Finance report and subsequent COP29 decision to triple climate finance to USD 300 billion annually by 2035 reflect growing ambition, but this still does not match the scale of the investment required. The chronic shortfall in delivery is not merely a technical issue but a reflection of limited political will, fiscal constraints in donor countries, and a reluctance to reorient domestic budgets toward international climate obligations.

In terms of climate finance instruments, the landscape remains fragmented and complex. While public actors—including development finance institutions, governments, and multilateral funds—continue to play a central role in mobilising resources, private finance has grown substantially, surpassing USD 1 trillion in 2023. However, the predominance of private flows raises questions about their alignment with equity and public goods objectives, especially given the risk-averse nature of private capital and its tendency to avoid low-income, high-vulnerability contexts. Public finance often acts as a catalyst for private investment, yet there is insufficient evidence that current blended finance models are achieving transformative outcomes at scale. Furthermore, innovative instruments—such as climate-for-debt swaps and risk mitigation tools—remain underutilised and inadequately integrated into official reporting systems.

Sectorally, climate finance is heavily skewed toward mitigation, particularly renewable energy, transport electrification, and energy efficiency in buildings, largely driven by private investment. Adaptation finance remains a small share of the total and is disproportionately reliant on public funds. This imbalance neglects the urgent needs of vulnerable communities facing climate impacts and reflects the difficulty of generating private returns from adaptation investments. Dual-benefit activities that integrate mitigation and adaptation remain limited, though growing. The gap between aggregate finance flows and sectoral or regional needs reveals that impact and direction matter as much as scale. Addressing these discrepancies requires moving beyond volume-focused metrics to assess the quality, targeting, and long-term outcomes of finance.

Climate finance governance mirrors broader geopolitical asymmetries, with institutions such as the IMF and World Bank often criticised for perpetuating conditionalities that restrict fiscal space and policy autonomy in developing countries. As climate-related challenges become more urgent and complex, governance structures must be reoriented away from donor-driven models and toward more democratic, inclusive, and locally grounded systems. This includes recognising diverse knowledge systems, integrating procedural justice into finance delivery, and strengthening the role of recipient countries in agenda-setting and implementation. Governance should be understood not merely as a set of technical procedures, but as a deeply political process shaped by power dynamics, legitimacy, and competing narratives of justice.

Legal and institutional developments offer emerging pathways for accountability. The recent advisory opinion by the International Court of Justice on states' legal obligations to address climate change could help redefine climate governance by embedding duties of prevention, intergenerational equity, and human rights protection. Although non-binding, such legal interpretations strengthen normative expectations and increase the reputational costs of non-compliance. Similarly, the New Collective Quantified Goal (NCQG) on climate finance represents an opportunity to embed stronger access, transparency, and accountability mechanisms across the entire finance ecosystem—from sources and intermediaries to beneficiaries. However, its success depends on the willingness of stakeholders to move beyond political symbolism and to implement structural reforms that close the gap between commitments and delivery.

In conclusion, the future of climate finance hinges not only on increasing volumes but on fundamentally transforming how finance is mobilised, governed, and assessed. Ensuring finance is accessible, transparent, aligned with national priorities, and geared toward justice-based outcomes is critical to achieving the goals of the Paris Agreement. Without such shifts, climate finance will continue to reproduce the very inequalities it seeks to address, and the decisive decade for climate action will fall short of its potential. Without a binding international mechanism to enforce equitable and sufficient financial contributions, the shared resource at risk is not only the global climate but also the trust and cooperation required to mobilise adequate support for vulnerable and developing countries.

4.6 Bibliography

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5 Mitigation potential of sustainable lifestyle changes in Europe

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This section (Study 14) will be submitted to a peer-reviewed journal.

5.1 Introduction

Relevance of lifestyle change targeting GHG emissions

The Paris Agreement assumes a global acceleration of government ambitions for reducing greenhouse gas (GHG) emissions following the Paris agreement[1]. In the Europe-27 region (EU-27 hereafter), the European Green Deal was presented in 2019 as a strategy and roadmap towards complying with Europe's internationally agreed commitments[2]. In 2021, the European Climate Law[3] was adopted, which embodies of the core climate neutrality goal of the European Green Deal. It makes the 2050 climate-neutrality goal legally binding for all EU member states and specifies an intermediate goal of 55% less greenhouse gas emissions by 2030 (related to 1990).

Globally, there is a large stock of literature exploring the potential of lifestyle change to reduce the human carbon footprint and limit global warming to 1.5 °C (Costa et al., 2021; Grubler et al., 2018; Hertwich & Peters, 2009; Ivanova et al., 2020; Koide et al., 2021; van de Ven et al., 2018; van Heerden et al., 2025). Research aims to balance human needs and demands with climate mitigation targets through demand-side mitigation options covering food, housing, and mobility and other energy-consuming domains. Studies show that households could play a much larger role in reducing GHG emissions than is currently recognised in international climate negotiations. According to a literature review done by Newell (2021) opportunities for household GHG reductions range from two-thirds to 72% of the current output. For the EU-27, authors found that lifestyle change may contribute 20% of the overall greenhouse gas (GHG) emission reductions required for net-zero by 2050 through transportation modes, energy use, and consumption patterns (Costa et al., 2021; van Valkengoed et al., 2025).

However, achieving long-term, sustainable change in people's lifestyle is not straightforward. Driving climate-related behavioural changes is a complex task, with multiple factors influencing outcomes. Understanding and addressing drivers and barriers is essential for designing effective climate policies that go beyond technical solutions and include social and behavioural dimensions. There is known to be a wide range of factors that shape human behaviour—and the sets of behaviours that constitute various lifestyles—at the societal level. Numerous theoretical frameworks across disciplines and perspectives have been developed to explain and systematise the

1 United Nations. (2015). Paris Agreement. United Nations Treaty Collection. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

2 European Commission: Directorate-General for Communication. (2023). The European Green Deal: delivering the EU's 2030 climate targets. Publications Office of the European Union. https://data.europa.eu/doi/10.2775/783179.

3 Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law). Official Journal of the European Union, L 243, 2021. Entered into force 29 July 2021. Available at: https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng

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drivers of human behaviour (Pettifor et al., 2023; United Nations Environment Programme, 2016). The framework presented in UNED (2016) distinguishes the following broader societal determinants beyond individuals' "personal situation" (such as age, gender, education, and income) (see Figure 11):

- **Socio-technical conditions:** These include the broader economic context (e.g. costs in relation to income levels), the availability and quality of infrastructure (e.g. public transport usage is strongly influenced by the density and reliability of the transit system), and cultural norms (e.g. traditional acceptance of public transport, regional dietary preferences). Media influence and the political-legal environment also play key roles—such as which values are promoted in public discourse or what regulatory frameworks are in place.

- **Physical and natural boundaries:** These refer to geographic and environmental conditions that shape lifestyle possibilities. For example, climate affects heating and cooling needs as well as the comfort and feasibility of walking, cycling, or using public transport. Geography—including terrain and topographical features like waterways—can influence infrastructure development, such as the layout and accessibility of transport systems. Natural resources and biodiversity also define certain limitations and opportunities for sustainable living.

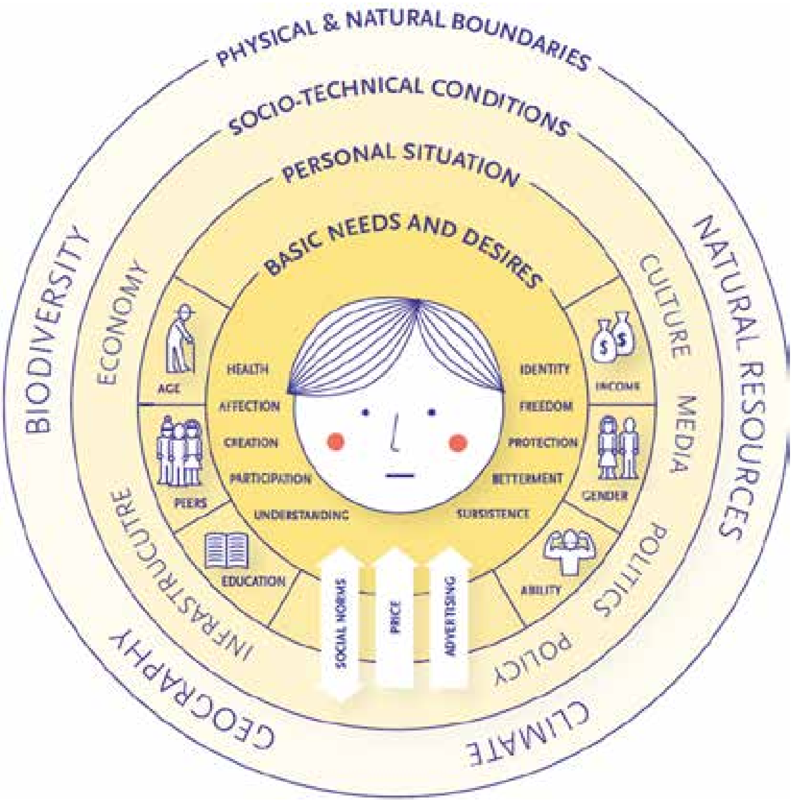

Figure 11: Determinants of sustainable lifestyle (United Nations Environment Programme, 2016)

Thus, while substantial research has been conducted on options for and the potential of fostering environmentally friendly behaviours, the potential impacts of policies targeting lifestyle changes —such as reducing consumption or shifting preferences— are still underrepresented in integrated assessment models (IAMs) (Andreou et al., 2022; van den Berg et al., 2019). It is the focus of this study.

Our concept of sustainable lifestyle

We have adopted the definition of "**sustainable lifestyle**" from the UNED (2016), according to which a "sustainable lifestyle" is:

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- A cluster of habits and patterns of behaviour embedded in a society.
- Patterns facilitated by institutions, norms and infrastructures that frame individual choice.

In short, the goal of a sustainable lifestyle is to minimise the use of natural resources and generation of emissions and wastes, while supporting fairness and prosperity for all.

Thus, in the study, lifestyle change refers to broad, long-term, and sustainable adjustments in people's way of living. Besides, the study's scope goes beyond assessing the emissions savings potential only, focusing also on land-use and cost implications, whereas we have adopted a broad understanding of "costs", including also household expenditures in fuels for mobility, expenditures for energy in housing, and the impact of diet change on land uses.

While lifestyle change and behaviour change are closely related, they differ in important ways. **Behaviour change** often results from external factors, such as a price increase or a crisis like the COVID-19 pandemic. These influences can temporarily alter habits, i.e., people may reduce travel during restrictions or adapt to higher gasoline prices but once the external factor disappears or stabilises, behaviours frequently revert to previous patterns (Levin et al., 2022; Tsanko, 2024). Even though one may argue that the COVID pandemic has demonstrated people's adaptive ability to drastically downsising their lifestyle and research may have shown that people did value the reconceptualisation of wellbeing that went along with it (Boström, M. (2020)). By contrast, **lifestyle change** carries an important element of intentionality: it represents a conscious, deliberate choice shaped not only by external drivers but also by evolving values, attitudes, and preferences. As a result, lifestyle change holds greater potential than short-term behavioural adjustments to foster long-lasting shifts toward sustainable living within planetary boundaries. Crucially, this does not absolve governments of responsibility. On the contrary, effective legislative and regulatory frameworks are necessary to provide the conditions under which individual and institutional actions can be most impactful (Lorek & Fuchs, 2013).

Statistical data shows that effect on lifestyle has been totally reversed once the COVID related restrictions had been lifted. According to Eurostat[4], chain-linked volume index of individual consumption (COICOP, 2020=100) in EU-27 showed a decline of 0.6% and 8% in 2020, with respect to 2015 and 2019, respectively. However, the rebound effect is noticeable in the next years, increasing around 5% from 2020 to 2021, 10% from 2020 to 2022, and 11% from 2020 to 2023.

Van den Bergh et al. (2019) search for a definition of lifestyle change suitable for the implementation of lifestyle changes in IAMs, specify that *"Lifestyle changes are the changes that lead, or aim to lead, to the avoidance, shift and in some cases, improvement (depending on the context) in energy service demand, irrespective of their intent".* Their argument is that IAMs, while recognising the importance of understanding the motivations behind behavioural change, are inherently limited in capturing the decision-making processes and intent-oriented behaviours that drive such change. As a result, IAMs primarily focus on quantifying the environmental impacts of lifestyle shifts—what can be termed impact-oriented behaviours. This limitation also applies to our study, which models the environmental outcomes of lifestyle changes that are assumed to occur at the societal level. However, we argue that it is precisely the role of narrative scenarios to explore and articulate the underlying motivations, value shifts, and societal dynamics that lead to these changes in lifestyle factors that IAMs alone cannot adequately represent, and which adds realism to scenarios and simulation results. IAM-driven assessments of lifestyle change should therefore place greater emphasis on developing plausible narratives grounded in empirically supported drivers of change and informed by the range of transformations observed in historical precedents.

[4] Eurostat. (n.d.). Household final consumption expenditure by purpose (COICOP 2018) [nama_10_cp18]. Eurostat. https://ec.europa.eu/eurostat/databrowser/view/nama_10_cp18__custom_17661302/default/table

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Technological substitution is usually adopted as part of the lifestyle options through the application of the "Avoid–Shift–Improve" (A–S–I) framework (Wilson et al., 2020) in research papers (Álvarez-Antelo et al., 2024; Arnz et al., 2024; Shah et al., 2021; Zhang et al., 2024) and by the IPCC in its 6th assessment report (Intergovernmental Panel on Climate Change (IPCC), 2023). Although this framework distinguishes three different types of demand-side mitigation options: "avoid", "shift", and "improve" (see table 3), **in this study, we only consider "avoid" and "shift" actions to be lifestyle changes, excluding "improve" actions**. Note that there is a clear hierarchy between them in terms of environmental outcome, with "avoiding" being the most and "improve" the least effective option.

Table 3: "Avoid", "shift", and "improve" demand-side mitigation options. Modified from (Wilson et al., 2020).

	LIFESTYLE CHANGE		TECHNOLOGICAL SUBSTITUTION
	AVOID	**SHIFT**	**IMPROVE**
	consuming less of a good or service	**consuming more resource-efficient forms of a good or service [that provides a similar utility]**	**upgrading the resource efficiency of an existing good or service so that it provides the same utility**
MOBILITY	• Travel less • Fly less	• Public and non-motorised instead of private motorised transportation	• Replace combustion with electric engine
HOUSING	• Move to a smaller place • Turn thermostat down	•	• Replace cladding, windows, heating (retrofit)
DIETS	• Buy less food • Reduce food waste	• Plant-based instead of meat-based diet	• GMOs/practices that require less water/fertilisers/ pesticides

As one can tell from the definitions, there is a fine line between the three categories. Replacing a good or service consumed by a more resource-efficient, for example, a diesel-powered car by an electric one, while maintaining the same consumption habits falls into the category of "IMPROVE" and is, thus, not considered a lifestyle change (and therefore also not part of the scope of this study). However, if the purchase of an electric car, due to its limited battery range, means that consumers change their mobility behaviour towards fewer and shorter travels, it may be considered. The three categories are to some extent context-dependent (as also argued by van den Bergh (2019)), and "the boundary between what constitutes changes in behaviour and technology can be blurry as the latter influences many of the former (Costa et al., 2021). In addition, it is not always easy to determine whether the more resource-efficient good or service that is consumed provides a similar or the same utility. To take the example of the electric car, depending on the charging infrastructure available and the development of battery range as well as one's personal needs, it may be argued that the electric car does not provide the same utility as a combustion-engine car. We want to underline that by no means we want to imply that "shifting" versus "improving" means settling for something with an inferior utility. For example, shifting to a more plant-based diet most likely increase the diets nutritional value and comes with multiple health benefits, but, subjectively, may be perceived as being less tasteful. So, whether its utility is higher or lower depends on the point of view.

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Mitigation potential of mobility, housing and diets

Studies of lifestyle change identify mobility, housing and diets as the domains with the highest mitigation potential (Ivanova et al., 2020; Newell, 2021). According to Hertwich and Peters (2009), globally, these three sectors alone are estimated to comprise 17%, 19% and 20% of total GHG emissions, respectively.

Ivanova et al. (2020) found the highest mitigation potential in the domain of transport. Specifically, the "one less flight policy may reduce 0.8-1.9 tCO_2eq/cap in average. Living car-free policy has a median mitigation potential of 2.0 tCO_2eq/cap, while partial implementations estimate a potential in between 0.6-1.0 tCO_2eq/cap. Active and public transport alternatives assume average carbon intensities at 0.00 and 0.09 $kgCO_2eq$/km, while motorbikes at 0.23 tCO_2eq/km. Telecommuting practices may reduce commute emissions by 0.4 tCO_2eq/cap in average, while car-pooling/sharing and fuel-efficient driving have an average carbon savings of 0.3 tCO_2eq/cap. In total, an average mitigation potential higher than 1.7 or 4.6 tCO_2eq/cap, depending on the policies implemented and the presence of carbon-free technologies in the power mix.
The same reference, Ivanova et al. (2020), reviews the mitigation potential in housing. The authors reported that the shift to a passive house is associated with an average reduction of 0.5 tCO_2eq/cap, while smart metering may have an average reduction of 0.2 tCO_2eq/cap. Living in a smaller space and co-housing (higher occupancy rate) offer carbon reductions of 0.3 tCO_2eq/cap in average. Finally, hot water saving and lowering room temperature by 1-3 ºC bring about ana average carbon saving of 0.3 and 0.1 tCO_2eq/cap, respectively. A total of 1.4 tCO_2eq/cap.

According to the literature review carried out by Hallström et al. (2015)[5], a global dietary change to vegetarian diet could reduce in between 20-35% of the GHG emissions worldwide (110-1110 kg CO_2e/yr), together with a reduction of land use demand of 30-50% (570-1010 m^2/yr). Ivanova et al. (2020), on the other side, reported in their review that a vegetarian diet may have a mitigation potential between 1.5 and 0.01 tCO_2eq/cap. Additionally, food waste reduction may help with an average mitigation potential of 0.3 tCO_2eq/cap, while the management of unavoidable food waste would have a modest 0.03 tCO_2eq/cap in average.

Although the previous papers have contributed with relative values of the potential mitigation of lifestyle change, their combination in absolute terms based on population and economy long-term projections was not addressed. This was considered to be a logical task for IAMs. A summary of global, regional and national impacts of the lifestyle changes in terms of GHG emissions, final energy and useful energy can be found in table 3 of Andreou et al. (2022)[6]. Regarding the EU-27 region, the IAM called GCAM estimated that 3% of the cumulative emissions from 2011 to 2050 could be mitigated in mobility (carpooling, car sharing, shift to public transport), while recycling of organic waste could do it a 1.1%, and thermostat setting in housing achieved a reduction of 0.6% in the same indicator.

EU-27 GHG emissions from passenger transport could be reduced by about 220 Mt CO_2eq by 2050 without technological changes, related to the baseline (continuation of past trends) (Costa et al., 2021). On the other hand, the social adoption healthy diet recommended by WHO[7] would result in 190 Mt CO_2eq (53%) less emissions than the baseline scenario in 2050.

5 E. Hallström, A. Carlsson-Kanyama, P. Börjesson, Environmental impact of dietary change: a systematic review, Journal of Cleaner Production, Volume 91, 2015, Pages 1-11, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2014.12.008.

6 Andreou, A., Fragkos, P., Fotiou, T., & Filippidou, F. (2022). Assessing Lifestyle Transformations and Their Systemic Effects in Energy-System and Integrated Assessment Models: A Review of Current Methods and Data. Energies, 15(14), 4948. https://doi.org/10.3390/en15144948

7 WHO, Weltgesundheitsorganisation and FAO 2003 Diet, Nutrition, and the Prevention of Chronic Diseases: Report of a WHO-FAO Expert Consultation (Geneva: World Health Organization)

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Objective & research question

The **overall goal** of this study is to examine the potential impact of household lifestyle change on climate change mitigation in the EU-27, focusing on the key areas contributing to climate change (1) transport, (2) buildings, and (3) diets. The study focuses on household consumption and aims to answer the following research question:

RQ1. What are the emissions, land use and cost implications of changes in households towards a more sustainable lifestyle (mobility, housing and diets)?

RQ2. What is the role of lifestyle changes on the EU's pathway towards net-zero?

In pursuit of this goal, we have set the following sub-objectives:

Clarify the concept of "sustainable lifestyle", adapted for decarbonisation scenarios in IAMs and coherently with actual social and political barriers.

Quantify the mitigation potential of a sustainable lifestyle under two different scenarios: a continuation of past trends and a technological decarbonisation of the economy.

Compare and analyse results of simulations carried out with three different IAMs.

Analyse the complexity and policy realism of the lifestyle implemented in the model.

Present conclusions and recommendations in a clear, intuitive, and accessible manner making them accessible to the different target groups: the scientific community, policy makers and the general public.

5.2 Method

This study adopted a multi-model comparison approach, considering the same standard reference and policy scenario to the different models, comparing the outcomes of the simulations, and assessing and surfacing the underlying structural differences of the models that account for the different simulation results. This approach increases both model transparencies, the robustness of simulation results, and, ultimately, the confidence to inform with which policymakers.

To achieve the objectives of the study, a systematic method has been proposed. The approach includes a set of qualitative and quantitative tasks to arrive at well-defined and harmonised policy scenarios which form the basis for model simulations and the inter-model comparison of results. The final output of this study is a policy brief which summarises the relevant insights and recommendations of the study for stakeholders and policymakers.

Step 1: Defining the study scope

- Integration of policymakers/stakeholders' comments and suggestions for the definition of research objectives and question (policy response mechanism, PRM).
- Definition of study scope (geography, timeframe, sectors included, number of scenarios and reference scenario/s) and selection of participating models based on partner interest and model capabilities
- Conceptualisation and operationalisation of lifestyle change (mobility, housing, diets) through literature review.
- Identify most effective lifestyle changes for climate change mitigation from the literature.
- Identify key drivers of and barriers to lifestyle change, existing good practices to add policy realism to the policy scenarios.
- .

Step 2: Defining the scenarios (reference and policy scenarios)

- Development of policy scenario narratives.
- Selection of reference scenario and harmonisation across models
- Select parameters/variables (e.g. modal shift, diet shift, housing energy consumption reduction, etc.) from existing lifestyle change scenarios described in the literature to parametrise narratives

Step 3: Defining simulation outputs

- Agreement on outputs of the analysis (indicators and units)

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Step 4: Simulating the scenarios and analysing and comparing results
- Check IAMC format of outputs with https://validation.iam-compact.eu/
- Comparison between models
- Comparison with literature review (Findings of similar research studies and their results)

Step 5: Developing conclusions and policy recommendations

In the coming sections we provide a more detailed description of each research step.

5.2.1 Defining the study scope

The study scope was defined on the basis of the definition of the research objective and question, which were co-developed with project stakeholders (see section 5.2.1.1 below). Models participating in the study were selected based on the partners' interest in the study and the capabilities of their models to address the research question. Ssection 5.2.1.3 provides a brief description of the models WILIAM, GCAM and PROMETHEUS that have participated in the study. Model capacities also largely predetermined the study **time frame**, **geographical scope**, and **definition of lifestyle (behaviour) change**, which are summarised in the table below.

Table 4: **Study scope**

Geographical scope:	EU-27.
Temporal scope:	Simulations go from 2015 (mobility and housing)/2020 (for diets) to 2050. The lifestyle changes are introduced starting from 2025.
Participating models:	WILIAM, GCAM and PROMETHEUS. Models are described in section 5.2.1.2.
Subject of study:	Households (household consumption) with a focus on mobility, housing and dietary demand.
Reference scenarios:	No-Policies (continuation of historical trends from 2015 without application of climate policy), NDC-LTT (application of policies to meet the national determined contributions by 2030 and additional long-term targets by 2050, aiming to avoid 2ºC of global anthropogenic temperature increase over preindustrial level). Reference scenarios are described in section 5.2.2.2.
Policy scenarios:	Two levels of ambitions were formulated (see section 5.2.2.2) A **moderate lifestyle change scenario** aiming at a more modest lifestyle change that largely reflects past lifestyle changes observed in the real world ("best-in-class"). This scenario was parametrised to be 50% of the change assumed under the high change scenario. A **high lifestyle change scenario** aiming at a more radical yet unprecedented lifestyle change.

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Impacts:	**Emissions:** This refers to the emissions saved because of the reduced energy demand and the reduced demand for meat-based food (and related land use change). Only emissions directly related to households and their personal transport, housing and food demand is included while grey emissions such as those embodied in the lifecycle of products or buildings are excluded from the study. Due to limitation of the models, we account only for CO_2 for mobility and housing related GHG emissions and for diets, we consider CO_2, CH_4 and N_2O of AFOLU-related emissions, aggregated and converted into CO_2 equivalent emissions for comparison. **Land use changes**: Changes in people's diets (e.g., less meat consumption) affect land-use. Here we focus mostly on changes in crop land and pastures resulting from the modelled diet change. **Cost implications:** As a result of the reduction in energy consumption for transport and housing, household expenditures for energy may decrease. We have studied the impact of the lifestyle transition on household expenditures, expressed as expenditures (in annual monetary flow in $2015) of households for transport, housing and food in real terms. **Other impacts** that have been studied are, in particular, the impact on the energy system transformation (changes in final energy by sector and the fuel mix, variation of total final/primary energy consumed, comparison between 2020 and 2050). Impacts simulated are further described in section 5.2.3

5.2.1.1 Defining the research objective and question - stakeholder feedback

The study research objective and question were co-developed with project stakeholders (including policymakers, industry associations, and civil society representatives) in the framework of the project's policy response mechanism (PRM). Two workshops were organised:

1. First stakeholder workshop (July 2024): The objective was to **provide feedback on the results of the 1st cycle** and to **clarify the objective and research questions.** A summary report can be found in Deliverable 2.3 (section 2.4). Section 5.2.1.1 below gives a detailed overview of stakeholder feedback.
2. Second stakeholder workshop (December 2025): The objective was to **obtain feedback on the selection of lifestyle changes** affecting mobility, housing and diets that will be modelled, thus to co-design the lifestyle change scenarios.

Stakeholder comments related mainly to the realism (feasibility) of the life style changes modelled. Stakeholders wanted to know

- Whether the modelled lifestyle change could be linked to empirical studies (i.e. whether there are real-world examples demonstrating the feasibility of achieving a given change)?
- What effective policy measures are required to drive such a lifestyle change and their limitation, whether they are incumbent upon the individual (i-frame) or on society (s-frame), and what these policies would cost (political costs, societal costs, financial costs, etc.)?
- Whether results were different for different socio-economic, demographic and energy-consumption groups and territories?

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- Whether it was possible to model two-part tariffs to incentivise flexible consumption while protecting consumers and flexible vs. inelastic consumption in households?
- What is the effect of the energy consumption associated with energy communities at scale of the energy system was in terms of emissions and cost?

Stakeholders also made suggestions for improvement. They suggested implementing different degrees of lifestyle change in modelling to account for different degrees of ambition, asked for a better contextualisation of the modelled lifestyle change in the policy brief, and an evaluation of the modelled changes on people's quality of life. They expressed interest in the sectors mobility, housing and food, and asked for the inclusion of land use and agricultural changes needed to provide food for changed diets.

Stakeholder feedback was analysed within the modelling teams, shaping the scope of the study in the second cycle:

- The **research question was adapted** to focus not only on the impact on emissions, but to include the impact of lifestyle change on costs and land use/agriculture.
- **Comprehensive scenario narratives were developed** that provide contextual information on how the study authors envisage the change in people's behaviour towards more sustainable lifestyles will be achieved through a set of policy interventions. Where available, narratives were backed with results from empirical studies and real-world example where similar change on societal level has already been achieved.
- **Scenarios were parametrised to reflect different degrees of ambition**: high-level of change versus moderate level of change.
- The models (GCAM, WILIAM and PROMETHEUS) able to analyse the impacts of lifestyle change were selected.

Some of the stakeholder interests remain outside the scope of the study

- The models used in this **study cannot explicitly represent energy tariffs** since they require explicit hourly representations of the energy markets (electricity and heat, mainly). Consumption patterns can only be annually represented in the models.
- **Energy communities** are specific points in the grid, or isolated energy systems. Therefore, they need special and temporal granularity to analyse them, something that is **outside the capabilities of the integrated assessment models** of this project.
- Due to model limitations, **different (socio-economic, age) household types in the EU-27 could not be modelled** in this study.
- The IAMs used in this study are **unable to reproduce an i-frame (individual lifestyle change)** since they are not agent-based models. IAMs mainly employ the s-frame (social lifestyle change).
- Although the global context would enrich the scenario, the **decision was to focus only on the EU-27** and be able to reproduce the NDC-LTT scenario for Europe as a representative baseline of the EU Green New Deal in all models.

5.2.1.2 Comparing models and their features

This section describes available policies related to the three topics of interest, i.e., housing, diets and mobility, in the participating integrated assessment models of this study. Summary tables presenting and **comparing models and their capacities in modelling behaviour change** can be found in Deliverable 5.6 (section 6.2.3).

GCAM model

The Global Change Analysis Model (GCAM) is a consolidated IAM aimed at exploring the human-Earth system dynamics of alternative long-term scenarios within a single computational platform at both global and regional scales (Calvin et al., 2019). The model runs in five-year time steps until the end of the century and is designed to analyse the interdependencies between the (1) energy, (2) agriculture, forestry, and other land use (AFOLU),

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(3) water, (4) socio-economic, and (5) climate systems. GCAM has been largely applied in different national and global studies including the scenarios by the Intergovernmental Panel on Climate Change (IPCC, 2022b), the development of the Shared Socioeconomic Pathways (Horowitz et al., 2022), or the U.S long-term strategy (Horowitz et al., 2022). Moreover, it is a community model, which can be downloaded from an open-source repository (https://github.com/JGCRI/gcam-core), and includes a complete documentation GitHub site, that gathers all the details of the different systems within the model, including input assumptions, parameters, equations, or solving algorithms (https://github.com/JGCRI/gcam-doc).

In GCAM, three lifestyle change categories are modelled: transport, buildings, and food.

For mobility: GCAM transport dynamics relay on service demand of the available modes, size classes, and technologies (Kyle & Kim, 2011; Mishra et al., 2013). Different fuels are accounted (e.g., liquids, electricity, hydrogen, gas), and different sectors are considered: international aviation, international shipping, passenger transport (walk, cycle, domestic aviation, train, bus, 2/3 wheelers, and 4 wheelers), and freight transport (domestic ship, rail, and light, medium and heavy trucks). For this exercise, overall transport demand (both passenger and freight), modal preferences (passenger only), and average car occupation have been modified in line with the study policy scenarios.
For diets: GCAM relies on the *ambrosia* package (Kanishka et al., 2021) to compute the food demand. It is based on the theory of Edmonds et al. (Ferreras et al., 2023), which divides the food consumption into two categories: staples, which represents basic foodstuffs, and non-staples, which represents non-basic higher priced foods. Demand for staples increases at low income but eventually peaks and begins to decline with higher income. Demand for non-staples increases with income over all income ranges; however, total (staple + non-staple) demand saturates asymptotically at high income. GCAM consider 21 food items (e.g., beef, corn, dairy, fruits, oil crops, fiber crops, nuts and seed), that can be aggregated into sectors and sub-sectors (e.g., protein-animal, protein-plant). For this exercise, consumer preferences for animal products have been exogenously modified in line with the LED scenario reported by Grubler et al. (Grubler et al., 2018).
For housing: GCAM disaggregates the building sector into residential and commercial sectors and models three aggregated services: heating, cooling, and other services. Several heating and cooling fuels are considered (e.g., biomass, coal, gas, liquids, electricity), and the floorspace can be exogenously specified or endogenously computed (Grubler et al., 2018a). For this exercise, the floor space, the thermal efficiency, and the level of building service demand have been modified in line with the LED scenario reported by Grubler et al. (Grubler et al., 2018).

PROMETHEUS model

PROMETHEUS (Fragkos et al., 2015a) is a global energy system model covering in detail the complex interactions between energy demand, energy supply and energy prices at the regional and global level. Its main objectives are: 1) Assess climate change mitigation pathways and low-emission development strategies for the medium and long-term, 2) Analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector, 3) Explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices. The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system. PROMETHEUS is a fully fledged energy demand and supply simulation model for energy system analysis, energy price projections, power generation planning and climate change mitigation policies. PROMETHEUS contains relations and/or exogenous variables for all the main quantities, which are of interest in the context of general energy systems analysis. These include demographic and economic activity indicators, primary and final energy consumption by main fuel, fuel resources and prices, CO_2 emissions, greenhouse gases concentrations and technology dynamics (for power generation, road transport, hydrogen production and industrial and residential end-use technologies).

PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (like Renewables, electric vehicles, Carbon Capture and Storage, energy efficiency) and policy instruments. The latter include both market-based instruments, such as cap and trade systems with differential application per region, and sector specific policies and measures focusing on specific carbon emitting activities. Key characteristics of the model, that are particularly pertinent for performing the analysis of the implications of alternative climate abatement scenarios, include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements (increased uptake of a new technology in one part of the world leads to improvements through learning by experience which eventually benefits the energy systems in other parts of the World).

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

In PROMETHEUS, two main lifestyle change categories are modelled: transport and buildings.

For mobility: PROMETHEUS represents the dynamics of the main passenger sectors based on the service demand of the modes and the available technologies. Different fuels are accounted (e.g., gasoline, diesel, kerosene, biofuels, electricity, hydrogen, gas), and different sectors are considered: international aviation, international shipping, passenger road, rail, air and maritime transport. For this exercise, overall transport demand, modal preferences (passenger only), and average car occupation are modified to represent the lifestyle changes and behavioural transitions.

For housing: PROMETHEUS represents three aggregated services in the residential sector: heating, cooling, and other services. Several heating and cooling fuels are considered (e.g., biomass, coal, gas, liquids, electricity), and the floorspace can be exogenously specified or endogenously computed. For this exercise, the floor space, the thermal efficiency, and the level of building service demand can be modified to represent different lifestyle changes.

WILIAM model

The **Within Limits Integrated Assessment Model (WILIAM)** is a recently released open-source IAM (Álvarez-Antelo et al., 2024; Mediavilla et al., 2025) that aims to explore the social, economic and environmental implications of long-term socio-ecological transition pathways at both global and regional scales, considering planetary boundaries as well as socio-economic constraints. WILIAM is based on the system dynamics approach to capture complex feedback loops and non-linear relationships between social, economic and environmental variables. WILIAM is made up of 8 modules: (1) demographics, (2) society, (3) economics, (4) finance, (5) energy (including transport), (6) materials, (7) land and water, and (8) climate.

In the current WILIAM 1.3.1 version lifestyle change is evaluated in 3 categories: mobility, housing, and food.

For mobility: this module corresponds to the representation of passenger transport computes the physical transport demanded by passengers for each transport mode and power train, the vehicular fleets needed to support it and its economic expenditure for households, energy consumption and emissions. Several policies can be implemented like a reduction in passenger transport demand, a modal and power train shift, a change in the fuel economy of vehicles, an increase in the vehicle occupancy rate, etc. Therefore, lifestyle change can be represented accurately and with a high granularity.

For diets: the land and water module estimates the land products demanded by the population and the economy, the land extension required for each use to provide these land products, and the emissions associated with these processes and land uses (LULUCF and agriculture emissions). Several policies can be implemented such as reforestation, dietary change, and reduction in food waste along the alimentary chain. Lifestyle change is mainly implemented through the last two policies described.

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For housing: this submodule calculates dwellings energy consumption and GHG emissions for three main climate-active gases (CO_2, CH_4 and N_2O). This submodule computes the useful energy necessary by energy commodity for the renovated, new and non-renovated dwellings stocks and its conversion into final energy depending on this energy demand (through technological conversion efficiencies) and for other uses (mainly electricity for devices). This conversion efficiencies depends on the technologies selected for these three stocks of dwellings, which depend on the cost of devices for households, which can be affected by subsidies per technology. Renovation pace of non–renovated dwellings is also affected by subsidies and determines useful energy consumption of dwellings. Therefore, lifestyle change is represented through the pace at which renovation happens, the technology choice and the energy used per dwelling.

5.2.1.3 Selecting lifestyle changes

The selection of lifestyle changes to be modelled in the study was based on Ivanova et al. (2020) who, in a meta-analysis of lifecycle assessment studies and multiregional input-output studies of household consumption, ranked the consumption options according to their mitigation potential measured in tons of CO_2eq/capita/yr.

The resulting list of the 43 most effective household-related mitigation options (13 for mobility, 21 for housing and 19 for food consumption) was classified by us into avoid-shift-demand, deviating in some cases from the same classification done by the IPCCC-WGIII for the 6th assessment report based on our conceptualisation of lifestyle change and stakeholder feedback (see Figure 12).

The list of lifestyle changes was presented to a group of stakeholders at a stakeholder workshop in December 2025, in the framework of the project policy-response mechanism. Stakeholders were asked
1.) to discuss the proposed classification according to the Avoid-Shift-Improve framework and
2.) to agree upon the selection of up to five lifestyle changes that they consider to be the most policy-relevant and rank them on a scale 1-5. Stakeholders could also suggest additional mitigation options.

Selected mitigation options were then linked with the capability of our models in effectively representing and simulating the selected lifestyle change (table 5), and a final set of lifestyle changes were defined (see table 6).

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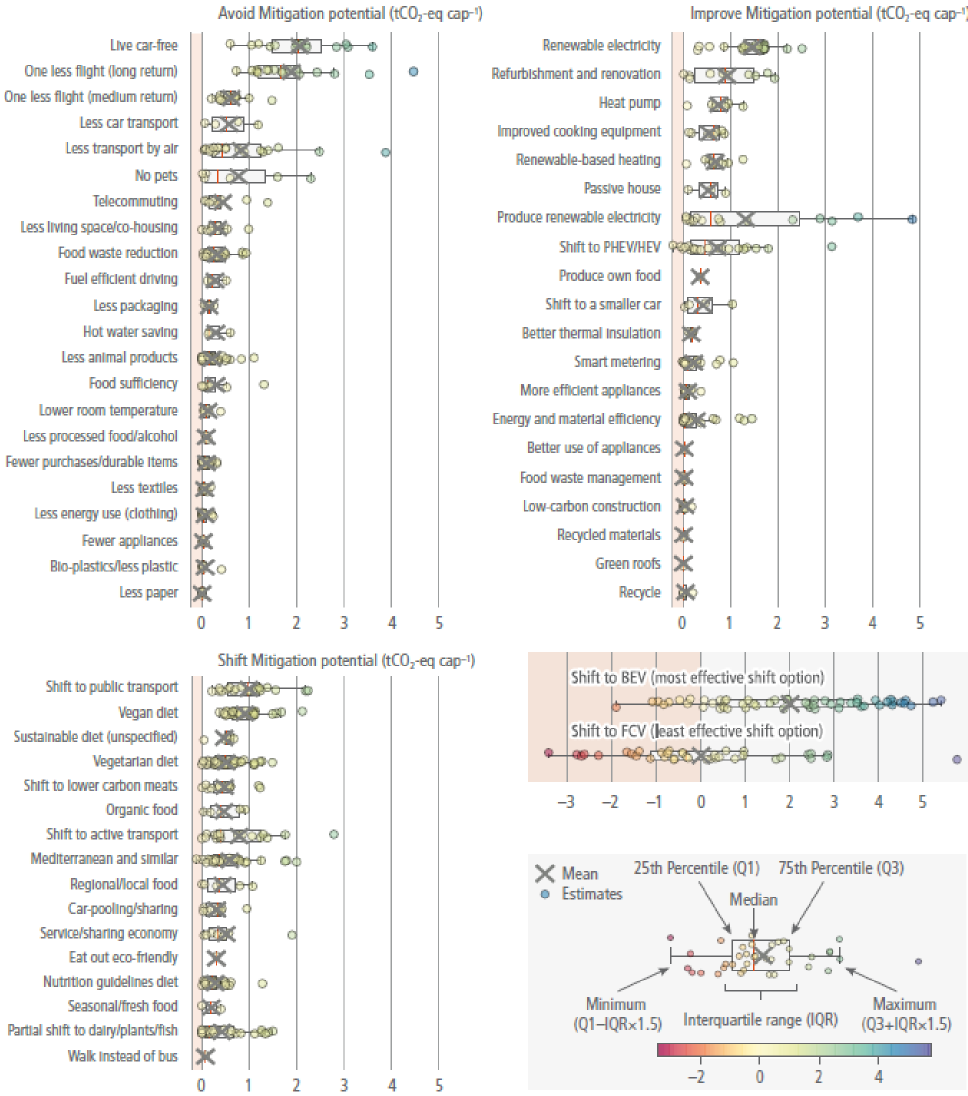

Figure 5.8 | Synthesis of 60 demand-side options ordered by the median GHG mitigation potential found across all estimates from the literature. The grey crosses are averages. The boxes represent the 25th percentile, median and 75th percentiles of study results. The whiskers or dots show the minimum and maximum mitigation potentials of each option. Negative values (in the red area) represent the potentials for backfire due to rebound, i.e., a net increase of GHG emissions due to adopting the option. Source: with permission from Ivanova et al. (2020).

Figure 12: Demand-side mitigation options based on Ivanova et al. (2020) and classified into A-S-I by the IPCCC-WGIII.

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Table 5: List of demand-side mitigation options based Ivanova et al. (2020)

A-S-I	Transport	Ranking	Comment
Avoid	live car-free	1	represent the tendency of declining car use/ownership (not 100% of population living car-free)
Avoid	One less flight (long return)		
Avoid	One less flight (medium return)	5	e.g. represented through a ban of short-haul (e.g. domestic) flights
Avoid	less car transport	1	linked to above, and result of, e.g. telecommuting
Avoid	less transport by air	5	
Avoid	telecommuting		
Avoid	Fuel efficient driving		
Shift	Shift to public transport	2	
Shift	Shift to active transport	3	
Shift	Car-pooling/sharing	4	
Shift	Walk instead of bus		stakeholders think that this lifestyle change does not make sense
Improve	Shift to PHEV/HEV		delete; this is not a lifestyle change
Improve	Shift to a smaller car		delete; this is not a lifestyle change
NEW	Use the car longer (increase lifetime /use time of vehicle)	1	new category proposed by stakeholders
A-S-I	**Buildings**	**Ranking**	**Comment**
Avoid	Less living space/co-housing	1	
Avoid	Hot water saving	3	
Avoid	Lower room temperature	4	
Avoid	Fewer appliances	2	
Avoid	Bio-plastics/less plastic		
Improve	Renewable electricity		
Improve	Refurbishment and renovation	5	stakeholder believe that there is an element of avoid and shift in it
Improve	Heat pump		
Improve	Improved cooking equipment		
Improve	Renewable-based heating		
Improve	Passive house		
Improve	Produce renewable electricity	5	stakeholder believe that there is an element of avoid and shift in it
Improve	Better thermal insulation		
Improve	Smart metering		
Improve	More efficient appliances		
Improve	Energy and material efficiency		
Improve	Better use of appliances		
Improve	Low-carbon construction		
Improve	Recycled materials		
Improve	Green roofs		
Improve	Recycle		
NEW	natural ventilation	5	suggested by stakeholders
A-S-I	**Food**	**Ranking**	**Comment**

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Avoid	Food waste reduction	1	
Avoid	Less packaging	5	
Avoid	Less animal products	3	
Avoid	Food sufficiency	2	
Avoid	Less processed food/alcohol		
Avoid	Bio-plastics/less plastic		
Shift	Vegan diet		
Shift	Sustainable diet (unspecified)		
Shift	Vegetarian diet		
Shift	Shift to lower carbon meats		
Shift	Organic food		
Shift	Mediterranean and similar		
Shift	Regional/local food	4	
Shift	Eat out eco-friendly		
Shift	Nutrition guidelines diet		
Shift	Seasonal/fresh food		
Shift	Partial shift to dairy/plants/fish		
Improve	Produce own food		
Improve	Food waste management		
NEW	Meat-reduced diet	3	suggested by stakeholders

The following lifestyle changes were modelled in the study.

Table 6: List of lifestyle changes modelled in study 14

Mobility	· Change in mobility demand (number of person-km travelled/yr) · Change in transport mode (% shares of non-motorised transport (NMT), trains, road (buses+light duty vehicles (LDV)), domestic aviation, international aviation) · Change in vehicle occupancy (number of people per vehicle)
Housing	· Change in residential floorspace per person (squaremeters/person) · Change in the use of domestic energy for space heating/cooling, hotwater, cooking and other domestic energy end-uses (% end use energy by type of domestic use)
Diets	· Change towards a more plant-based and less meat-based diet (gr/day) · Change in the generation of food waste (kg/yr)

5.2.2 Defining the scenarios

For the study, two reference and two policy scenarios were defined. Simulations were carried out for all four possible combinations:

Table 7: Scenario combinations defined

	No policies scenario describing a situation where no further action	**NDC-LTT scenario** describing a situation where further action to

	beyond the current one is taken to tackle the climate crisis.	decarbonise the economy is taken in line with the European Green Deal and according to the Nationally Determined Contributions (NDCs) and the Long-Term Targets (LTTs) of the EU-27 countries, which are set to be accomplished
Moderate change scenario describing a modest lifestyle change that largely reflects past lifestyle changes observed in the real world ("best-in-class"). This scenario was parametrised to be 50% of the change assumed under the high change scenario	**Scenario 1: No-policies + Moderate change**	**Scenario 2: NDC-LTT + Moderate change**
High lifestyle change scenario describing a more radical yet unprecedented lifestyle change	**Scenario 1: No-policies + High change**	**Scenario 1: NDC-LTT + High change**

Key terms used in the study are defined in the glossary (see Table 16 in annex 1).

5.2.2.1 Adding policy realism to scenarios

Policy realism is still a strong limitation of IAMs. As highlighted by many authors (Keppo et al., 2021; Krawczyk & Braun, 2025; Krumm et al., 2022; Nikas et al., 2020; Trutnevyte et al., 2019), integrated assessment models lack accurate representation of the complexity of societal transitions; specifically, the representation of heterogeneous behaviour like norms, conventions, conflict, negotiation, resistance to change, etc. We addressed this known gap, and also the expressed stakeholder concern through several approaches:

1. Reviewing and visualising the cause–effect relationships between policy, influencing factors, and lifestyle change

We explored the wide range of factors (both drivers and barriers to lifestyle change) that shape human behaviour—and the sets of behaviours that constitute various lifestyles—at the societal level, based on the framework presented in UNED (2016). The literature review focused specifically on factors beyond individuals' "personal situation" (such as age, gender, education, and income), and instead concentrated on broader societal determinants, i.e. socio-technical conditions and physical and natural boundaries.

The literature reviewed included both quantitative and qualitative studies, statistical analyses, and empirical case studies. While the literature review was not exhaustive, it aimed to identify the key determinants most relevant to lifestyle change. Findings from the literature informed the development of narrative scenarios and contributed to the construction of illustrative **causal loop diagrams** (see Figure 13 and Figure 14). These diagrams map out core causal mechanisms linking lifestyle change (as the effect) to policy interventions and other external influencing factors (as causes). The focus was on capturing primary relationships and feedback loops within the system. A fully developed causal loop diagram on food waste, presented in both graphical and textual formats, is provided in Annex 2.

Each relationship in a causal loop can be **positive** or **negative**. A positive relationship means that when one variable increases (or decreases), the connected variable moves in the same direction. A negative relationship implies an inverse effect—when one increases, the other decreases, and vice versa (Bala, 2017).

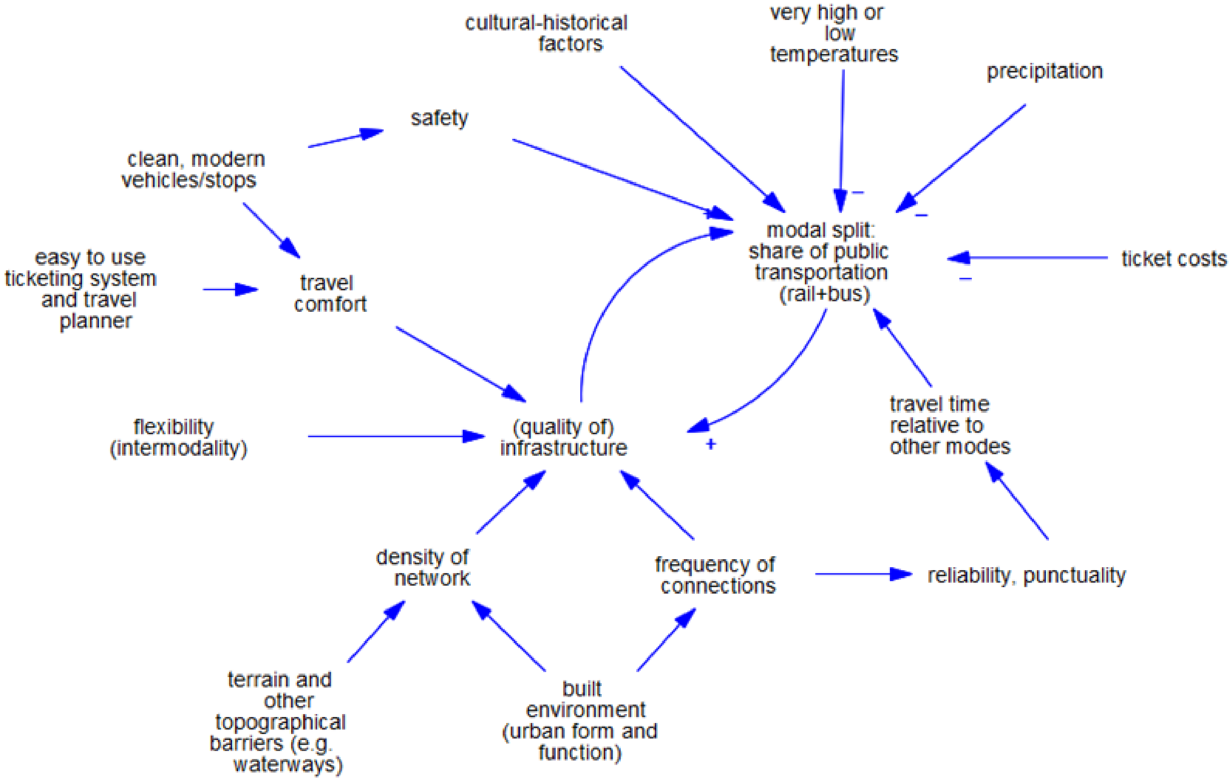

Figure 13: Causal loop diagram "Modal split: share of public transportation (rail + bus).

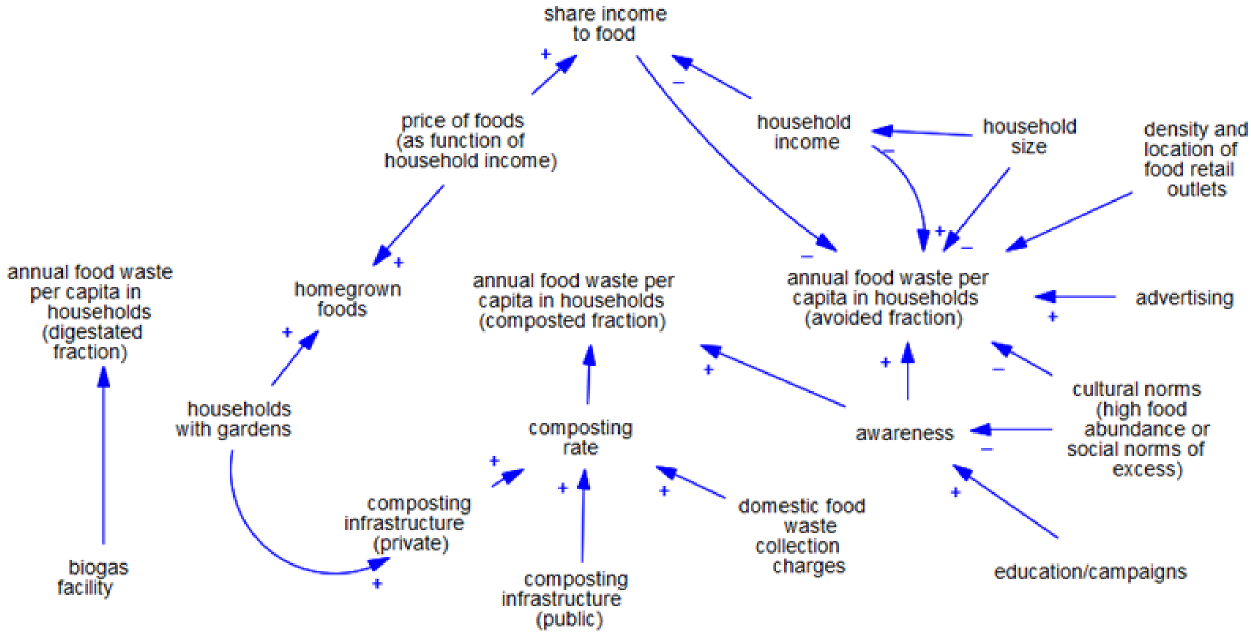

Figure 14: Causal loop diagram "Household food waste".

2.) Review of policies targeting lifestyle change and policy barriers

Stakeholders and policymakers requested concrete policy examples that could support the achievement of the target values assumed in our simulations. In essence, they wanted to understand how to design effective policies that would make the modelled household decisions more realistic and achievable.

We responded to that request by reviewing policies that have been implemented and evaluated in real-world contexts and have been described as successful. We identified actual policy instruments and strategies that have proven effective in influencing household behaviour with the aim to develop detailed and credible narratives that put our simulated outcomes into perspective. We followed three approaches:

- We used the causal loop diagrams that describe the main factors of lifestyle and lifestyle change for a targeted search of policies tackling each of these main factors (i.e. those that can be influenced by policies – essential the socio-technical conditions).
- We identified existing good practices from both Europe and around the world through desk research, applying a “best-in-class” approach. These examples provide insights into policy mechanisms that align with our target outcomes and offer a benchmark for designing impactful interventions.

We reviewed the CLEVER narrative framework to identify policies in the domains of mobility and housing proposed by CLEVER for their scenario parameter justifications.

3.) Development of extensive narratives

The key factors identified under 1. Review of cause-effect relations, and 2. Review of policies fed into the scenario narratives which are presented below.

5.2.2.2 Defining the narratives

The scenario narratives for the domains of mobility, housing, and diet describe how people’s lifestyle will change in the EU-27 between now and 2050. It is important to note that policy interventions described apply to both the moderate and high ambition scenario. The difference is not in the scale of the policy measures applied, but in the obtained result in terms of lifestyle change. This reflects the fact that there is a large degree of uncertainty regarding human behaviour and the effectiveness of policies to modify it at societal level.

Mobility

In our scenario, which is based on the CLEVER scenario (Bourgeois et al., 2023), the EU-27 will see a change in mobility behaviour by 2050 on three levels:

Annual mobility demand per person for all modes (except non-motorised mobility): There will be a relative, but rather small increase in passenger transport by 2050 for all modes combined (except non-motorised transport) with respect to the historic base year 2015. However, passenger transport demand will stay below the pre-covid demand and the strong upward trend that could be observed between 2012 and 2019 will essentially be reversed (European Environment Agency, o. J.) (Avoid action). The increase is a result of the principle of “equitable and fair sharing of energy services” applied in the CLEVER scenario, which allows low consuming European countries to increase their demand at the expenses of high consuming countries, which will significantly reduce demand. All EU-27 countries will stay within the convergence corridor defined as the possible range in order to stay within planetary boundaries (upper limit) while also satisfying basic individual needs for all (“sufficiency” “lower boundary”).
The assumed stagnation in passenger transport demand will be achieved, for work-related travel, by increasing teleworking. After the unprecedented surge in teleworking during the covid pandemic, telework and more flexible work organisation arrangements are becoming a more prominent and permanent feature for employers and

employees in Europe. In 2050, both EU-level and national regulatory measures[8] will have been put in place that properly safeguard teleworkers rights along with demands on firm level policies. Legislation will recognise the prevalence of teleworking and government and firm level policies combined will have managed to reduce work-related travel demand to a large extent.
For leisure-related travel, a shift in preferences to travel lower distances and avoid long-haul flights will take place motivated by people's increased eco-consciousness (e.g. flight shame).

Mode shift: The EU-27 will see a gradual shift away from motorised to non-motorised modes and from private to public transportation (shift action). Most importantly, the share of cars/light duty vehicles (LDV) will go down as people switch to public transportation (buses and trains), two- and three wheelers (e.g. pedelacs, mopeds, etc.) and non-motorised mobility (cycling and walking). In particular trains will see a high increase in demand, especially for mid- and long-range travels, at the expense of short-haul (domestic) flights. Regarding aviation, policies will target especially unnecessary or excessive flying. Domestic flights will essentially be phased out with the exception of countries with islands or very long internal distances. Since passenger travels by train are generally shorter than by air, a shift from air to rail decreases the total transport demand to some extent (see annual mobility demand).
The assumed mode shift is achieved through a combination of policies that incentivise the use of non-motorised and public modes of transportation and disincentivise private motorised transport and flying. Many of the policies are synergetic – for example, by dedicating more urban public space to pedestrians and cyclers, the space available for parking and driving is reduced, creating less favourable conditions for car usage. Policy levers used to achieve a mode shift can be divided into

- Fiscal measures and pricing
- Restrictive regulatory measures
- Investments in improving infrastructure and transport services
- Behavioural and educational campaigns.

Fiscal measures and pricing increase the cost of undesirable and subsidise wanted behaviour. Pricing measures include, for example, congestion charges to manage peak-hour traffic, increased fuel and carbon taxes, increased parking fees and progressive vehicle taxation—especially targeting large, high-emission cars. Measures targeting specifically aviation include (increased) aviation taxes, fuel taxes, and carbon pricing on flights.
Financial incentives include subsidised public transport (both urban and interurban) through free or discounted fares, especially for low-income groups. Tax benefits and other forms of economic support (e.g. company car, commuter allowance that is not conditional upon the use of public or non-motorised transport means) that incentivise the use of the care are phased out. Governments will set up mobility programmes for public-sector employees such as public transport subsidies or bike allowances, and will promote remote work and flexible schedules.

Restrictive regulatory measures ban undesired mobility behaviour. Measures include establishing low-emission zones and zero-emission zones to limit or ban high-emission vehicles in city centers, creating car-free zones to prioritise pedestrians and cyclists, and implementing lower speed limits and traffic calming measures in residential and school areas to enhance safety and encourage active modes of transport. Regulatory spatial planning measures will counter rural and urban sprawl and promote the "15-minute-city", resp. "30-minute rural community", thus a compact, accessible, and walkable urban model in which people can live, work, shop, learn, and pursue their leisure activities all within a 15/30-minute radius.
Regarding aviation, measure include banning/limiting short-haul flights where viable rail alternatives exist, restrictions on airport expansion and others. Public sector travel policies are put in place that restrict work-related

[8] https://osha.europa.eu/sites/default/files/documents/Regulating_telework_post-COVID-19_Europe_en.pdf

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air travel and prioritising train travel or virtual meetings.

Investment in infrastructure and services focuses on improving the public transport network and, more generally, creating urban environments that are attractive for walking and biking.

Investments into expanding and modernising public transport networks, including vehicles and stations/stops, increase frequency, affordability, reliability, convenience and safety. Increasing travel convenience includes a vast array of measures to enhance intermodal connectivity through mobility hubs, bike-and-ride facilities, shared bikes and e-scooters with docking stations at transit hubs and integrated ticketing systems makes it easier to combine walking, cycling, and public transit into seamless journeys. It also includes measures to make

Investments into making urban areas more attractive for walking and biking include building safe, continuous and barrier-free cycling and pedestrian infrastructure, repurposing road space for bus lanes, bike lanes, wider sidewalks, and green infrastructure.

Behavioral and educational campaigns focus on promoting awareness of the health, environmental, and financial benefits of walking, cycling, and public transit. Measures include school and community-based mobility education, media campaigns, events and pilot projects such as car-free days, pop-up bike lanes, temporary street closures, etc. Information campaigns provide practical information on available alternatives to private motorised transport and flying (e.g. car pools, night trains, holiday destinations reachable by land transport, etc.).

Vehicle occupancy (avoid action): Vehicle occupancy for light-duty vehicles will rise because of the growing use of car-sharing services and a decline in household car ownership. This shift is facilitated by increased teleworking and the growing trend of trip sharing, making a second car unnecessary for many households.
Additionally, with a greater share of travel shifting to trains and buses, existing capacity on these forms of public transportation will be utilised more efficiently before new trains are added to the network. Consequently, the load factors for trains and buses will increase. As demand for public transportation continues to grow, the available capacity in existing train and bus services will fill up, leading to the introduction of additional trains and buses. This increase in service capacity will create a positive feedback loop, attracting more passengers due to the enhanced service and greater flexibility of public transportation.

Housing

In our scenario, and based on the CLEVER scenario, the EU-27 will see a change in housing behaviour by 2050 on two levels:
Reduction in residential floorspace/person: By 2050, the average floor area per person has declined slightly—a seemingly modest shift, but one constrained by significant structural factors. Chief among these is the slow turnover of the existing housing stock, which limits the pace at which residential floorspace can be reduced. In parallel, demographic trends—such as an ageing population and declining birth rates—continue to drive the formation of smaller households, reinforcing the demand for more individualised living spaces.

This stabilisation marks a reversal of a long-standing trend toward increasing living space per capita, which had been propelled by shrinking household sizes and the expansion of dwelling sizes. The anticipated change will stem from two key developments:
a) A stabilisation or reduction in the average size of dwellings.
b) A deceleration in the decline of average household size.

Achieving this shift will require coordinated action at local, national, and EU levels. Binding EU and Member State legislation to limit soil sealing will prompt local governments to promote higher-density zoning, favoring

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multifamily buildings, cooperative housing, and the renovation of existing buildings over new single-family developments. Targeted subsidies will support retrofitting projects that divide large dwellings into smaller, more adaptable housing units.

Architecture, interior design, and urban planning disciplines will play a crucial role by developing innovative design and technical solutions for converting existing homes into compact, livable units—suitable for singles, multigenerational households, and flexible arrangements such as modular housing.

Further land-use policies will restrict short-term tourist rentals and the acquisition of second homes in areas facing housing shortages, while also encouraging the use of vacant properties. These measures aim to maximise the residential use of existing housing stock, thereby reducing the demand for new construction.

Specialised housing agencies and programmes[9] will support and provide information on alternative living arrangements such as home sharing and multigenerational living. They will facilitate home exchanges—particularly between elderly residents in large homes and those seeking more space—by acting as intermediaries and providing technical, legal, and logistical assistance. Financial incentives, such as covering moving expenses or rent differentials, will help ease the transition for those downsising to homes that better match their current needs.

Reduction in housing energy use: In our scenario a reduction of energy use is achieved by households deliberately reducing the consumption of hot water, space heating and fewer energy-consuming household appliances, resp. the elimination of standby power. It is not achieved through an efficiency improvement of the appliances beyond the exchange of appliances (e.g. boilers, heating, etc.) after their typical lifetime.

Hot water: The reduction in hot water use is achieved mostly through information campaigns and monetary incentives to save water. Information and education campaigns will inform consumers of all age groups on the importance of water and energy saving and on the most impactful habits to save hot water (e.g., showers instead of baths, reducing shower length and reduce number of showers per week in line with dermatological recommendations[10]). Monetary incentives to reduce consumption will be achieved through progressive water pricing, meaning that the price per unit of volume increases as the volume used increases beyond a certain threshold, in combination with residential water meters. The meters help households monitor and modify water consumption while the progressive prices ensures that excessive water consumption is disincentivised. Progressive water pricing has already been implemented in many European cities (e.g. Barcelona, Bruxelles)67.

Space heating: A reduction of heating energy will be achieved through a combination of consumer information and education campaigns and the regulation of space heating in public buildings. Campaigns targeted to all age groups will inform consumers on the (economic, environmental, etc.) benefits of lowering the thermostat levels. Besides, in public buildings maximum temperatures will be regulated[11].

Other energy uses: Other household energy use that will decrease include the energy needed for lighting, building management (e.g. ventilation, escalators, etc.), household appliances (e.g. washing machine, refrigerator, vacuum cleaner, etc.), electronics and others. Changes in user habits will be mostly achieved through

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[9] Such programmes exist today, for example, the “From Big to Better” Programme in Amsterdam/Netherlands, the programme of the Tower Hamlets Council in the UK that provides financial incentives for tenants downsising their homes through mutual exchange, with payments based on the number of bedrooms relinquished, or programmes in Germany and Ireland that aim to match younger individuals with elderly residents, where the young provide help around the house in return for reduced rent.

[10] Many Europeans shower or bath every day, while it is not considered necessary or even healthy by dermatologists (Shmerling, 2021). Avoiding one or two showers per week could probably save about 10% to 20% on total energy use (Toulouse et Attali, 2018 – p.24)

[11] This has been done, for example, in Germany (https://www.euractiv.com/section/eet/news/german-government-approves-2-gas-savings-plan/).

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information and education.

Diets

In 2050, the EU-27's population has made a dramatic **shift towards a more nutritionally balanced flexitarian diet with low levels of animal-source foods** in line with the flexitarian diet recommended by the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems, respecting regional food traditions and preferences (Willett et al., 2019). This change is motivated by health and environmental concerns, ethical concerns and economic factors. Specifically, red meat consumption will slump, while the consumption of legumes and nuts and seeds will increase. In general, the consumption of animal-based food goes down while that of plant-based food goes up (Springmann et al., 2023).
The change in dietary patterns will be achieved through strategic, coordinated multilevel approaches combining government and private action that targets the lifestyle choices of individuals[12] and households, and a reform of current agricultural subsidies ("Common Agricultural Policy") away from subsidising high intensity dairy and meat farming. Most importantly, the current policy of area-based direct payments based on will be abolished and replaced by a system of payments for public goods provided by farmers (Pe'er et al., 2020). The latter will increase meat prices to a level that factors in social and environmental externalities (i.e. impacts on health, climate, biodiversity, water and air quality, etc.). At the same time, fiscal incentives (e.g. VAT exemptions or similar) and food assistance programmes will promote the consumption of healthy foods, especially in low-income households. Educational policy measures that emphasise the individual's personal responsibility and choice, such as food labelling, clear dietary guidelines on healthy and sustainable diets, counselling by the health care professionals, will be continued and intensified, targeting specifically the early childhood which is key to shaping future dietary preferences. Marketing of food not meeting minimum nutrition standards will be effectively banned. The public sector will rigorously follow its own dietary standards (e.g. in school canteens, hospitals, etc.) (Mozaffarian et al., 2018).
While the envisaged dietary change alters significantly the composition of the population's food intake, the overall daily intake remains roughly the same. Nonetheless, reduction in food demand (and, hence, production) will be achieved by significantly **reducing food loss and food waste**, as stipulated by SDG 12.3 (United Nations Environment Programme, 2024)". The reduction of food waste will be achieved through a mix of better collection infrastructure, higher food waste collection charges, the above-mentioned increase in food prices to reflect externalities and educational and information programmes (Boulet et al., 2021; Schanes et al., 2018).

5.2.2.3 Quantifying the scenarios

Reference scenarios

In the study, we used two reference scenarios already described in the broad scenario logic, i.e., deliverable 4.4 of this project, section 4: Updates and changes to harmonisation. Both scenarios share common input data and targets for 2050. However, each IAM evolves differently based on its underlying mathematical structure and modelling logic, resulting in different outcomes – even during the historical period. This exercise acknowledges the efforts made to harmonise these tools, while also recognising the current limitations in aligning their representations of system behaviour.

- **No policies scenario:** this scenario represents a situation where no further action beyond the current one is taken to tackle the climate crisis. Commitments to further decarbonise the economy are stopped

[12] This approach of combined government, private and NGO action has, for example, been successful in achieving an increase in the average intake of wholegrain in Denmark from 36g (2008) to 82g (2019) (https://www.theguardian.com/lifeandstyle/2025/apr/23/the-wholegrain-revolution-how-denmark-changed-the-diet-and-health-of-their-entire-nation)

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or delayed, and no new policies are adopted. Trends regarding decarbonisation follow current implemented policies and therefore no deep and fast decarbonisation pathways are expected, and emissions may even increase again. This scenario is originally created in van de Ven et al. (2023).

- **NDC-LTT scenario:** Under this scenario, further action to decarbonise the economy is taken in line with the European Green Deal and according to the Nationally Determined Contributions (NDCs) and the Long-Term Targets (LTTs) of the EU-27 countries, which are set to be accomplished. A wide range of policies is adopted, to comply with these objectives in time. This scenario is originally created in van de Ven et al. (2023)**Error! Bookmark not defined.**.

Policy scenarios

The narrative of lifestyle change has been translated into concrete, quantified targets, which are summarised in Table 8 below. The **scenario assumptions for mobility and housing** are based on the CLEVER scenario (Bourgeois et al., 2023). The CLEVER scenario was developed through a bottom-up approach that aggregates national trajectories for 2050 across the EU-27, the UK, Norway, and Switzerland, developed with input from academic, research, and civil society organisations across the EU. For the study, since we are treating the EU-27 as one region in our models, we have used a weighted (by population) average of the national parameters of the CLEVER scenario.

CLEVER aims to balance long-term climate goals, energy security, and practical feasibility, while ensuring a decent living for all Europeans through the principles of *sufficiency* and *equity* (just and fair transition).
Sufficiency is understood as a "*set of measures and daily practices that avoid demand for energy, materials, land, and water while delivering human well-being for all within planetary boundaries*" (IPCC, 2023, page 29). Equity is built into the concept, which strives for a decent quality of life for all and, thus, inherently aims for an equitable transition also described by the doughnut economics theory (Raworth, 2017).

Concretely, in the CLEVER scenario a corridor has been defined for all parameters (2050 targets) with the lower bound representing the minimum "sufficiency" level required for a decent life and the upper bound representing the maximum allowed to stay within the planetary boundaries (most notably, below a global temperature increase by 1.5°C). The estimate of 26-28 $GtCO_2$ as the maximum EU CO_2 budget for the period between 2020 and 2041 (year of CO_2 neutrality) is used. Different national perspectives are respected by allowing a divergence of national trajectories and 2050 targets that reflect different levels of economic wealth and current consumption levels. In other words, countries converge towards similar levels of resource (energy) use with those with historically a high demand having to reduce and those with a low demand being allowed to increase their use.

Sufficiency levels are difficult to define and there is no universal agreement on which levels of resource use are necessary for satisfying basic human needs and maintaining a "sufficient" quality of life, *in part due to their dependence on peoples' culture, context and physical characteristics* (Rao & Min, 2018). For example, for mobility demand, Millward-Hopkins et al. (2020) define a large range between 5,000 and 15,000 pkm/cap/year as minimum final energy requirements for decent living standards. Rao and Min (2017) define a set of universal, irreducible and essential material conditions for achieving basic human wellbeing, along with indicators and quantitative thresholds, which can be operationalised for societies based on local customs and preferences.
Nevertheless, the target values proposed by CLEVER are largely in line with other demand side scenarios such as the Low Energy Demand Scenario (Grubler et al., 2018) or the EUCalc scenario[13], etc., and they are generally very much above the "bare minimum" needed for basic human existence.

[13] https://www.european-calculator.eu/model/

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Scenario assumptions on diets are based on the EAT-Lancet diet (Willett et al., 2019) that combines goals on human health and environmental sustainability by recommending a diet that is both nutritionally adequate and within the planet's ecological limits, and on the quantification thereof of (Springmann et al., 2018).

Responding to suggestions from the project stakeholder group, **two policy scenarios** were defined:

- A **moderate change scenario** aiming at a more modest lifestyle change that largely reflects past lifestyle changes observed in the real world ("best-in-class"). This scenario was parametrised to be 50% of the change assumed under the high change scenario.
- A **high change scenario** aiming at a more radical yet unprecedented lifestyle change.

Table 8: Policy scenarios

Sector	Lifestyle changes	Moderate change scenario	High change scenario
Mobility	1. Change in end-use passenger transport (pkm/capita/year) from 2015 to 2050	-396	-792
	2. Change in transport mode shares (Percentage (%) of passenger-km by mode in 2050 as compared to 2015)		
	Non-motorised transport (NMT)	4,35%	5,92%
	Trains	11,94%	16,60%
	Road (bus + LDV)	69,91%	66,96%
	Domestic aviation	0,82%	0,30%
	International aviation	12,99%	10,22%
	3. Change in car occupancy (average number of people per car in 2050)	1,675	1,95
Housing	4. Change in residential floorspace per person (% of average residential m2/person from 2015 to 2050)	3,38%	6,76%
	5. Change in the use of domestic energy (Relative change (%) from 2015 to 2050 of end use energy by type of domestic use)		
	Space heating	-27,42%	-54,84%
	Domestic hot water	-22,50%	-45,00%
	Cooling	320,59%	320,59%
	Specific electricity	-17,37%	-34,74%
	Domestic cooking	-15,53%	-31,05%
Diets	6. Change towards a more plant-based and less meat-based diet (gr/day)		
	Animal-based food	-29,06%	-58,12%
	Plant-based food	19,70%	39,40%
	Others	-46,02%	-92,05%
	7. Change in the generation of food waste (kg/yr)		
	Animal-based food	-14,27%	-21,31%
	Fruits and vegetables	-16,65%	-24,73%
	Others	-15,39%	-22,06%

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5.2.3 Defining the simulation outputs

The harmonisation of simulation outputs is crucial to obtain comparable results. We have selected common output indicators that operationalise the three types of impacts of household lifestyle change specified in the research question:

1.) Reduction in GHG emissions,

2.) Changes on land-use and

3.) Cost implications (expenditures).

Reduction in GHG emissions:
Emissions were reported in CO_2 emissions, respectively CO_2-equivalent emissions (CO_2, N_2O, CH_4) for AFOLU emissions. The focus on carbon dioxide as the only greenhouse gas for mobility and household was this is the only gas included in PROMETHEUS.

Mobility: Direct emissions of carbon dioxide (CO_2) released in the activity of passenger transport, including both private and public modes. This excludes freight transport as well as international bunkers.

Housing: Direct emissions of carbon dioxide (CO_2) released in the activity of fuel combustion in residential households (dwellings), excluding transport, commercial buildings, and institutional buildings.

Diets: Emissions linked to Agriculture, Forestry, and Other Land Uses (AFOLU). AFOLU refers to human use of and influence on land areas, including agricultural practices, forestry, and other land uses like grazing or urbanisation, thus accounts for the emissions directly linked to agricultural production (specifically CH_4 and N_2O) and the indirect emissions related to land use change that result from, e.g. a decreased need for pastures and cropland due to the reduced need for green fodder and feed crops. Emissions from agricultural production stem mainly from the enteric fermentation of ruminant animals (cows, sheep, goats) (CH_4) as they digest food, from animal manure (CH_4 and N_2O) and from the use (N_2O) and production of fertilisers (CO_2), but also from fossil fuel use on farms for operating machinery (CO_2). CO_2 emitted in fertiliser production and for operating farm machinery are not included under AFOLU.
Since agriculture and land use are not included in PROMETHEUS only results for GCAM and WILIAM were reported.

Changes to land-use
Changes in people's diets (e.g., less meat consumption) affect land-use. Land use and land use change (LULUC) are critically important because they directly influence the environment, climate, biodiversity, food security, and as a basis of peoples' livelihoods. For example, a reduction in meat consumption decreases the need for green fodder and feed crops, thus affecting the demand for pastures and cropland. GCAM and WILIAM include a representation of land uses.
The indicator used to compare across models is the land cover change from 2015 to 2050.

Cost implication for households
The economic expenditures required to purchase fuels in housing and mobility have been used as indicator of cost implication in households. Specifically:

- Monetary consumption of households for mobility (private) in real terms. Activity of passenger transport, including only private (public transport is considered government expenditures). This excludes freight transport. Units: annual monetary flow in constant dollars.
- Monetary consumption of households for energy fuels in housing in real terms. This excludes commercial buildings and institutional buildings. Units: annual monetary flow in constant dollars.

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5.3 Results

It is important to note that all figures in the results section are cumulative for the 27 EU member states.

- PROMETHEUS reports results of EU-28 (incl. UK). This should be considered in all the figures.
- GCAM reports results of EU-27 in two groups (EU-12 + EU-15), which were aggregated.
- WILIAM reports results of EU-27 by country, which were aggregated.

Our approach assumes that the lifestyle changes in the domains mobility, housing and diets act in combination (as defined in the policy scenarios), and the total impact is the sum of the impact of each domain. Van Heerden et al. (2025a), conducting an inter-model comparison exercise focused on demand-side measures similar to our study, find that there is some interaction effect between the lifestyle measures, although its importance for the overall mitigation potential is limited.

5.3.1 Impact of lifestyle change on GHG emissions

In the following, we present the results of the scenario simulations, comparing the two policy scenarios “Moderate/high lifestyle change” with the references scenarios “No Policies” and “NDC-LTT” separately for the three sectors “household transport”, “household mobility” and “household diets”. This section focuses on emissions, expressed in terms of accumulated gases emitted over the simulation period (2025 to 2050).

The **combined CO_2 reduction of passenger transport, housing and dietary change** between 2025 and 2050 for WILIAM and GCAM is shown in table 9 and 10 shows the combined **CO_2 reduction of passenger transport and housing** for WILIAM, GCAM and PROMOTHEUS. Under the assumption of **high-impact lifestyle changes**, total CO_2 emissions for mobility, housing and diet are reduced on average by approximately **23.9%** relative to the *No Policies* reference scenario, and by **20%** relative to the *NDC-LTT* scenario.

Table 9: Total emissions reduction between 2025 and 2050 for mobility, housing and diet change (in CO_2 equivalent. Gases: CO_2, CH_4, N_2O).

No-policies	WILIAM	GCAM
Moderate change	-15,57%	-19,67%
High change	-22,09%	-25,71%
NDC-LTT		
Moderate change	-10,97%	-17,29%
High change	-17,21%	-22,80%

Table 10: Total emissions reduction between 2025 and 2050 for mobility and housing (in CO_2)

No-policies	WILIAM	GCAM	PROMETHEUS
Moderate change	-16,39%	-19,49%	-7,51%
High change	-23,22%	-25,30%	-11,68%
NDC-LTT			
Moderate change	-12,08%	-19,01%	-4,80%
High change	-17,20%	-24,62%	-7,56%

5.3.1.1 Mobility

The assumed lifestyle changes related to mobility leads to a drop in cumulated emissions (CO_2) in all three models (see Figure 15, data in Table 11). Emission trajectories also show a very similar picture with emissions gradually decreasing from 2025 to 2050. However, while WILIAM and GCAM achieve very similar reductions (~19,6%, resp.

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23,7% under assumptions of moderate change and 26%, resp. 30% of high lifestyle change), PROMOTHEUS shows much lower (factor 3-4) reductions, which can be explained by limited market-driven diffusion of clean transport technologies without a specific policy included and higher projected transport activity.

Table 11: Simulation results transport (CO_2 emissions reduction between 2025 and 2050)

No-policies	WILIAM	GCAM	PROMETHEUS
Moderate change	-19,60%	-23,74%	-5,41%
High change	-26,17%	-30,25%	-8,52%
NDC-LTT			
Moderate change	-15,18%	-22,95%	-4,69%
High change	-19,02%	-28,84%	-7,36%

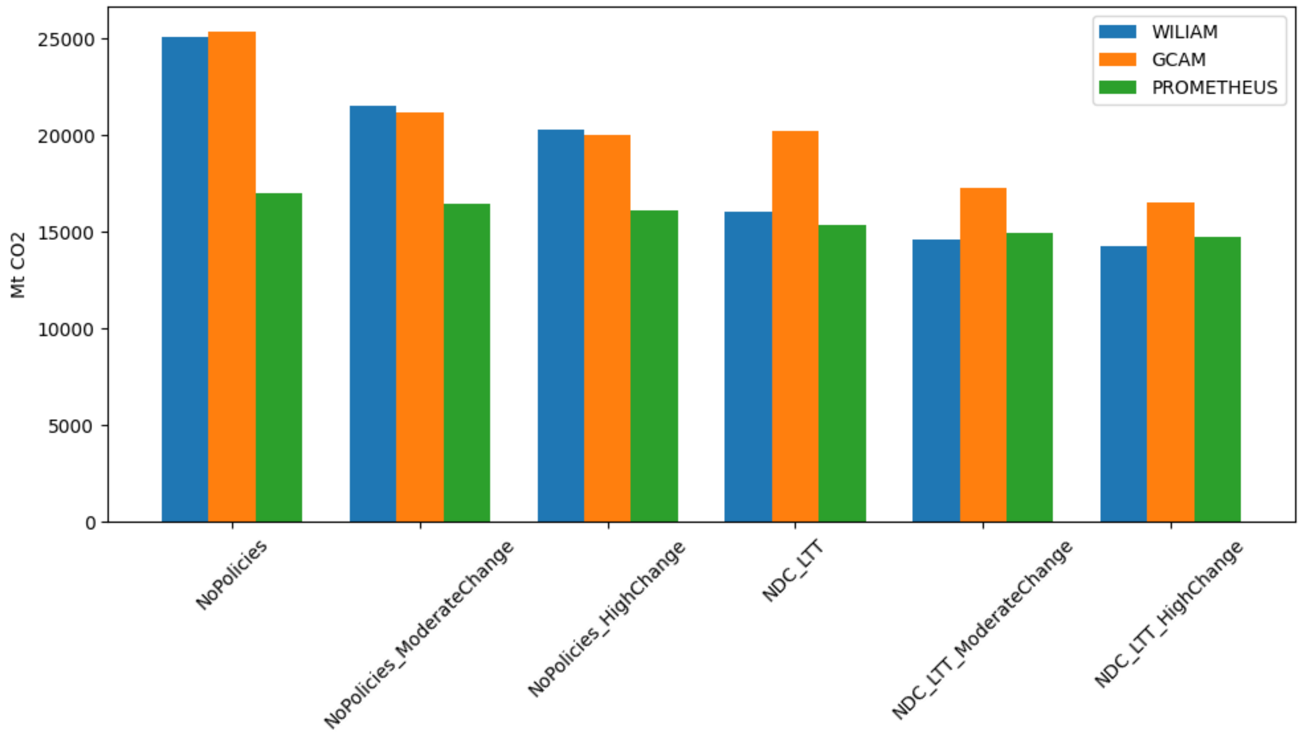

Figure 15: EU-27 carbon budget released in passenger transport (cumulative CO_2 emission in Mt over the period 2015-2050).

5.3.1.2 Housing

The assumed lifestyle changes related to housing leads to a drop in cumulative emissions (CO_2) in all three models (see Figure 16), with all three models obtaining similar results. When compared to a no-policies scenario, the emission reduction potential of the simulated high lifestyle changes ranges from -13.03% (GCAM) to -16.71% (PROMETHEUS) and from -8,35% (PROMETHEUS) to -14,04% (WILIAM) when compared to the NDC-LTT scenario (see Table 12).

Table 12: Simulation results housing (CO_2 emissions reduction between 2025 and 2050)

No-policies	WILIAM	GCAM	PROMETHEUS
Moderate change	-6,77%	-8,94%	-10,85%
High change	-14,40%	-13,03%	-16,71%
NDC-LTT			

Moderate change	-6,68%	-6,22%	-5,23%
High change	-14,04%	-10,80%	-8,35%

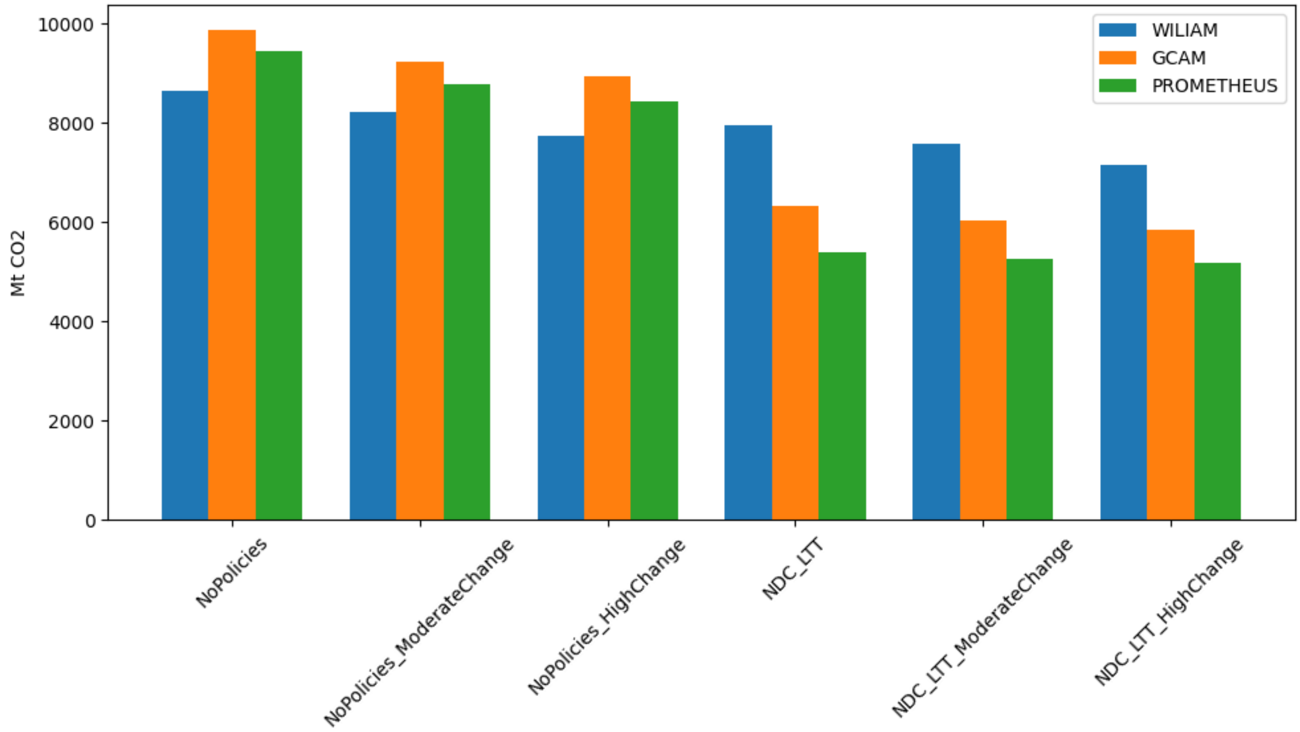

Figure 16: EU-27 carbon budget released in housing (cumulative CO_2 emission over the period 2015-2050)

5.3.1.3 Diets

Figure 19 shows the emissions linked to Agriculture, Forestry, and Other Land Uses (AFOLU) emitted over the period 2025-2050 under scenarios of moderate or high dietary change.

The assumed dietary change leads to a significant decrease in cumulative AFOLU emissions (expressed in CO_2 equivalents) GCAM and WILIAM when compared the No-Policies with and without lifestyle change (see Table 13). However, in WILIAM, the NDC-LTT scenario (with and without social transition towards the sustainable lifestyle) results in cumulative emissions that turn negative, due to the set of technological transition embedded in the scenario. What may seem counterintuitive at first in the results is that the emission reduction in the moderate and high lifestyle change scenarios is lower than in the reference scenario. The reason for this lies in particular feedback included in WILIAM which is the ratio in the energy system between the net energy output of the system and the energy that is required to produce the net energy for the various end uses, called EROI ("energy returned on energy invested") of the system. The EROI of the energy system depends very much on system's energy mix. Since fossil fuels have a much higher EROI than renewables over their lifetime, the energy system's EROI drops the more it shifts towards renewable technologies. A second (shorter-term) effect that comes into play is the fact that the deployment of many new energy production facilities requires a lot of upfront energy investments, which also drop the system's EROI significantly[14]. In WILIAM, the assumption is that the reduced demand of energy that results from the changed consumption habits allows reducing the use of fossil fuels as final energy (gasoline,

[14] For more information, see (Capellán-Pérez et al., 2019).

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diesel, natural gas). In other words, the energy saved is energy coming from fossil resource. As a result, the system's EROI drops, which eats up parts of the reduced energy demand resulting from the changed household consumption (this is also true in the cases of mobility and housing, but here the effect is not apparent when looking only at the emissions results). In the NDC-LTT+high/moderate lifestyle change scenarios, this effect of a declining EROI, which cancels parts of the emissions saved due to the changed consumption, is higher than under the reference scenario, which explains why the reference scenario seemingly performs better. It is important to note that over a longer period of time, once fossil fuels have been phased out, the lifestyle change scenarios will perform better than the reference scenario.

Looking at the **emissions trajectories** we can observe that in both models, under the NDC-LTT + High/Moderate change scenarios, AFOLU emissions drop for a few years (2025-2035 in GCAM and in 2025-2030 in WILIAM), but then pick up again and rise sharply until 2045 (GCAM), respectively, 2050 (WILIAM) after which they decrease again (GCAM), respectively, stay on a high level until 2069 after which they drop again in the case of WILIAM. The No-policies + High/Moderate change scenarios show a similar trajectory, but with the increase of AFOLU emissions starting already in 2022 and reaching a lower level.
This rise and fall of AFOLU emissions can be explained by the concurrent increase in the use of bioenergy (wood and energy crops), which is higher in the NDC-LTT scenario than in the No-policies scenario since the technological mix defined in the NDC-LTT scenario implies a higher use of biofuels. The increased extraction of wood in forests generates higher emissions in the LULUCF sector. Afforestation policies, which are concurrently included (WILIAM) capture parts of the LULUCF emissions emitted, but this effect has a considerable time lag as trees first need to grow. In both scenarios, forest areas increase for both primary forest and plantations while crop land increases only slightly under the NDC-LTT scenarios and remains constant in the no-policies scenarios (WILIAM).

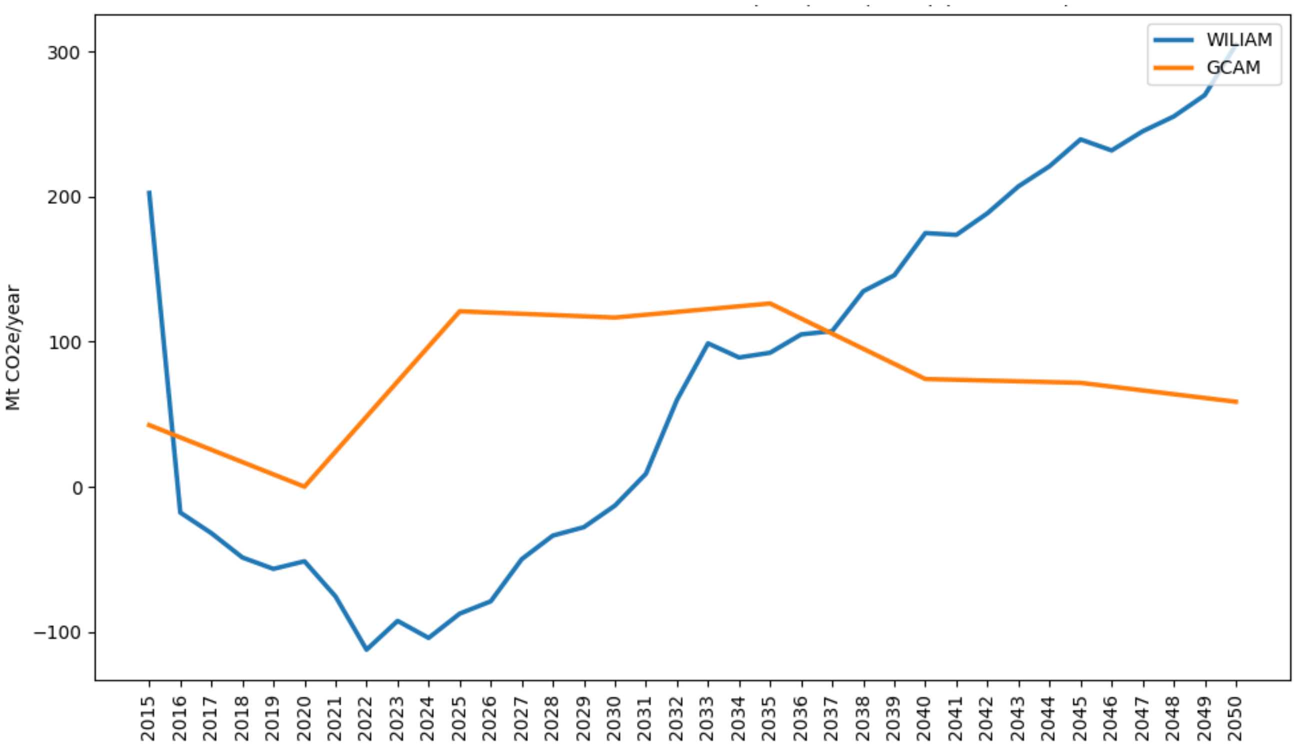

Figure 17: EU-27 AFOLU Sector: Annual Emissions (CO_2, CH_4, N_2O) (No-Policies reference scenario)

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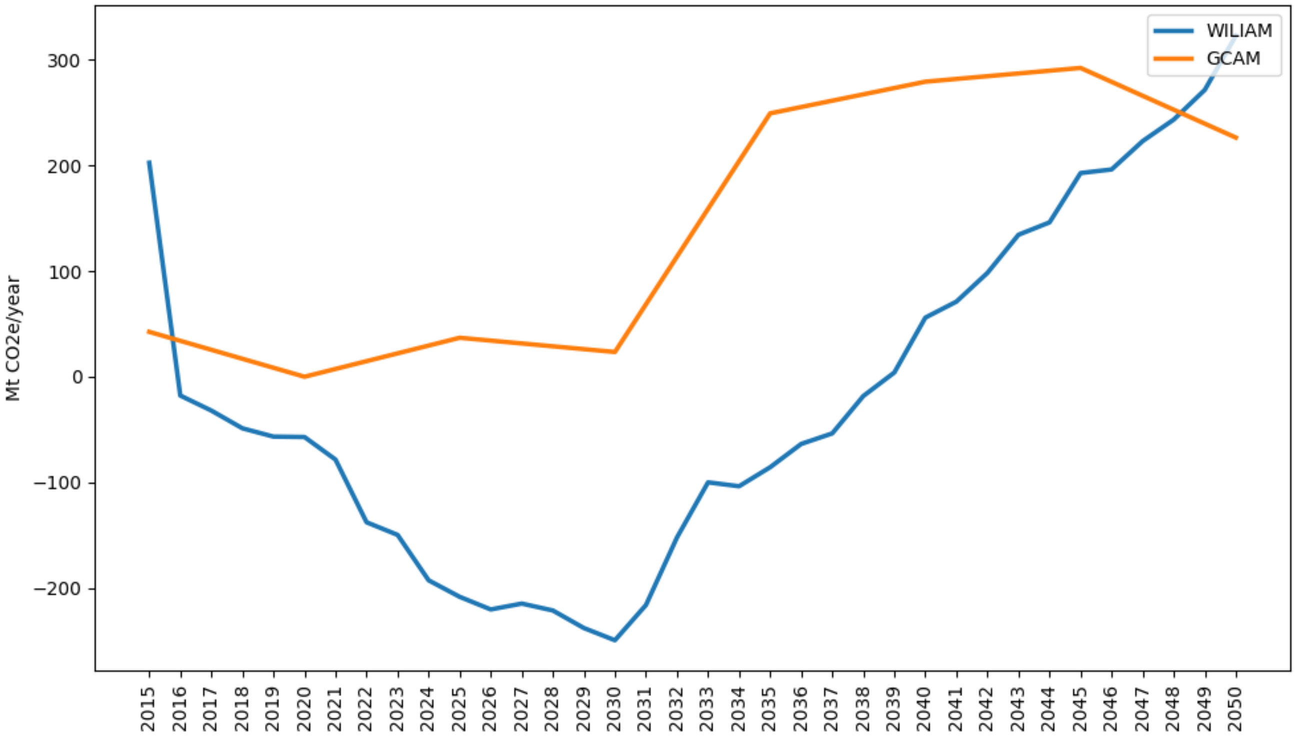

Figure 18: EU-27 AFOLU Sector: Annual Emissions (CO_2, CH_4, N_2O) (NDC-LTT reference scenario)

Table 13: Simulation results AFOLU related emissions (in CO_2 equivalents)

No-policies	**WILIAM**	**GCAM**
Moderate change	-9,00%	-21,46%
High change	-13,03%	-29,66%
NDC-LTT		
Moderate change	+99,96%	-11,73%
High change	+17,12%	-16,96%

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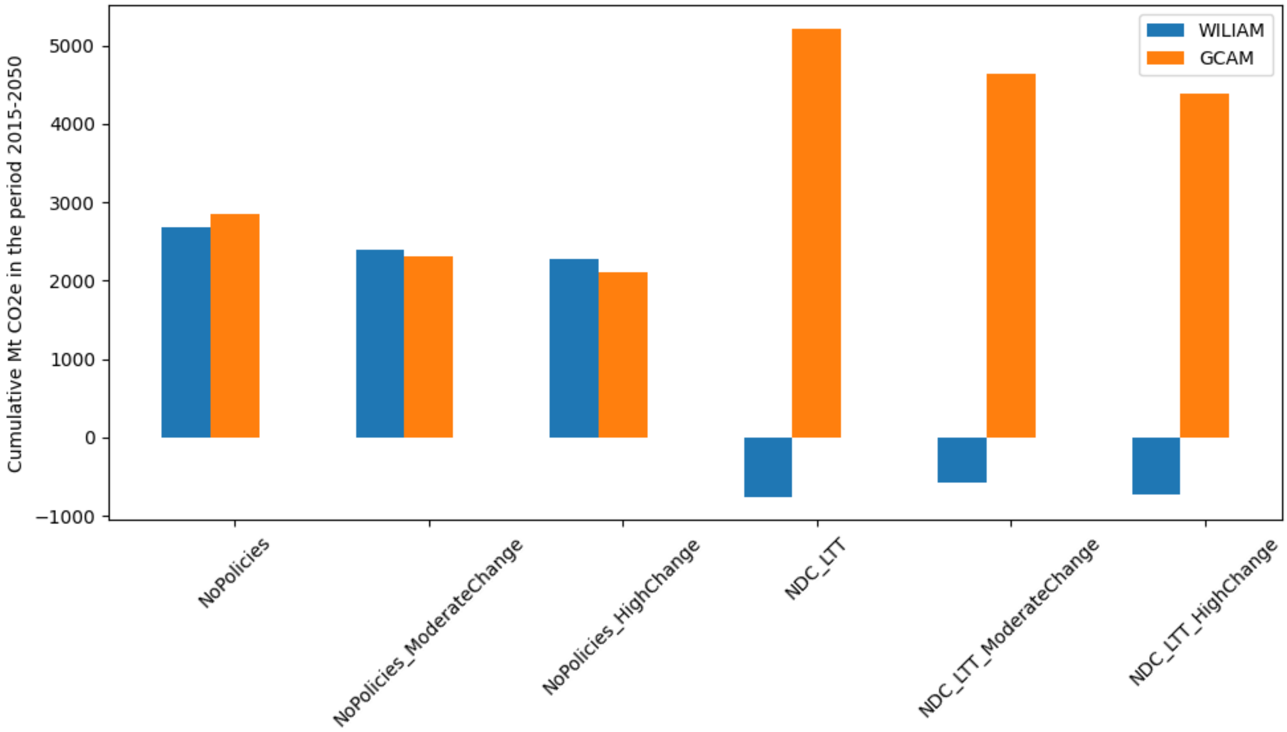

Figure 19: Cumulative CO_{2eq} emissions related to Agriculture, Forestry, and Other Land Use (AFOLU)

Table 14: Simulation results CH_4

No-policies	WILIAM	GCAM
Moderate change	-2,83%	-10,49%
High change	-4,59%	-17,13%
NDC-LTT		
Moderate change	-1,98%	-9,69%
High change	-3,43%	-15,97%

Table 15: Simulation results N_2O

No-policies	WILIAM	GCAM
Moderate change	-1,59%	-4,07%
High change	-2,22%	-6,01%
NDC-LTT		
Moderate change	-1,04%	-3,32%
High change	-1,59%	-4,98%

5.3.2 Impact of lifestyle change on social costs

5.3.2.1 Mobility

According to EUROSTAT data transport related expenditures constituted around 13.2% of EU aggregated households consumption expenditures in 2018 (Transport costs EU households over €1.1 trillion - Products Eurostat News - Eurostat). This adds up to 1.1 trillion euros or 7.2% of EU´s GDP in 2018.

However, in this study to understand the cost related implications of this lifestyle changes we will only look at the costs associated with the energy expenditures of passenger private transport paid by households. Given the relevance transport has on households' expenditure and budgeting and how the economic cost derivatives could be a limiting factor on the implementation of policies that lead to this lifestyle change it´s important we examine the cost implications of this change especially for mobility.

As we can see in Figure 20 (data in Table 16), these scenarios imply a reduction on the cumulative expenditure for transport fuels in the period examined that is consistent with the lifestyle change adopted and the emissions reduction scales seen in Table 11. Regarding the lifestyle change (less travel, in different more sustainable modes and higher vehicle occupation) these results highlight the potential of cost of fuels not as a barrier but as an enabler for this change in the transport sector.

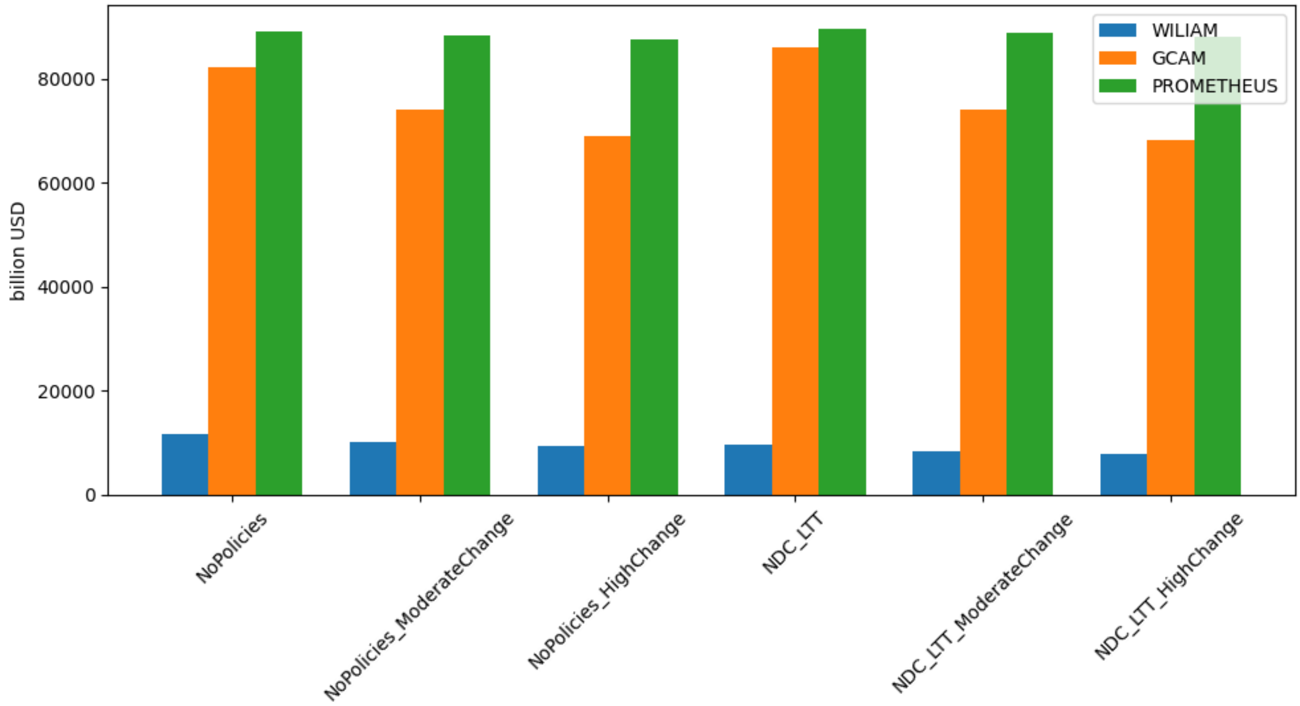

Figure 20. Cumulative households' expenditures in fuels for private passenger transport in the period 2015-2050. Units: USD_2010 in GCAM and PROMETHEUS, USD_2015 in WILIAM.

Table 16: Simulation results private passenger transport (expenditures between 2025 and 2050)

No-policies	**WILIAM**	**GCAM**	**PROMETHEUS**
Moderate change	-13,26%	-10,14%	-0,94%
High change	-20,55%	-16,06%	-1,73%
NDC-LTT			
Moderate change	-13,47%	-13,85%	-0,95%
High change	-19,01%	-20,64%	-1,86%

However, it´s important to point out that a full cost implications examination of this lifestyle change for households should also take into account other spheres not properly captured in this study as vehicle maintenance and acquisition, given that there are relevant differences between current fleet standards and low carbon substitutes (for example, EVs) regarding costs. Under this light, lower maintenance cost and lower expenditure of households on energy in transport may promote a higher available budget for the acquisition of these vehicles.

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5.3.2.2 Housing

According to EUROSTAT data housing related expenditures accounted for almost a quarter (24.1%) of all households' expenditure in 2022 for the EU regions households, making it the largest expenditure households must face both in relative and absolute terms. However, as our focus is set on the energy consumption of buildings by households, we will leave out several categories of this housing expenditures and focus exclusively on COICOP expenditure "04.5 Electricity, gas and other fuels", to understand the cost implications of this lifestyle change on households' energy for housing bill. Although the results vary across models, the potential for cumulative cost reduction under the lifestyle scenarios is comparatively lower for the energy consumption in housing than mobility as seen in the Figure 21 (data in Table 17. It must be mentioned, however, that as for the mobility sector the impact on expenditures is positive, as a reduction in the cumulative cost of energy for housing is still achieved, even though it´s lower.

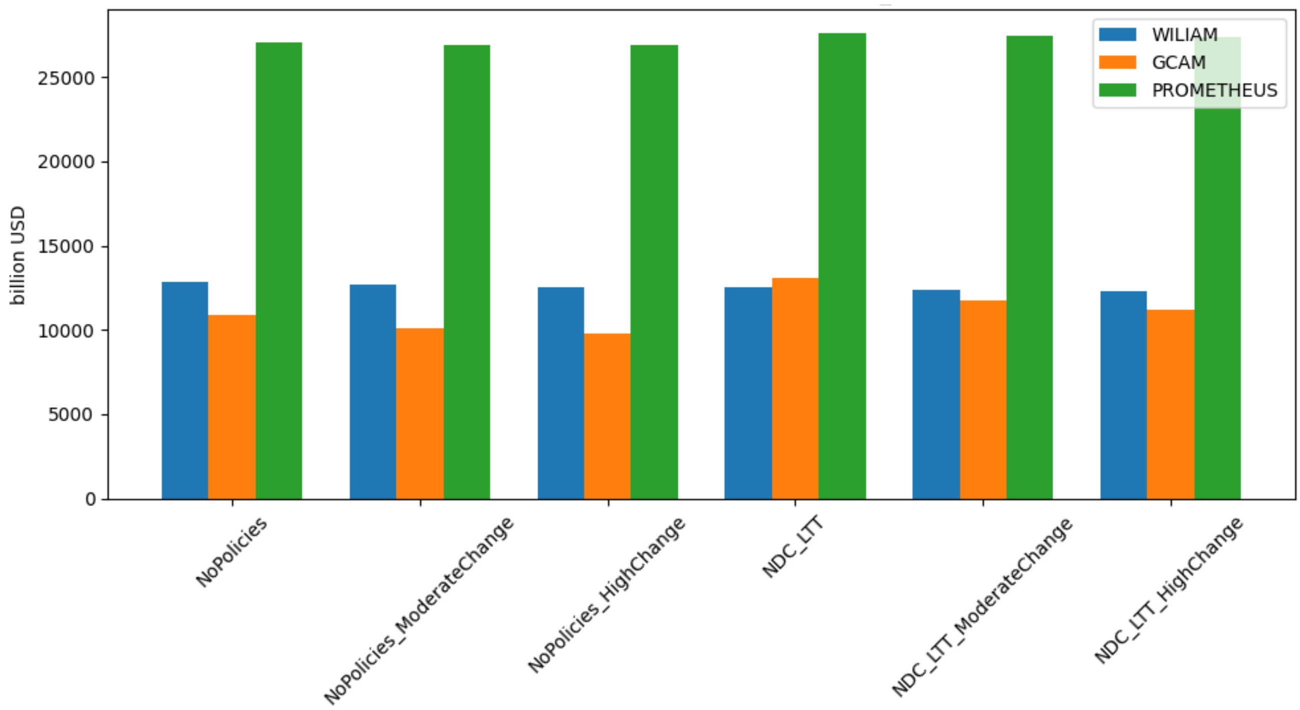

Figure 21. Cumulative household expenditures in fuels for housing in the period 2015-2050. Units: USD_2010 in GCAM and PROMETHEUS, USD_2015 in WILIAM.

Table 17: Simulation results housing (CO_2 emissions reduction between 2025 and 2050)

No-policies	**WILIAM**	**GCAM**	**PROMETHEUS**
Moderate change	-1.08%	-7,57%	-0,61%
High change	-2,24%	-10,00%	-0,81%
NDC-LTT			
Moderate change	-1,00%	-10,04%	-0,64%
High change	-2,10%	-14,13%	-0,82%

5.3.3 Impact of lifestyle change on land uses

Figure 22 presents the impact on land uses for both GCAM and WILIAM models. We can conclude that land uses are more affected by the baseline scenario and the model than the lifestyle change. From 2015 to 2050, both IAMs show a negligible impact (0-1%) of the new diet in the distribution of natural forests by 2015 between NoPolicies and NDC-LTT_HighChange. However, WILIAM has a noticeable decrease of natural land (-7,3 Mha) and rainfed cropland (-2,5 Mha) from the NoPolicies to NDC-LTT scenario in 2050, reducing the pressure of harvesting food. Results are directly linked to the meat reduction assumed in the new, more eco-friendly, lifestyle that implies less resources for livestock. GCAM reports an increase of 10% of cropland, while WILIAM does -1%. The transfer is mainly from “other land” such as grassland and other natural areas to both rainfed and irrigated cropland.

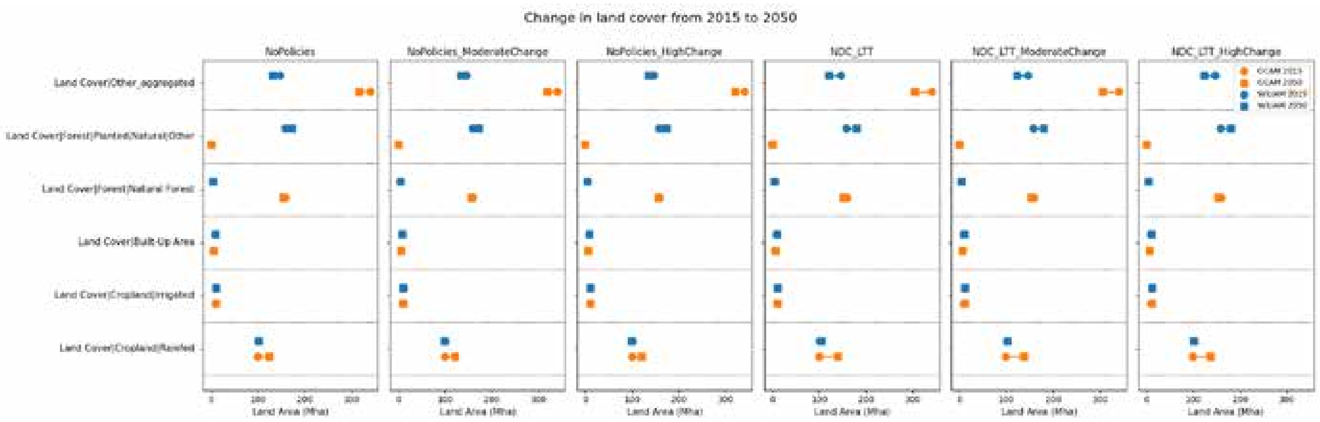

Figure 22. Land-cover change from 2015 to 2050 in the scenarios simulated with WILIAM and GCAM.

5.4 Discussion

The policy interventions modelled achieve **significant cumulative emission reduction across all three models**. While cumulative reduction rates may differ considerably when looking at each domain (mobility, housing, diets) separately, total reduction rates are more similar, especially between WILIAM and GCAM (with PROMETHEUS being an outliner in mobility, see Table 11).

The **spread of results (expressed as % change)** between the moderate and high lifestyle change scenario is generally smaller than the variation between the results of the different models. The heterogeneity of simulation results is due to structural differences between the models, differences regarding scenario assumptions affecting the reference scenarios, but also a lack of full harmonisation of data used as data inputs for the models. For the same reasons, emission trajectories are often considerably different, with the NDC-LTT trajectories tending to be better aligned than the No-policies trajectories.

Furthermore, it is relevant to note that, out of the achieved reduction, around **63% (WILIAM) and 58% (GCAM)** comes from lifestyle changes related to **passenger transport, 25% (WILIAM) and 25% (GCAM)** to those related to **housing** and **12% (WILIAM) and 17% (GCAM)** to those related to diet change. It´s important to point out, however, that dietary changes may have a greater impact than these shown, given complex feedback loops of agriculture, land, biodiversity and ecosystems as carbons sinks that may not be properly captured in this study, the emergence of bioenergy as a resource in the scenarios simulated (which pushes AFOLU emissions upwards) and the imputation criteria for regional emissions (production vs consumption based emissions for food products and international trade). In any case, this order for mitigation potential options (transport, housing and diets) is consistent with findings from literature on lifestyle change (see Figure 14 on this study, and Figure 7 in Ivanova et al., 2020).

Despite this study´s limitations that may underestimate mitigation potential for the different options (especially regarding diets) **results show a notable and relevant potential for mitigation of emissions** through lifestyle change on an s-frame approach with total emissions reduction **ranging, approximately, from 17-25% for the high lifestyle change scenario or 10-19% for the moderate change scenario**, showing that even under high commitment and climate action scenarios (NDC_LTT) lifestyle change may prove key to achieve the different climate goals.

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Necessary further work addressing the study´s limitations may show an even greater potential for mitigation, especially in the diet's domain, which may contradict current literature trends. A closer interdisciplinary collaboration between modellers and psychology urges in recent research applying the Motivation, Agency and Past Behaviour (MAP) framework to lifestyle change[15].

5.5 Conclusions

Lifestyle changes in the EU-27 could reduce emissions by 10–25% of total regional production-based emissions. Model comparisons show that mobility has the highest mitigation potential (25%), followed by housing (12-17%) and diets. These contributions remain significant even under ambitious policy scenarios, highlighting the importance of integrating lifestyle factors into climate strategies. Lifestyle change has a stronger effect in the NoPolicies scenario due to higher baseline emissions in comparison to the NDC-LTT pathway, yet it still adds valuable mitigation beyond the NDC-LTT pathway. Our findings suggest that while the economic impacts of lifestyle changes are difficult to quantify, household energy costs for transport and housing decline proportionally with emissions, alleviating concerns about feasibility. Although cost estimates for diets are lacking, evidence indicates similar trends as meat and processed food consumption decreases, though this study is limited by the absence of price evolution data.

The model intercomparison reveals inconsistencies in historical household expenditure data and land-use values across models, highlighting the need for harmonisation in future work. Nonetheless, results confirm the substantial decarbonisation potential of lifestyle changes, with household cost impacts generally beneficial. While policy realism remains a concern—given that measures such as smaller dwellings, reduced travel, or lower heat consumption may face resistance—these perceptions can be mitigated by emphasising cost savings. Further research is needed to address potential societal rejection and its implications for policy implementation. This work acknowledges the limitations faced in both conceptual and numeric parts. This team has imagined a future based on the existing literature we have nowadays, where we have quantified a plausible change in our societies as we know them. However, social disruptions (black swan events, etc.) could modify the behaviour of the population deeply across countries and agents, which would surely conduce to a different future. Regarding this work we emphasise the need for this change to be done conscientiously and voluntarily (what we defined as lifestyle change opposed to behavioural change), seeking to avoid greater climate damages.

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ANNEX 1 (Chapter 5 – Lifestyle change

Study glossary

Key terms used in the study are defined in the glossary below (see table 18):

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Table 18. Glossary of definitions used in study 14.

	Definition	Examples
Storyline or narrative[16]	An a priori consistent story or narrative of how the future may evolve. Storylines define the core of each scenario, describing its main characteristics, drivers and dynamics. They are qualitative descriptions of the trajectories of the economic, social, technological, environmental, and political evolution that the world may follow in the near future[17]. They also provide information on relationships and feedback loops between key drivers; hence, it implicitly includes a certain number of policy objectives and targets. The most common narratives in the general literature are the Shared Socioeconomic Pathways (SSPs). They represent a relevant set of storylines since they are standard in the climate science community (this does not mean that we cannot simulate other storylines which are not considered within the SSPs). References: O'Neill et al. (2017)[18], Shukla et al. (2022), (Ribeiro et al., 2022)[19]	Business As Usual Fossil-fuelled Development Inequality Green Growth Regional Rivalry Post Growth
Hypotheses[16]	Assumptions made in the model, subject to uncertainty, in which they work as exogenous inputs, that, generally, refer to biophysical realities that are not controllable by human societies. Hypotheses can also be defined as an uncertain assumption, represented as a quantitative parameter, that does not usually depend on political actions. However, there are thousands of parameters that do depend on political issues but are not scenario parameters because for model usability reasons they are assumed to be fixed sometimes for the sake of simplicity and modelling feasibility.	Oil reserves Mineral reserves Tipping points "How much oil is available at X extraction cost in region Z?"

[16] https://doi.org/10.5281/zenodo.13906925

[17] We consider 2050 the "near future", as it is the year in which the results of the model are reliable.

[18] Brian C. O'Neill, Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, Bas J. van Ruijven, Detlef P. van Vuuren, Joern Birkmann, Kasper Kok, Marc Levy, William Solecki,The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, Volume 42, 2017, Pages 169-180, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2015.01.004.

[19] Ribeiro, J., Bingre, P., Strubbe, D., Santana, J., Capinha, C., Araújo, M. B., & Reino, L. (2022). Exploring the Effects of Geopolitical Shifts on Global Wildlife Trade. *BioScience*, *72*(6), 560-572. https://doi.org/10.1093/biosci/biac015

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	Definition	Examples
	The key issue regarding hypotheses is that they can be changed, but this generates different baseline scenarios, not policy-action scenarios. They can also be used to explore uncertainty scenarios.	
Baseline or reference scenario[16]	A baseline scenario is an explorative scenario in which most of the exogenous model parameters are hypotheses calibrated to represent a concrete pathway, typically being current/historical trends, but it does not explicitly include policy measures. These kinds of scenarios refer to IAMs employed in their "free-running" state. Normally, the reference scenario reproduces issues (e.g., the impossibility to reach certain objectives such as staying below 1.5°C average global temperature increase) that prompt us to simulate alternative futures by introducing specific policies. Baseline scenarios are often also called Reference, No policy or Business As Usual (BAU) scenarios. They allow researchers to clearly identify -in the modelling results- the separate influence of the introduced policies by measuring changes in results from the baseline. References: (Pielke & Ritchie, 2021)[21] (Markovska et al., 2023)[20]	(European Commission. Directorate General for Energy. et al., 2021)
Policy-action scenario[16]	These scenarios are applied on top of baseline scenarios, so that every scenario starts as a baseline and gradually becomes a policy-action one. It includes a series of policy measures which are simulated to gauge their effectiveness in reaching the goals of the storylines. Policy-action scenarios are also called normative scenarios. References: https://archive.ipcc.ch/ipccreports/tar/wg2/index.php?idp=126 (Pielke & Ritchie, 2021)[21]	Same names as for storylines

[20] Markovska, N., Batas Bijelic, I., Rajakovic, N., Pfeifer, A., Puksec, T., Duic, N., Wergles, N., Capellán-Pérez, I., Álvarez-Antelo, D., Campos Rodríguez, J. M., Parrado-Hernando, G., Mediavilla Pascual, M., Lifi, M., Meyen, N., Wiese, K., Francesco Marin, D., Papagianni, S., Adam, A., Morlin, G., … Kratena, K. (2023). *D8.4: Recommendations on policy and social behaviour*.

[21] Pielke, R., & Ritchie, J. (2021). Distorting the view of our climate future: The misuse and abuse of climate pathways and scenarios. *Energy Research & Social Science*, *72*, 101890. https://doi.org/10.1016/j.erss.2020.101890

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	Definition	Examples
Policy[16]	A set of ideas or a plan of what to do in particular situations that has been agreed by a group of targeted people, business organisation, government or political party. Different types of policies can be defined depending on their scope, and they mustn't be confounded with policy measures which are more specific. References: https://dictionary.cambridge.org/es-LA/dictionary/english/policy	Energy Policy Trade Policy Labour Policy Health Policy Environmental Policy
Storyline/scenario policy goal[16]	Broad, general policy objective at societal level which are the basis for developing policy recommendations. We further distinguish between goals identified as drivers of a given storyline (storyline drivers), and those which the model users may want to check if a given storyline is able to fulfil (other goals). Considering a "Green Growth" storyline, an example of a storyline goal is "absolute decoupling of environmental pressures from economic growth". An example of other goals under a Green Growth story is "Preserving or improving life expectancy" or "Gender equality/Non-discrimination of women and girls". Both types of goals act as "benchmarks" to gauge whether a simulated scenario leads to a desirable solution to the identified problems. They are also indicators that allow us to evaluate the feasibility of the storylines. Therefore, they require measurable variables that can be used as indicators to verify the fulfilment of these goals. Indicators can be compared against a threshold or a target.	Full net decarbonisation by 2050 Achieve full employment Maintain a certain level of societal equity Transition to 100% renewables Annual GDPpc growth of 3% SDGs, etc.
Policy objective[16]	It refers to the generally formulated desired outcome of a policy. It should not be confused with policy target (see below), which refers to a specific quantified level or rate set for the chosen objective. These are tried to be achieved by means of modelling concrete policy measures, which may cater to more than one policy objective.	Decarbonisation Transition to renewables Reduce unemployment Reduce inequalities GDPpc growth Decrease energy use in buildings

	Definition	Examples
Policy target[16]	Quantifiable intended effect (or expected outcome) of a policy measure. Also defined as the operationalisation or quantification of the policy objective, although a policy target can be linked to more than one policy objective[22]. In IAMs, most policies are typically modelled as policy targets. They focus on interrelations between dimensions and does not go to the detail of each of them, which is necessary to model policy measures. IAMs research sustainability general strategies.	Increasing public transport passengers by 20% Reducing meat consumption in the diet by 10%
Policy instrument[16]	Mechanisms and tools to implement policy measures and eventually reach policy targets. It should also be considered that a same policy instrument may contribute to implement different policy measures and reach different targets. References: Böck et al., 2020	Laws Subsidies Taxes Campaigns to raise awareness
Sufficiency scenario assumption[23]	The sufficiency principle is defined by the FULFILL project as creating the social, infrastructural, and regulatory conditions for changing individual and collective lifestyles in a way that reduces energy demand and greenhouse gas emissions to an extent that they are within planetary boundaries, and simultaneously contributes to societal well-being. *"sufficiency scenario assumption"* means the projected changes for a given sufficiency lever (e.g. shared housing) on a set of sufficiency indicators (e.g., square meters per capita), from a starting point to a target year, including a characterisation of the pace of change with a defined time step, as they could result from such a construction. Source: deliverable 6.2 of the FULFILL project.	
Sufficiency lever[23]	Changes in habits, activities and services, that contribute to less energy and GHG—intensive lifestyles. Source: deliverable 5.3 of the FULFILL project.	Reducing living space sizes.
Driver[23]	Modifications brought to infrastructures and societal frameworks, such as policy measures, that support and enable the sufficiency levers. Source: deliverable 5.3 of the FULFILL project.	Development of a more compact and frugal infrastructure.

[22] It is important to highlight that there exists a hierarchical many-to-many relationship between most of the concepts. In this case, a policy objective can be linked to many policy targets. The same happens with policy goals, that can be linked to many policy objectives, and with policy targets that can be linked to many policy measures.

[23] https://fulfill-sufficiency.eu/our-research/

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	Definition	Examples
Consumption corridor[24]	A consumption range for a given indicator, "bounded by two thresholds [...] A lower threshold based on 'decent living' and an upper threshold representing a level of services compativle with a 1.5ºC global warming trajectory". Source: CLEVER scenario made by the négaWatt Association in 2023.	

[24] négaWatt Association. (2023a). *CLEVER energy scenario* -. CLEVER - Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables. https://clever-energy-scenario.eu/

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ANNEX 2 (Chapter 5 – Lifestyle change)

Causal loop diagram of food waste in households

Food waste in data

In 2022, annual household food waste in the EU was estimated to be around 72 kg of fresh mass per inhabitant, which accounts for 54% of the total food waste (Eurostat[25]). Food waste was also generated upwards in the food supply chain (primary production, processing and manufacturing, retail and other distribution of food and restaurants and food services), albeit to a lesser extent (46%) as strategies exist for reducing food waste at these steps. EU MS obligation to report annually on food waste started in 2020 (Waste Framework Directive (2008/98/EC), and the latest available data are for 2022 – the period of observation is, thus, too short to observe trends in food waste generation. Eurostat data show a wide variance between countries ranging from 30 kg/cap in Spain to 107 kg/cap in Italy for households. However, these data must be interpreted with some caution given that the quality of the estimates may vary considerably due to the different data collection/estimation methodologies that are applied.

Nevertheless, we can learn from the case of the United Kingdom and Japan where food waste has been tracked consistently for many years, that significant reductions can be achieved (United Nations Environment Programme, 2024). In the United Kingdom (76 kg/cap in 2023), per capita reductions of -18% have been achieved from 2007 to 2021 (14 years), in households, food service, retail and manufacture. In Japan (60 kg/cap in 2023), a per capita change of -31% has been achieved from 2008 to 2017 in households, food service and retail.

Food waste definition

Different definitions of food waste are in use in the EU. Eurostat defines food waste as "any food that has become waste under these conditions: it has entered the food supply chain, it has then been removed or discarded from the food supply chain or at the final consumption stage, it is finally destined to be processed as waste." Importantly, food also includes inedible parts, where those were not separated as by products[3] from the edible parts when the food was produced (including all the stages of production, processing and distribution), such as bones attached to meat destined for human consumption, orange peels, seeds, etc.

The Horizon-funded FUSIONS project defines that food waste "refers to any food and non-edible parts of food that are removed from the food chain for recovery or disposal (including composting, fallow/unharvested crops, anaerobic degradation, bioenergy production, cogeneration, incineration, discharge into the sewage system, landfills or back into the sea)" (Tostivint et al., 2016).

Regarding the global monitoring of SDGs, a distinction is made between food loss (SDG 12.), which refers to losses for key commodities in a country across the supply chain, up to and not including retail, and food waste, which refers to food and inedible parts wasted at the retail and consumer levels (SDG 12.3). The former is monitored by the FAO and the latter by the UNEP (United Nations Environment Programme, 2024).

Policy context

The fact that food waste is a significant problem has been recognised both globally and in the EU. On the global level, the Sustainable Development Goal (SDG) 12 (Target 12.3) on Responsible Production and Consumption, captures the aim to halve per capita global food waste at the retail and consumer levels and to reduce food loss across food supply chains by 2030 (United Nations Environment Programme, 2024).

On the EU level, the European Commission proposed in 2023 to set legally binding food waste reduction targets

[25] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates

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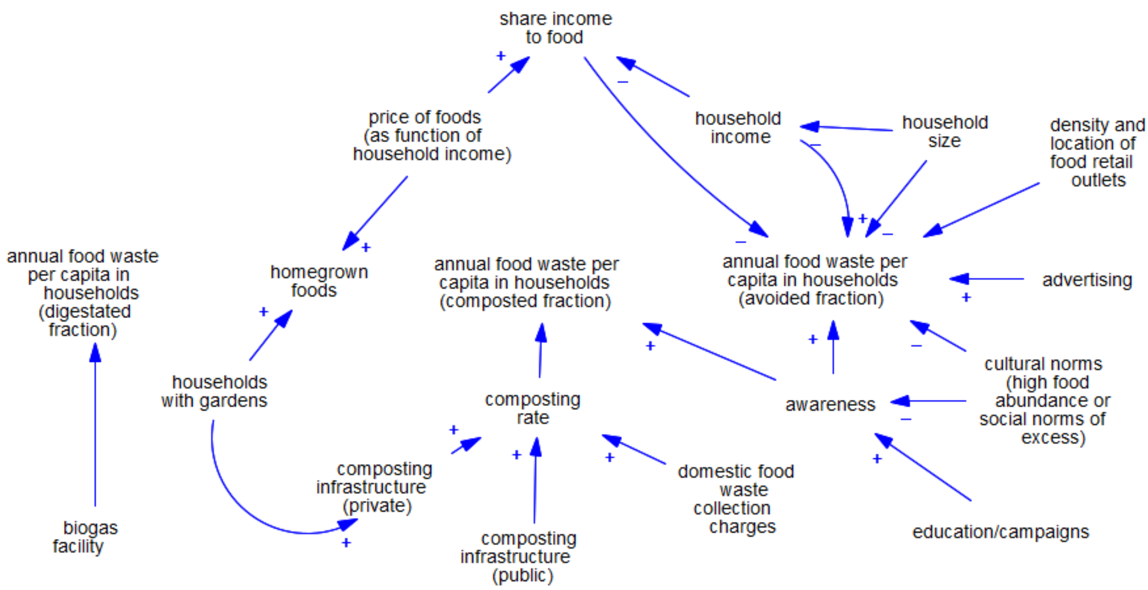
for 2030, as part of the revision of the Waste Framework Directive.[26] Proposed targets encompass a reduction of

- 10%, in processing and manufacturing
- 30% (per capita), jointly at retail and consumption (restaurants, food services and households)

by 2030 taking as a baseline the first EU-wide monitoring of food waste levels carried out in 2020. The Commission's legislative proposal is subject to negotiation with the European Parliament and the Council of the European Union. A preliminary political agreement has been reached on 18 February 2025, which maintains the levels of the targets proposed by the Commission and calls for an extensive review of the targets by 2027. Besides, the EU has taken a number of actions to support member states in their endeavour to reduce food waste such as the EU food Loss and Waste Prevention Hub, the European Consumer Food Waste Forum, European citizens' panel on food waste, etc.[27]

Determinants of food waste

The loop diagramme presented in 2.1 explores which causal factors affect the amount of household food waste generated by households. Household food waste is a complex and multi-faceted issue that cannot be attributed to single variables (Schanes et al). There are relevant factors on the micro (individual), meso (household) and macro (external to household) level (Boulet et al., 2021). The macro level can be further divided into "socio-technical conditions", which can be influenced by policies, and physical and natural boundaries, which are a given (United Nations Environment Programme, 2016). In this multi-level system, individual factors interact with each other within and across levels, and may reinforce or attenuate each other. For example, greater awareness of food waste is linked to younger population, who also predominantly adopt a lifestyle that is liked to increased food waste (e.g. eating out, lack of meal planning, etc.). The causal loop diagramme focuses only on macro-level factors (socio-technical conditions -culture, media, policy, infrastructure, economy- and physical and natural boundaries such as geography or climate) and excludes individual or household-related factors (e.g. household composition in terms of age, gender, income, educational level, etc.), and shows only what are deemed to be the most important factors.



26 https://food.ec.europa.eu/food-safety/food-waste/eu-actions-against-food-waste/food-waste-reduction-targets_en

27 https://food.ec.europa.eu/food-safety/food-waste/eu-actions-against-food-waste_en

Figure 23. Causal loop diagramme "Food waste reduction"

The diagram distinguishes between the **composted/digested and the avoided fraction of food waste** of households. **Preventing food waste ("avoid action")** has the least environmental footprint and is, hence, preferrable over **composting or digesting food that is not consumed ("shift action")**. Even though composting means that organic waste is turned into fertile soil, closing the organic materials cycle, the composted food has undergone several steps of production, processing and distribution which involves the input of energy and water, and which is wasted if the food is not consumed.

Annual per capita household food waste (composted or digestated fraction) depends primarily on the **availability of composting infrastructure** and on the **awareness of the importance of composting** the organic fraction of the household waste. The availability of private (or communal) composts ("home composting") depends on the share of households disposing of a garden (private or communal). Research shows that composting rates are higher in **rural areas** for that reason, and that the utilisation of food is generally less wasteful in rural areas (Chereji et al., 2023). Reasons are attributable to differences in lifestyles: rural population tends to grow own food, eat out less, consume less convenience food, use traditional methods of recycling household food waste, and have a lower income (see "share of income to food"), which is associated with a lower generation of waste etc. In the EU the **availability of containers for and domestic collection of organic waste** is widespread, also because the Waste Framework Directive makes the implementation of separate collection of bio-waste is mandatory in all EU member states. Nevertheless, collection rates of organic waste are lower than for other types of waste[28] for various reasons: organic waste is smellier, and has to be disposed more often, collection infrastructure is often less well developed than other for other types of waste, etc. Unlike other types of recyclable waste (glass, paper and cardboard, metals and plastics), which have seen increasing recycling rates in the past, the recycling of biowaste has not seen a similar increase. In sum, the **burden and effort involved in collecting organic waste** may be a serious reason for low use of existing collecting infrastructure. This is a serious problem as organic waste that decays in landfills produces methane, which is a highly reactive greenhouse gas.
Regarding domestic food waste collection charges are negatively associated with food waste (Boulet et al., 2021).

The second important factor is **awareness of the problem of food waste**. Some studies show that awareness is higher in young population, who predominantly live in urban areas. This may seem contradictory to the often-confirmed finding that rural areas, dominated by the elderly demographics, generate less food waste. Reasons are that the elderly population tends to adhere to a less wasteful lifestyle, and also because the awareness and intention alone do not necessarily lead to a significant change in behaviour, also called attitude-behaviour gap (as shown in (Schanes et al., 2018)).
Stefan et al. (2013) argue that food waste is not so much driven by conscious intentions (as the determinant of individual behaviour), but that food-related household practices are a better indicator for the amount of food wasted. Relevant household practices and routines are the careful planning of grocery shopping, shopping routines that lead to overprovisioning of food (e.g. buying "treats" for different family members, bulk purchases, oversised packaging, trying to compensate for bad eating habits by buying healthy and perishable food, shopping frequency, the size of the supermarket, etc.), storing (e.g. the systematic storing and categorising of food to avoid overlooking expiry dates, but also stockpiling of large amounts of food in the home or the habit of freezing food to extent shelf-life), cooking (own cooking versus convenience food, etc.), eating (eating habits and diets, frequent eating out), and managing leftovers (ability to cook with leftovers, etc.).
There is also a **cultural element in routinised household practices**: for example, the overabundance of food available in the home at any time may be culturally considered a sign of hospitality and wealth (e.g. the case of

[28] https://www.compostnetwork.info/policy/biowaste-in-europe/

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Brasil quoted in Schanes et a. 2018).

Nevertheless, studies generally find a positive correlation between attitudes and awareness and food waste (Boulet et al., 2021), which affects both, the avoidance of waste and the proper disposal of food waste so that it can be recycled. Information and education campaigns present one of the most widespread tools used for food waste prevention and reductions and have been implemented all over Europe. Campaigns may either target awareness of the problem of food waste and/or provide information on measures that can be taken to avoid waste (e.g. on waste cooking, on the meaning of date labelling). The **effectiveness of campaigns** to correct information deficiencies and modify attitudes depends very much on their **design** – i.e. how target-group specific and targeted in addressing specific knowledge gaps they are (Schanes et al., 2018).

As mentioned previously, **cultural-historical factors** also play a role in how people deal with food and food waste. According to Boulet (2021), cultural and place-based factors include culturally and geographically defined notions of edibility (e.g. chicken feet and crests are considered delicacies in some countries and waste in others), norms about food sharing, and ideals of abundance. Societies which have in the recent past experienced food scarcity, and which remained in the collective memory, also tend to be less wasteful. **Advertisement and marketing** are known to have had an important role in shaping our Western consumer society, in creating a culture of overconsumption and excess, and in triggering unhealthy desires and cravings.

UNEP data show that **economic wealth (typically measured in GDP/capita)** is a weak determinant of food waste in households, at least between high income, upper-middle income and lower-middle income countries (for lower income countries there is insufficient data). Data suggest that the average observed household food waste in high income, upper-middle income and lower-middle income countries varies by just 7 kilograms per capita per year (United Nations Environment Programme, 2024). However, a difference is that, while in high income countries loss usually occurs at the final consumers (54% in the EU), in lower-income countries food loss occurs mainly during the earlier stages of the food supply chain, i.e. production and industrial transformation, mainly due to a lack of financial, technical and managerial resources (Dorward, 2012).

On the **level of disposable household income**, the correlation is also not clear-cut. While many authors find that higher disposable income families waste more than poorer households, other researchers find little or no correlation between income and food waste (Secondi et al., 2015). Other household-level characteristics that have been found to correlate with food waste generation, but remain outside the scope of study 14 (as they would require modelling food waste bottom-up) such as age, educational level, etc.

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6 Decarbonisation in the built environment

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6.1 Summary

Decarbonisation of end-use sectors is of immense importance towards the battle against the climate crisis, with the buildings sector, globally, having a large mitigation potential. Considering the significant prospect of renewable-based electrification for reducing CO_2 emissions in the buildings sector, in this work, we evaluate decarbonisation trends in both the residential and the commercial sectors by 2050, with a focus on electrification, across different scales and contexts.

Our work differentiates from existing studies by coupling top-down with bottom-up perspectives, not only capturing the macroeconomic implications and systemic constraints of electrification but also incorporating the technological detail and sector-specific dynamics necessary to assess realistic transition pathways. We draw on stakeholder knowledge and integrate it into a hybrid modelling ensemble, comprising an integrated assessment model, three energy system models, and a sectoral model focusing on the buildings sector, to simulate current policy and high-ambition scenarios from the global to the continental (European Union) scale, and from the continental to the national scale. This enables a more granular assessment of sectoral dynamics and context-specific challenges, illustrated by a country-by-country analysis for the European Union member states, as well as dedicated case studies for a Global South country (India) and a European Union member state (Greece).

Our results show that in most regions worldwide electrification increases in 2050 compared to 2030; however, there are significant differences in the electrification pace between 2030 and 2050 among regions, highlighting their different policy ambition levels and structural and contextual characteristics. Furthermore, we find variations between regions in achieving their long-term electrification potential. Developing regions not capable of increasing the share of electricity in their final consumption mix, fail to decarbonise their residential and commercial sectors, while regions falling far behind their electrification potential, fail to deeply decarbonise them. Overall, our work shows that expected electrification levels differ between scales and depend mainly on national contexts as well as climate and socioeconomic conditions.

6.2 Introduction

The buildings and construction sectors are key players in the fight against climate change as they influence global energy systems; combined, they are responsible for 30% of the global final energy consumption and 27% of the total energy sector CO_2 emissions (IEA, 2023h). Considering the substantial increase in energy demand by mid-century, total direct emissions from the buildings sector need to contract sharply, while indirect emissions also need to go to zero by decarbonising power generation and district heating (IEA, 2022g).

In the IPCC's Sixth Assessment Report (AR6), future emissions in the buildings sector were evaluated using four global scenarios: three based on top-down modelling from the AR6 scenario database and one bottom-up model (Cabeza et al., 2022). The scenarios include: IEA's Net Zero Emissions by 2050 (NZE), a normative scenario that outlines a narrow but achievable pathway for the global energy sector to reach net zero CO_2 emissions by 2050 (Bouckaert et al., 2021); the Sustainable Development Scenario (SDS), another normative scenario that integrates the impacts of COVID-19 on health and economies, and works backwards from climate, clean air, and energy access goals to determine necessary actions (IEA, 2020); IMAGE-Lifestyle-Renewable (LiRE), which builds on the Shared Socioeconomic Pathway #2 (SSP2) baseline and meets the Representative Concentration Pathway 2.6 (RCP2.6) radiative forcing target through carbon pricing and increased adoption of lifestyle changes, such as limiting per capita floor area and appliance use in developed countries (van Vuuren & et al, 2021); and Resource Efficiency and Climate Change-Low Energy Demand (RECC-LED), a global bottom-up model assessing the role of resource efficiency in climate mitigation. RECC-LED estimates energy and material flows based on housing stock growth, population, and per capita floor area (Pauliuk, 2021), and was informed by the Low Energy Demand

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(LED) scenario, which sought to equalise access to a decent standard of living between developed and developing countries (Grubler, 2018). These scenarios were assessed against corresponding baselines, such as the IEA Current Policies Scenario (CPS) (IEA, 2020) and SSP2.

Results revealed stark differences in projected outcomes: under IEA-NZE, global buildings emissions are projected to fall to 29 MtCO_2 by 2050, compared to 1.7 GtCO_2 in IEA-SDS and 3.7 GtCO_2 in IMAGE-LiRE, while IEA-CPS projects 13.5 GtCO_2, equal to the 2018 levels. Residential direct emissions under IEA-NZE drop to 108 MtCO_2, four times lower than in RECC-LED, six times lower than in IEA-SDS, and eleven times lower than in IMAGE-LiRE. In terms of per capita emissions from residential buildings, the global average of 0.85 tCO_2 in 2019 is projected to decline across all scenarios by 2050, ranging from 0 tCO_2 in IEA-NZE to 0.21 tCO_2 per person in IMAGE-LiRE, a 75% reduction compared to 2019.

Towards mid-century, energy demand from buildings and construction will continue to rise without demand-side mitigation strategies, driven by rising incomes, shifts in income distribution, improved access to energy in developing countries, greater ownership and use of energy-consuming appliances, and a rapid growth in global floor area (Gertler et al., 2016). The IEA projects the global building floor area to grow by 75% in the next 30 years, with around 80% of the increase in emerging markets and developing economies (IEA, 2022g). Without targeted policy actions, the energy used in buildings could increase up to around 70% in 2050 (IEA, 2023h).

The literature highlights two major emerging trends in residential buildings' energy demand: cooling and electricity demand. In a warming world with growing populations and expanding middle classes, demand for cooling is expected to rise significantly (Masson-Delmotte et al., 2021). Air conditioners using halocarbons are the dominant cooling technology, with over 4 billion units in operation, a number that could grow to 14 billion by 2050 (Peters, 2018). In this regard, the Kigali Amendment to the Montreal Protocol promotes a transition to low global warming potential (GWP) refrigerants, which, alongside renewable energy integration in buildings, offers a pathway to reduce cooling-related emissions (UNEP and IEA, 2020).

As regards demand for electricity, its use in buildings reached over 43 exajoules (EJ) in 2019, accounting for more than 18% of global electricity demand, representing a 161% increase since 1990 (Cabeza et al., 2022). Electricity is used for a wide range of plug-in devices, refrigerators, lighting, cleaning appliances, and increasingly, for thermal energy services such as cooking, water heating, and space heating. The growing adoption of heat pumps is a major factor in this shift. Heat pumps, whether standalone or connected to district systems, can efficiently provide both heating and cooling (Lowes et al., 2020). When powered by low-carbon electricity, they are considered as a key technology in the global transition towards secure, cost-effective, and sustainable heating (Ruhnau et al., 2020). Installing heat pumps instead of fossil-fuel-based boilers significantly reduces CO_2 emissions in all major heating markets, even with the current electricity generation mix, an advantage that will increase further as electricity systems decarbonise (IEA, 2022d).

According to the IEA-NZE scenario, heat pumps installed will increase from 180 million units in 2020, to 600 million units in 2030, and 1,800 million units in 2050, covering 7%, 20%, and 55% of the total energy demand for heating, respectively, with significant uptake in countries belonging to the Organisation for Economic Co-operation and Development (OECD) and emerging economies (IEA, 2021b). In the EU, the "REPowerEU" plan presented by the European Commission (EC) back in 2022, suggests doubling of the deployment rate of heat pumps within the coming years in order to reduce the dependence on Russian natural gas (European Commission, 2022). However, the wider deployment of heat pumps will increase both electricity demand and halocarbon emissions (UNEP and IEA, 2020), and will also require increased electricity generation from variable renewables, as well as adjustments to the design of energy systems at both the building and district levels (IEA, 2022f). From a supply side perspective, this will necessitate new power generation capacity, while flexibility in energy systems will be essential to accommodate high shares of electrified heating (Thomaßen et al., 2021). As electricity generation becomes progressively cleaner, electrification of areas previously dominated by fossil fuels emerges as a crucial economy-wide tool for reducing emissions (IEA, 2021b).

From a demand-side perspective, this transformation will require flexible operation enabled by smart system integration, including renewable energy and energy storage solutions within buildings, integrated with automated controls, energy management systems, and e-mobility (Wemhoener, 2020). By 2030, heat pumps will increasingly

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become a source of flexibility for the energy system, enabling efficient coupling of variable PV and wind with the use of electricity for heating/ cooling purposes (Botzov et al., 2023). Flexibility mechanisms like dynamic pricing and smart thermostats and active controls can unleash heat pumps' demand-side response potential and help achieve higher shares of variable renewables in the grid (IEA, 2022d). In combination with economic drivers, flexibility and electrical and thermal (power-to-heat by electrically-driven heat pumps) energy storage deployed in smart buildings are expected to further advance energy-conscious behaviours and uptake at the consumer and the commercial levels (Ooka et al., 2025).

In this regard, behavioural changes, i.e., low-carbon choices when purchasing products, or in everyday activities that reduce carbon emissions, and citizen participation can also form part of a cost-effective practices to support the wholesale transformation of energy systems, especially in the buildings sector, and support the vision of a zero-carbon buildings stock by 2050 (IEA, 2021a). In the residential sector, a roughly 10% reduction in the cooling and heating of homes could potentially be achieved by 2030 through behavioural changes (IEA, 2022g).

In particular, one of the most significant behaviour changes relates to adjusting space heating and cooling temperatures. IEA modelling suggests that lowering heating and raising cooling set points can save significant energy and carbon emissions from buildings, allowing the time needed for clean and efficient measures to take place (IEA, 2021c). Studies in occupied buildings show that such changes are always context-specific and must take into account technical, economic, social and physiological factors in people's situations and environments (IEA, 2022e).

Integrated assessment models (IAMs) and energy system models (ESMs) often fall short in capturing the broader societal and policy-relevant dimensions associated with the transition to electrified buildings, such as widespread adoption of heat pumps and electric vehicle (EV) charging, limiting their utility for designing equitable and targeted electrification policies. In particular, they rarely assess the emissions, cost savings, and resilience benefits of demand-side flexibility, the effectiveness of policies aimed at encouraging behavioural change in households, or the differing affordability and accessibility of such changes across different socioeconomic groups. Furthermore, these models tend to overlook the comparative emissions and cost-savings of building fabric improvements versus technology replacements (e.g., heat pump installations), especially when behavioural factors are critical to realising these benefits.

While coupling IAMs and ESMs with short-term dispatch models has improved representations of system dispatching and operational flexibility (Kleanthis et al., 2025), these approaches still fall short in capturing the full potential, real-world feasibility, and social equity implications of demand-side flexibility at the household level, particularly regarding how different forms of demand response can contribute to system resilience, cost-savings, and emissions reduction. Addressing these gaps is essential to inform the development of policies that are not only effective in driving decarbonisation but are also inclusive, socially equitable, and resilient.

Building on previous IAM COMPACT studies; see, for example, (Trutnevyte et al., 2024), as well as the recent work of (van Heerden et al., 2025b), which demonstrates the substantial decarbonisation potential of renewable-based electrification in the buildings sector, this study extends the analysis by explicitly examining how top-down and bottom-up modelling approaches yield differing insights into the decarbonisation potential in the residential and the commercial sectors. We focus on electrification trends by 2050 across different scales and contexts; from the global to the continental (EU) scale, and from the continental scale to the national level, with case studies in a Global South country (India) and an EU member state (Greece), highlighting context-specific challenges and opportunities.

While previous research has highlighted the challenges of downscaling global modelling results to regional and national levels, our study contributes to this debate by systematically comparing electrification trends and decarbonisation potentials across these scales, thereby highlighting potential misalignments that could undermine effective policy design and improving the consistency and policy relevance of scenario insights for both supranational and national decision-making. The national specific contexts were selected for their contrasting socioeconomic, climatic, and energy system characteristics: India represents an emerging Global South economy with rising energy demand, while Greece typifies an EU member state grappling with its own energy transition challenges. This contrast allows us to explore how context influences feasibility, costs, and emissions.

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Beyond the scope of (van Heerden et al., 2025b), our work bridges top-down and bottom-up perspectives by linking top-down IAMs with detailed bottom-up ESMs and sectoral models. This integrated approach captures both the macroeconomic implications and systemic constraints of electrification, while also incorporating the technological detail and sector-specific dynamics necessary to assess realistic transition pathways. This enables us to incorporate critical factors such as demand-side flexibility, behavioural change, and justice dimensions, aspects that are often overlooked in macro-scale modelling.

The overarching research question we address is: *'How do top-down and bottom-up modelling frameworks compare in assessing the buildings sector's decarbonisation potential by 2050 across multiple scales and contexts, with a particular focus on electrification trends, demand-side flexibility, and equity considerations, also accounting for emissions and costs?'* By answering this question, our study provides novel insights into the consistency, divergence, and policy relevance of model-based assessments, supporting the design of robust, context-sensitive, and socially equitable decarbonisation strategies.

The work outlined in this chapter has been carried out as a component of the IAM COMPACT's "2nd Policy Response Mechanism (PRM-2)" cycle (Heussaff & Zachmann, 2022), under the Theme: "Citizens in the Transition[29]" (see Deliverable 2.2 "Scoping Relevant Research Questions"[30]). The "Citizens in the Transition" theme focuses on lifestyle changes in mobility, diets, and housing, household decarbonisation, and distributional impacts of climate policies, and produced three modelling studies.

This study focuses on the topic of buildings decarbonisation and its subsequent aspects were recognised as an issue of high concern for high-level policymakers, from national governments to the EC. More details about the identified stakeholder needs in relation to this topic are provided in the next section. To sufficiently address this topic, a working approach involving a hybrid modelling ensemble, combining both top-down and bottom-up models, has been developed. Here, we present the soft-linking process between the models and the results from their combined application. Furthermore, a short discussion and an outlook on further research is provided.

6.3 Methods and tools

We follow a multi-method, stakeholder-driven modelling approach that combines the expertise and perspectives of stakeholders with multi-scale modelling leveraging a hybrid modelling ensemble comprising an IAM, three ESMs, and a detailed sectoral model for the buildings sector. We select a stakeholder-driven approach, as it can bring a more diverse range of views into the integrated assessment and the energy system modelling process, by building a better understanding of the social context and supporting more inclusive decision-making. **Figure 24** illustrates the structured process through which stakeholder input is systematically integrated into the modelling framework to ensure that decarbonisation pathways for the buildings sector are both analytically robust and directly relevant for policy development.

[29] https://iam-compact.eu/news-events/core-working-group-workshop-citizens-transition

[30] DOI 10.5281/zenodo.10464771

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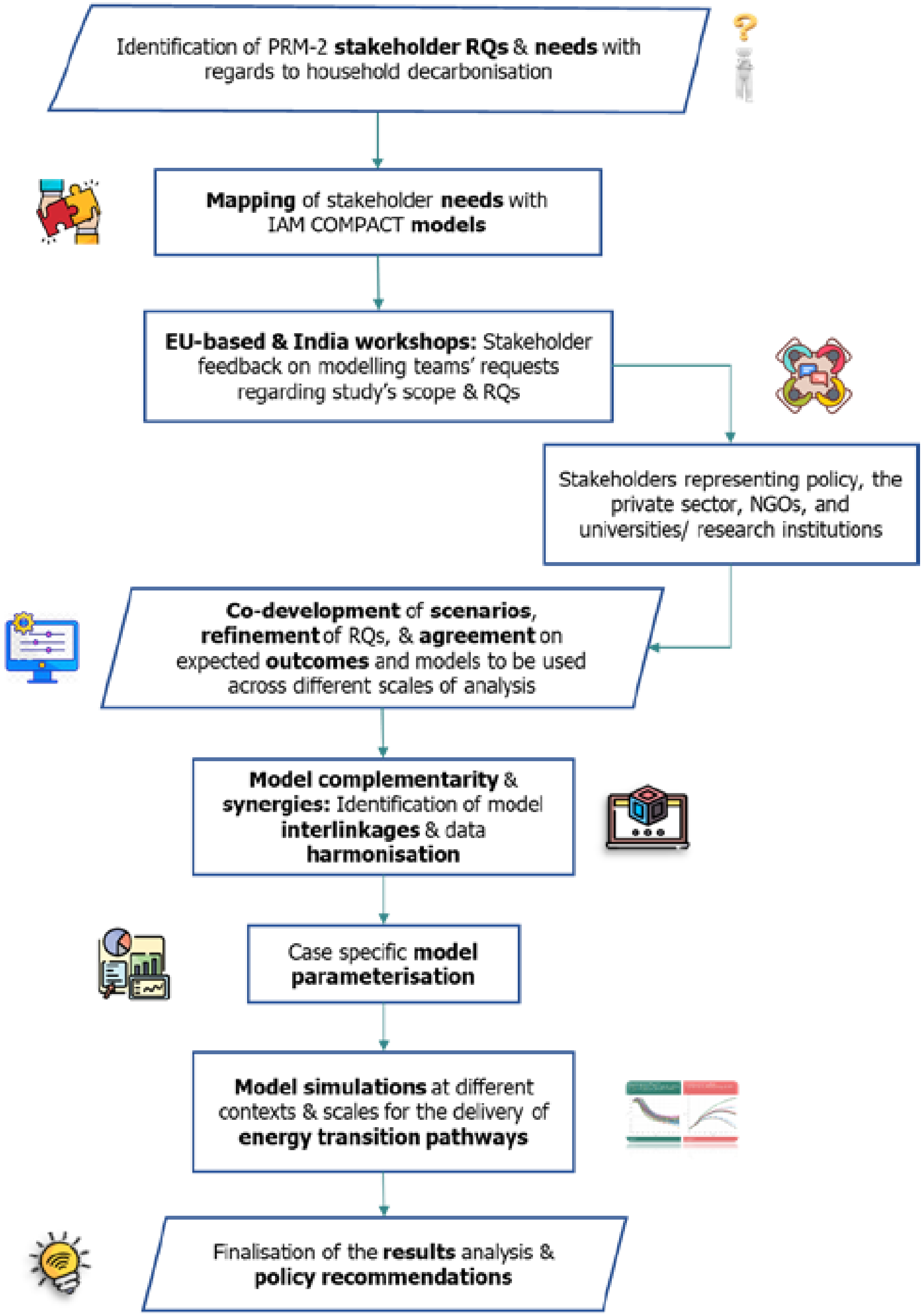

Figure 24: Methodological flowchart of the multi-method approach.

The first part of our working approach begins with the collection and refinement of stakeholder RQs and needs during the PRM-2, explicitly addressing key policy concerns such as household electrification, heat pump deployment, energy efficiency measures, and demand-side flexibility. Stakeholders were interested inter alia in analysing the environmental and economic effects of flexible household consumption on the broader energy system and comparing the emission and cost savings of energy-efficiency measures versus technology replacements. These stakeholder needs are systematically mapped onto the full IAM COMPACT modelling ensemble[31], ensuring that the appropriate models are selected to address the identified stakeholder RQs and needs (**Table 19**).

[31] https://iamparis.eu/detailed_model_doc

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Table 19. Mapping between stakeholder needs and the IAM COMPACT models that can address them.

Stakeholder Needs (SNs)	IAM COMPACT model that can (in some cases even partly) address the need
SN1. Analyse the effects of new energy consumption patterns (e.g., flexible household energy consumption) on the broader energy system. Examine the environmental and economic effects of new energy usage profiles by households.	PROMETHEUS; EnergyPLAN; Aalto-EU-TIMES; AIM-Enduse India; DREEM
SN2. Identify the impact of energy consumption patterns associated with energy communities at scale on the energy system, in terms of emissions and cost.	DREEM
SN3. Model flexible vs. inelastic consumption in households. Identify the impact of two-part tariffs as a measure to incentivise flexible consumption while protecting consumers.	DREEM
SN4. Improve energy demand modelling from a demographic (different ages and income group) and regional perspective. Different energy profiles of households, considering demographic, and regional factors.	DREEM
SN5. State the realism of the derived results, as well as whether it is incumbent upon the individual (i-frame), or on society (s-frame) to drive the changes.	Depends on each model's perspective
SN6. Compare the emission and cost savings, as well as resilience benefits of implicit vs. explicit demand-side response.	DREEM
SN7. Identify the costs of supporting behavioural change in buildings, such as through providing grants, and how this (i). changes the affordability of behavioural change for citizens, and (ii). differs by socioeconomic group.	DREEM
SN8. Compare the emission and cost savings of building fabric improvements vs. technology replacement (e.g., heat pumps).	PROMETHEUS; Aalto-EU-TIMES; AIM-Enduse India; DREEM
SN9. Analyse side events in other regions than Europe.	PROMETHEUS

The type, methodology, and spatial and temporal resolution of the selected models for the model applications in the context of this study are detailed in **Table 20**. After internal discussion among modelling teams, the selected models with their indicative applications and an initial scenario design for each study was agreed and then presented to our Core Working Groups (CWGs) -a wider policy audience selected on geographical and sectoral criteria- for discussion and co-design in a workshop setting. To implement these activities, an online stakeholder engagement workshop titled "Citizens in the Transition" was organised as part of the PRM-2 cycle and was held in December 2024. Following an in-depth co-creation process with building sector experts, direct stakeholder feedback was incorporated to shape the scope of the analysis and the refinement of RQs, guaranteeing that model outputs respond to practical policy concerns, including affordability, social equity, and system resilience.

A set of guiding questions that differed based on the particularities of each context and scale analysed within this study was used in order to retrieve the required stakeholder feedback (**Table 3**). Stakeholders represented all parts of the quadruple helix model of innovation, which acknowledges four principal actors in the innovation ecosystem: research, policy, industry, and society (Kleanthis et al., 2022), representing inter alia government representatives, the private sector, NGOs, and universities/research institutions. We also co-developed a set of input assumptions to design scenarios, co-defined desired outputs, and concluded on the models to be used across different scales of analysis, as well as on the soft-linking approach to be followed (**Table 20**).

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Table 20. Type, methodology, and spatial and temporal resolution of the participating models for the application at hand. The parentheses indicate interlinkages between the models (the models in the parentheses provided data).

Model	Type	Methodology	Geographical granularity	Temporal granularity
PROMETHEUS (Fragkos et al., 2015b)	IAM; Top-down	Simulation	Global (10 regions)	Yearly
EnergyPLAN (Lund et al., 2021) (+PROMETHEUS, Aalto-EU-TIMES, DREEM)	ESM; Bottom-up	Simulation	EU (or National)	Hourly
Aalto-EU-TIMES (+PROMETHEUS)	ESM; Bottom-up	Optimisation	EU (country-by-country)	Intra-annual time slices
AIM-Enduse India (Vishwanathan et al., 2019) (+PROMETHEUS)	ESM; Bottom-up	Optimisation	National	Intra-annual time slices
DREEM (Stavrakas & Flamos, 2020) (+PROMETHEUS)	Sectoral; Bottom-up	Simulation	National (up to household)	Hourly

As part of the India case study, a stakeholder workshop on "Building Sector and India Net Zero 2070" was held at Indian Institute of Management Ahmedabad (IIMA) in August 2024. The workshop served as a platform to exchange knowledge, share best practices, and gather insights to inform future policy and research directions in support of India's net-zero ambitions. It focused on India's commitment to achieving net-zero emissions by 2070, with a specific emphasis on the decarbonisation of the building sector. The event was designed to facilitate an in-depth dialogue among key stakeholders, including building sector experts, real estate financial managers, and academics (professors, researchers, postgraduate, and PhD students). A total of 65 stakeholders participated in the workshop, comprising approximately 8 building sector experts, 5 financial managers from the real estate sector, and 52 academic participants whose combined expertise provided a multi-disciplinary perspective on decarbonisation pathways for the building sector of India). Discussions centred on the opportunities and challenges of decarbonising the building sector in India. Key themes included addressing rising energy demand, identifying policy priorities, and bridging implementation gaps.

Table 21. Questions posed to the stakeholders during the "Citizens in the Transition" workshop with regards to assessing the decarbonisation potential of the buildings sector across multiple scales and contexts.

Context & Scale	Questions posed to stakeholders
Global level (World)	· What are the most important options to transform the global residential sector in the context of climate neutrality? · How effective are the global policy instruments to reduce emissions from households? · Which contextual factors at the global level are most relevant for household decarbonisation?
Regional level (EU)	· What are the most important options to transform the EU's residential sector in the context of the vision of climate neutrality? · What is the role and impacts of specific "Fit for 55" measures and transition options? · How effective are the EU policy instruments to reduce emissions from households? · Which contextual factors at the EU level are most relevant for household decarbonisation?
National level (Greece)	· What are the key parameters to consider for the effective implementation of each level of ambition pathway? · What barriers might hinder the adoption of medium and high-level measures, and how can these barriers be addressed? · How effective are current policies and incentives in promoting high-level interventions?

	· How well do the proposed intervention pathways align with household preferences and financial capabilities? · What role do socioeconomic factors play in the feasibility and adoption of high-level interventions?
National level (India)	· What are the net zero pathways for residential buildings towards India's net zero 2070? · What are the high impact opportunities (policy priorities) for residential buildings towards India's net zero 2070?

The second part of our working approach starts with the identification of model complementarities (such as differences in temporal granularity, sectoral resolution, and policy representation) and synergies, enabling cross-scale (global, EU, national) integration and data harmonisation (**Figure 25**). This ensures that insights from global models remain relevant and actionable at national and regional levels, a frequent gap in traditional modelling approaches that this framework explicitly addresses (**Table 22**). Scenario development and model simulations are conducted across multiple contexts to capture the diversity of policy environments, infrastructure readiness, and socio-economic conditions. Embedded feedback loops allow for continuous refinement, enhancing the policy relevance of results and ensuring that emerging insights can inform real-time policy adjustments.

The initial model application involves the global-scale application of **PROMETHEUS** to simulate scenarios incorporating projections based on the updated SSPs (K.C. et al., 2024) and different levels of climate policy ambition, including current policies (CPs) –"CP-EI" scenario- and Nationally Determined Contributions (NDCs) with Long-Term Targets (LTTs) –"NDC-LTT" scenario- to provide results to the other models. As a next step, simulation results on primary energy consumption and CO_2 emissions for the EU-27+UK are fed from PROMETHEUS into the **Aalto-EU-TIMES** model to provide boundary conditions and harmonise energy demand and emission targets. This adds another layer of granularity in the EU modelling, both in terms of technology and subsector specific outcomes and national-scale results. Regional-scale results from PROMETHEUS, in terms of primary energy consumption and energy price trends, are also fed into two national-scale models, namely **AIM-Enduse** (India) and **DREEM** (Greece), considering the global scenarios' levels of climate ambition. All three models utilise specific results from PROMETHEUS either as direct inputs, or to harmonise their own scenario assumptions.

Scenarios in Aalto-EU-TIMES align with the boundary conditions stemming from the global results of "CP-EI" and "NDC-LTT", and integrate various EU policies, namely national energy-efficiency targets, shares of renewable energy sources in gross final energy consumption, etc., as well as implementation of NDCs and LTTs, or National Energy and Climate Plans (NECPs) for EU member states. Furthermore, the AIM-Enduse India application include both business-as-usual and net-zero scenarios, which also align with the boundary conditions of the "CP-EI" and the "NDC-LTT" results for India and follow the specifications of the 2018 India's "*Cooling Action Plan*". On the other hand, scenarios in the DREEM model are aligned with the targets set by the revised Greek NECP-2024, as well as the boundary conditions stemming from the downscaled EU-level "CP-EI" scenario of Aalto-EU-TIMES for Greece. Lastly, results in terms of primary energy consumption for the EU-27 plus the UK from Aalto-EU-TIMES and household flexibility demands from DREEM are fed into **EnergyPLAN**, facilitating both top-down and bottom-up interlinkages, to provide a deep dive in the EU's aggregated household electricity flexibility by 2050. The models provided outputs in terms of residential and commercial sectors' emissions, final energy consumption, share of renewable energy sources (RES) in the energy mix, and total costs of energy transition pathways. Apart from the harmonisation based on the modelling results, the models were harmonised with regards to technological cost and efficiency data.

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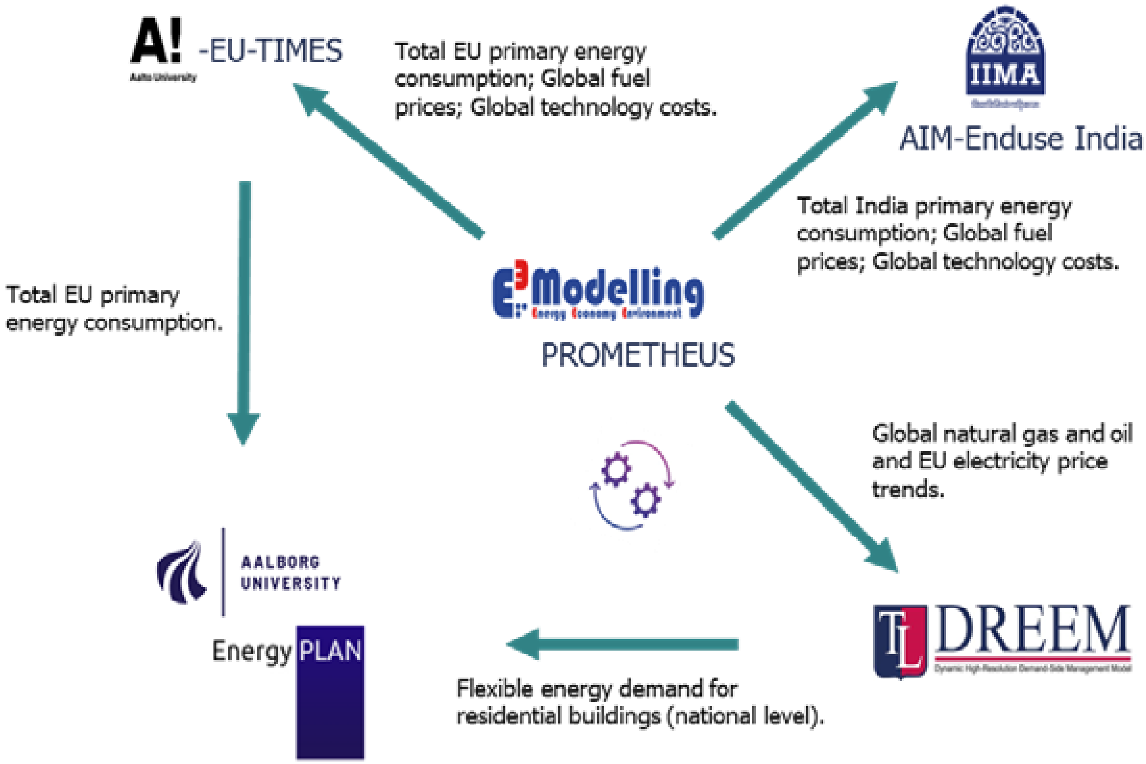

Figure 25. Implemented interlinkages and data flows between the models participating in this study.

Table 22. Added value derived from the potential interlinkages between the models participating in this study.

Output model à Input model	**Description**
PROMETHEUS à Aalto-EU-TIMES	PROMETHEUS's technology costs from learning enhance Aalto-EU-TIMES's ability to optimise energy supply at the EU/national level by giving an estimate about how fast the technology costs will be reduced during the coming years (as opposed to this being an exogenous assumption).
PROMETHEUS à AIM-Enduse India	PROMETHEUS's projections enhance the ability of AIM-Enduse India to estimate the energy demand and emissions from the buildings sector in India by providing estimates of how key factors (e.g., primary energy consumption) will evolve over time, rather than relying on exogenous assumptions.
PROMETHEUS à DREEM	Linking PROMETHEUS to DREEM enables the use of consistent energy price trends as inputs, enhancing the accuracy of cost assessments for renovation and technology options in the Greek residential sector, ensuring realistic market conditions and supporting robust economic evaluations.
Aalto-EU-TIMES à EnergyPLAN	Aalto-EU-TIMES optimises energy technologies, and EnergyPLAN tests these optimised strategies under real-world, hourly operational conditions, providing insights into operational costs, flexibility, and renewable energy integration.
DREEM à EnergyPLAN	DREEM can inform EnergyPLAN about the flexibility potential in the residential sector, helping simulate how demand-side management impacts system costs and emissions.

Our working approach concludes with a comparative analysis of national, regional, and global model results, providing insights into the consistency and differences between the various modelling approaches. This comparison highlights the trade-offs of various decarbonisation strategies, offering actionable guidance for designing socially equitable and economically feasible buildings decarbonisation policies. Details about the models participating in this study are provided below.

6.3.1 PROMETHEUS

PROMETHEUS (Fragkos et al., 2015b) is used to provide the global-level information needed for the analysis, capturing the detailed interplay between energy demand, supply, and pricing across the different world regions. The model is designed to explore medium- and long-term energy transition pathways by examining how various low-emission strategies and climate policies affect energy markets, emissions, and economic outcomes. By simulating both sides of the energy equation- how energy is produced and consumed- the model finds market equilibrium at regional levels, then aggregates these to reflect global fuel markets. Regional systems are linked through international trade, technological progress, and diffusion effects, so changes in one area, such as wider uptake of renewables, or shifts in consumption patterns, spill over elsewhere. PROMETHEUS calculates future energy demand and fuel mix by sector, supply mixes (including power generation technologies), carbon emissions, energy prices, and investment needs up to 2050. It provides detailed energy balances and quantitative indicators (e.g., emissions, fuel prices, technology shares, and energy demand) to assess how specific policies reshape both demand and supply structures over time.

6.3.2 EnergyPLAN

EnergyPLAN is a tool for simulation of the entire energy system including all sectors, i.e., heating, cooling, industry, transportation, as well as electricity and gas grids (Lund et al., 2021). Hourly temporal resolution allows for detailed modelling of variable renewable energy generation in addition to weekly and seasonal differences in electricity and heat demands. EnergyPLAN is a deterministic model based on analytical programming, making calculations very fast even for complex energy systems. EnergyPLAN optimises the operation of the energy system rather than the investments, which is instead done exogenously by the user. In **Figure 26** an overview of technologies, energy demands, and flows as represented in EnergyPLAN can be seen.

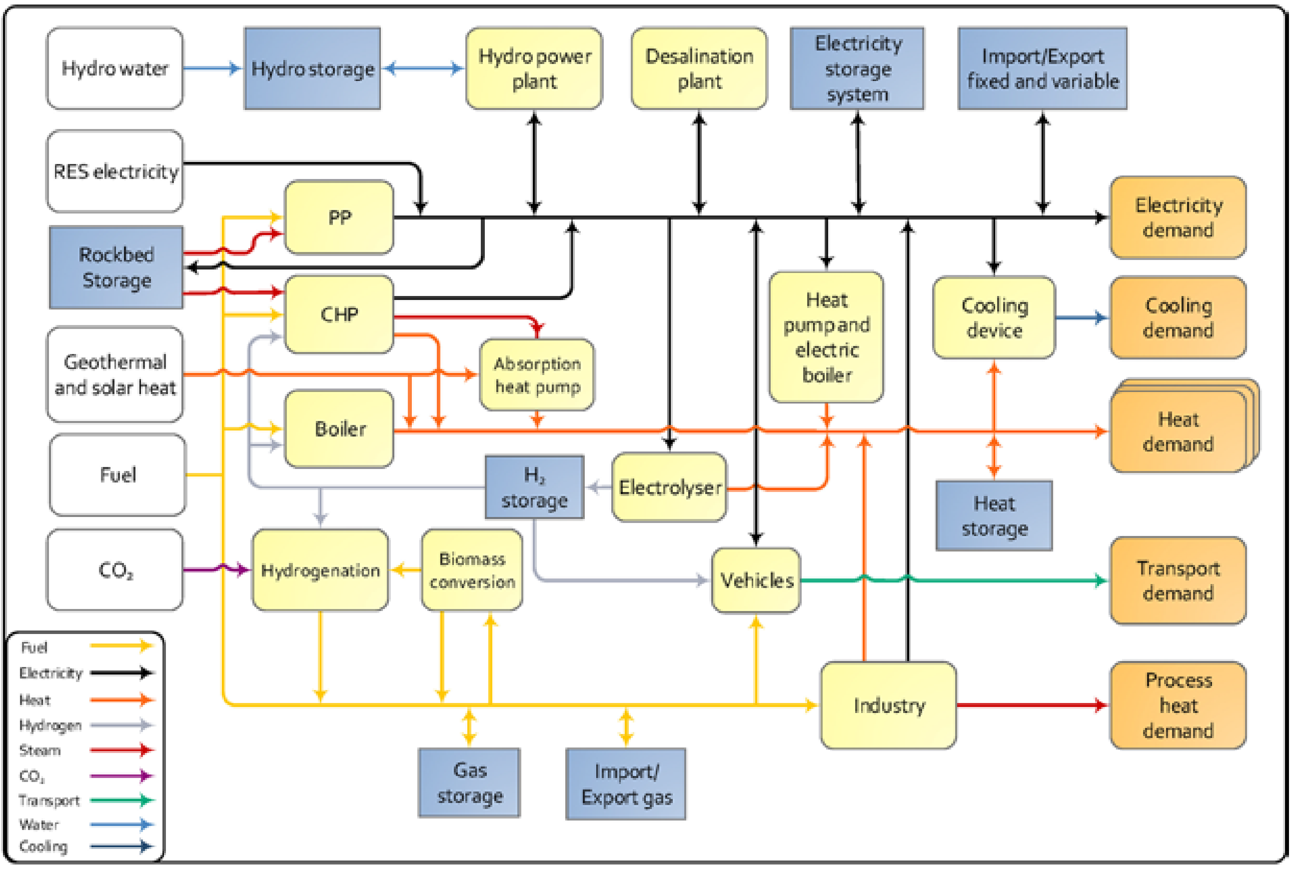

Figure 26. Overall technology and flow model for EnergyPLAN **(Lund et al., 2021)**.

A number of data inputs are needed to simulate an energy system in EnergyPLAN: energy demands (heat, electricity, transport, industry, etc.); energy generation technologies and resources (wind turbines, power plants, gas boilers etc.) and energy conversion technologies (electrolysers, gasification plants etc.); system characteristics (simulation and operation strategies, technical limitations such transmission capacity); cost (fuel costs, fixed and variable operation and maintenance costs). Resulting outputs are annual and hourly energy balances with annual productions, total costs including fuel consumptions, import and export of electricity (Lund et al., 2021).

EnergyPLAN has been widely applied for modelling of energy systems, with most studies focusing on the

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development of scenarios with shares of renewable energy integration (Østergaard, 2015). Studies typically employ several indicators for system evaluation, such as primary energy supply, CO_2 emissions, system costs, and excess electricity generation (Østergaard, 2015).

6.3.3 Aalto-EU-TIMES

In this study, Aalto-EU-TIMES, a recently developed variant of JRC-EU-TIMES (Joint Research Centre: Institute for Energy and Transport, Radu, D., Ruiz, P., Thiel, C., Sgobbi, 2013), is used. JRC-EU-TIMES is a technology-rich, bottom-up optimisation model developed by the EC's Joint Research Centre (JRC) to represent the European Union (EU)'s energy system from resource extraction through end-use sectors. Built on the TIMES platform (Loulou et al., 2016), it characterises supply, conversion, and demand technologies across power generation, industry, buildings, and transport, and determines the least-cost investment and operational pathways under defined policy, resource, and technology cost assumptions. The model operates at the country level for the EU-27 plus the UK, Norway, Iceland, and Switzerland with medium- to long-term time horizons (in five-year steps from 2010 to 2050), capturing interactions between fuel markets, infrastructure constraints, and emission reduction targets. JRC-EU-TIMES provides policymakers with detailed insights into how technology choices, energy flows, and costs evolve over time.

6.3.4 AIM-Enduse India

The Asia-Pacific Integrated Model (AIM)/Enduse India (AIM/Enduse-India) is a bottom-up, techno-economic energy system model, which is built on a disaggregated, sectoral representation of the economy. The model integrates the water module at the resource and technological level into the existing energy and environment systems to capture the impacts of existing and future policies for water, energy, and land systems on the major water- and energy-intensive sectors (Vishwanathan et al., 2019). The model uses recursive dynamics and runs in annual time steps. It optimises costs (technology, energy, and water) and resources (water, energy) by selecting a set of best available technologies based on given physical resources and technological and environmental parameters. A detailed characterisation of the inputs reflects an optimistic engineering view of technological progress. Economic parameters, such as taxes, subsidies, resource (energy, water, and land) technologies, policies, and social costs are also classified. The final service demand is exogenous and is driven not only by the gross domestic product (GDP) but also by end-use consumption and policies across various sub-sectors (Sudharmma Vishwanathan et al., 2023). AIM/Enduse India has been used in the current study to capture the major sectors of the energy and environment systems in India and quantify the impacts of multiple objectives (climate change mitigation, energy, and climate security) of existing and future policies related to emissions reductions, energy efficiency, technology transitions and so on. The energy supply (e.g., power generation, refineries, coal supply) module is endogenously linked with energy end-use sectors (industry, transport, buildings, and agriculture).

6.3.5 DREEM

The Dynamic high-Resolution dEmand-sidE Management (DREEM) model is a fully integrated energy demand and demand-side management simulation model, focusing on the building sector, which enhances the computational capabilities of the current Building Energy Systems (BES) and demand-side models, by not solely calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (e.g., consumers, citizens, etc.), and, then for other relevant energy system stakeholders (e.g., suppliers, retailers, DSOs, TSOs, etc.) (Stavrakas & Flamos, 2020).

The fundamental idea driving the development and the implementation of the DREEM model is that for end-users to actively participate in the energy transition, they must initially gain awareness of the benefits from investing in new energy products and services. In this context, the model's novelty lies in its potential to be used in a wide range of applications, not only to assess the existing technological infrastructure, but also to support the development of business models and regulatory innovations, which maximise the value of energy products and services, and monetise them, to fairly compensate end-users and other energy market actors. Overall, the DREEM model:

- Embodies key features towards the simulation of renewable energy, energy efficiency, and other demand-flexibility actions, like demand response, in the building sector.
- Builds on the concept of modularity consisting of sevelal components, each of which consists of additional modules, permitting greater flexibility in potential system configurations and computational efficiency (i.e., high time resolution and quick simulations), towards a broad spectrum of scenarios, to study different end-use scenarios (Figure 23).
- Enables the integration of upcoming technological advancements in a comprehensive manner, including the adoption of innovative technologies like heat pumps and EVs, aligning with energy transition scenarios that anticipate the complete electrification of the heating and the transportation sectors.
- Produces outputs for a group of buildings, for example, a neighbourhood, a district, a municipality, or an energy community.

Serves as a basis for modelling domestic energy demand scenarios within the broader field of local, regional, and national energy systems in different geographical/climate and socioeconomic contexts, within and beyond the European Union (EU), based on the availability of historical data and observations.

DREEM has been developed using the "Buildings" library, an open-source Modelica library dedicated to building energy and control systems. In addition to the Modelica models, Python scripts have also been developed to simulate specific components of the model and facilitate interaction with the Dymola simulation environment. The DREEM model is open access under the "GNU AFFERO GENERAL PUBLIC LICENSE[32]". The latest version of the model, including associate source code, datasets, and detailed documentations to enable the models' use, modification, and republication, are distributed through the TEESlab UPRC's GitHub[33] page. The updated modelling structure of DREEM is presented in **Figure 27**.

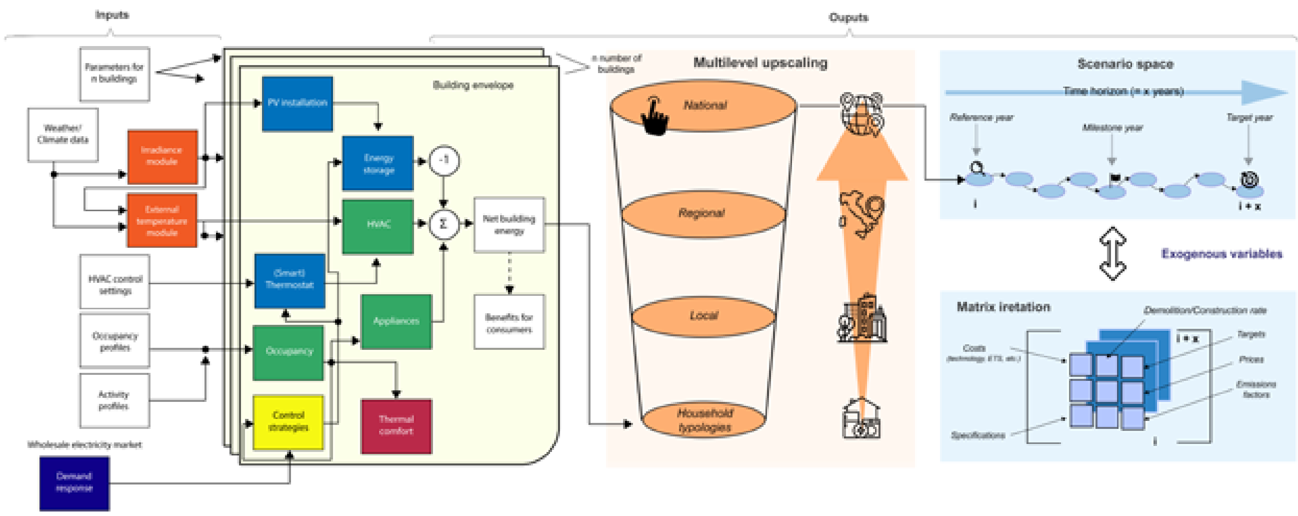

Figure 27. The architecture of the DREEM model as originally presented by **(Stavrakas & Flamos, 2020)** and as further developed, modified, and adjusted by **(Papantonis et al., 2025)**.

[32] https://www.gnu.org/licenses/agpl-3.0.txt
[33] https://github.com/TEESlab-UPRC/DREEM

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6.4 Global scale

6.4.1 Context

Strong growth in global power demand in 2024, fuelled by the expansion of electrification, is ushering in the new Age of Electricity. Global electricity consumption rose by an estimated 4.3% year-on-year in 2024, up from 2.5% in 2023. In 2024, most of the growth in global electricity demand occurred in emerging economies, with China accounting for 54% of the total growth. Out to 2027, developing economies will remain the engines of demand growth, accounting for around 85% of additional global electricity demand, with China providing more than half of the gains (IEA, 2025).

High-efficiency electric heat pumps are considered a central technology in the new Age of Electricity due to their ability to reduce emissions from space and water heating in the buildings sector. So far, installations of heat pumps remain concentrated in new buildings and existing single-family homes. Multistorey apartment buildings and commercial spaces will need to be a priority area if solid growth is to continue (IEA, 2023d). Energy efficiency retrofits also need to accelerate to ensure that new heat pumps installed in existing buildings are as efficient as possible and not oversised. This will lower the upfront capital and operating costs for consumers and reduce strains on power systems, especially if combined with smart controls for flexible operation (IEA, 2022h).

Over one-sixth of global natural gas demand is for heating in buildings – in the European Union (EU), this number is one-third (IEA, 2022h). The energy crisis has led to higher prices for residential gas heating and accelerated the uptake of heat pumps, strengthened by the rollout of government support policies. However, countries are still reluctant to ban gas boiler installations completely given the risk of high upfront investment costs of heat pumps, the lock-in effect of the existing gas infrastructure and current cost of living pressures for households. Recent announcements in several countries to delay such boiler bans show the end of natural gas in residential space heating is not yet in sight, but the transition away from gas is gaining speed (IEA, 2023b).

Globally, over 100 million households use heat pumps as a main heating source, with adoption concentrated in temperate and cold climates where seasonal performance factors (SPFs) are most favourable. This means that one in ten homes that require substantial heating are served by heat pumps (IEA, 2023b). As a result, heat pumps are providing around 10% of the global heating needs in buildings, but the pace of installation is growing rapidly in recent years. The share of heat pumps is comparable to that of fuel oil for heating and of other forms of electric heating but lower than the over 40% of heating reliant on gas heating and the 15% reliant on district heating. To align with all existing national energy and climate pledges worldwide including the NDCs, heat pumps will have to meet nearly 20% of global heating needs in buildings by 2030. In the NZE Scenario of the IEA, the number of heat pumps installed in the buildings sector globally will rise from 180 million in 2020 to around 600 million in 2030, meaning that heat pump installations in individual buildings are forecast to rise from 1.5 million per month currently to around 5 million by 2030. The world is almost on track to reach this milestone if new installations continue to grow at a similar rate globally as they did in 2021 (15%, which is double the average growth rate of the last decade) and 2022 (11%), driven by policy support and incentives amid high natural gas prices and efforts to reduce emissions. However, sales need to expand by well over 15% per year this decade if the world is to achieve net zero emissions by 2050 (IEA, 2023d).

In several regions, especially in the Nordic European countries and in France, heat pumps already have a considerable market share due to their beneficial total life-cycle cost, as a result of the lower electricity prices compared to other EU countries (Wemhoener, 2016). In 2022, Europe experienced a record year, with sales increasing by nearly 40%, particularly for air-to-water models, which saw a 50% rise (IEA, 2023d). China has been the world's largest market for new heat pump sales in recent years, maintaining the largest overall sales worldwide, while North America currently has the largest installed base in terms of total homes equipped with heat pumps (IEA, 2023b). In Northern China, district heating remains the most common heating solution in cities, but many of these households also have heat pumps installed for space cooling and providing additional heating from time to time. In Southern China, where winters are milder, air-to-air reversible units are a widespread solution for space heating, though sales were largely stagnant in recent years (IEA, 2023d). Air-to-water heat pumps mainly used for space heating are a small segment of the Chinese market, with deployment concentrated

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in colder northern provinces, but they saw growth of over 20% in 2022. Sales of air-sourced heat pump water heaters remained relatively stable at more than 1 million units sold. Around 40% of heat pumps worldwide are manufactured in China, making the country the largest producer and exporter of this technology, with most of its exports going to Europe (IEA, 2023c).

In the United States, heat pump purchases surpassed gas furnaces in 2022 after years of almost equal sales. Though most heat pumps are installed in new single-family homes in the United States (40% of new single-family homes are heated by heat pumps), the number of apartments using heat pumps as their primary heating technology more than doubled between 2015 and 2020 (IEA, 2023d). In parts of the United States (Vineyard & Baxter, 2021) and Japan (Asahi, 2023), heat pumps already represent a large share of the heating markets since they can also fulfil increasing demand for cooling. In these countries, the market and the value chains are well developed, and end-user awareness and acceptance are both high. Together, these regions, along with Korea, are also major manufacturing hubs, home to the industry's largest players (IEA, 2022h). In several other countries, the market share is significant for newly-built houses because heat pumps are often the best option to meet energy performance standards set by new building regulations (IEA, 2022d). However, heat pumps are still largely absent from heating markets in Central Asia and some parts of Eastern Europe, where high upfront costs remain a major barrier, and many homes are connected to district heating networks (IEA, 2023d). However, large-scale heat pumps are an effective option to decarbonise these networks, which remain heavily dependent on fossil fuels today (IEA, 2022h).

6.4.2 Stakeholder feedback

During the stakeholder workshop, participants highlighted several key considerations for improving the scope and relevance of the study. A prominent suggestion was the inclusion of a comparative analysis between EU-level and global-level measures to reduce emissions from the buildings sector; a perspective rarely explored in existing literature. Stakeholders emphasised the importance of incorporating examples from diverse regional contexts, such as Africa, the Far East, and Latin America, and accounting for countries' NDCs to better reflect the global variability in decarbonisation pathways.

Participants also stressed that achieving net-zero carbon emissions targets for new buildings by 2030 and existing buildings by 2050 would require much stronger and more comprehensive policies. These should address not only operational energy efficiency but also the whole-life carbon impacts from building materials and construction processes.

Concerns were raised regarding the limited number of countries with detailed, building-specific NDC targets or energy codes aligned with zero-energy building (ZEB) principles. As such, the acceleration of effective measure implementation, along with improved monitoring, reporting, and verification systems, was seen as critical.

Stakeholders also noted that the modelling of global scale scenarios must account for fundamental differences compared to the EU, particularly regarding energy access and infrastructure development. In many regions, closing the gap in grid infrastructure and ensuring universal energy access remain high priorities.

Stakeholders also emphasised the importance of accounting for regional differences in climate impacts when designing buildings' renovation pathways. In regions where the effects of climate change are already being felt more acutely than in Europe, such as countries experiencing severe heatwaves like India, the urgency and speed of building renovation and system upgrades become even more critical. In such contexts, the rapid decarbonisation of air conditioning systems was identified as a key factor that could significantly influence energy demand for cooling and emissions trajectories. Therefore, renovation strategies should be tailored not only to the local infrastructure and policy frameworks but also to the specific climate risks and adaptation needs of each region, with renovation (and thermal insulation) offering an important option to synergistically improve both mitigation and adaptation of households.

Finally, participants pointed to the need for scenarios to reflect global trade dynamics and technology supply risks. They noted that clean technologies like photovoltaics (PV), batteries, and heat pumps are heavily reliant on imports from China and other non-EU regions, raising concerns about the resilience of supply chains and the potential implications if access to these technologies becomes constrained.

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6.4.3 Scenario design and model parameterisation

PROMETHEUS simulates global-scale scenarios incorporating projections based on the updated SSPs (K.C. et al., 2024) and different levels of climate policy ambition, including current policies and Nationally Determined Contributions (NDCs) with Long-Term Targets (LTTs), to provide results to the other models:

"Current Policies (CP-EI)" scenario: The CP-EI scenario reflects the current portfolio of actual emission reduction policies and credible policy targets (already legislated) in place until 2030 across both developed and developing countries, including the EU. After 2030, the scenario assumes that climate policy efforts continue but are not further strengthened. Specifically, it is assumed that improvements in the emission intensity of GDP observed during 2020–2030 persist at the same rate beyond 2030. Additionally, the policy targets set for 2030 in each country/region, such as renewable energy mix targets and vehicle fuel standards, are maintained as minimum levels after 2030 to prevent any reversal of progress achieved.

"Nationally Determined Contributions (NDC-EI)" scenario: NDCs represent short-term ambitions codified in law or policy, though implementation remains vulnerable to political changes. The NDC-EI scenario assumes the implementation of the stated 2030 emission targets outlined in submitted or announced NDCs (submitted until 2022/2023), capturing all mitigation ambition updates during and after COP26. These NDC targets are applied on top of current policies modelled in the CP-EI scenario; in regions where current policies overachieve on the mitigation targets in NDCs, no additional emission constraints are applied. For the period after 2030, the same method based on constant carbon intensity of GDP reduction rates over 2020–2050 is applied as in the CP scenario.

"Nationally Determined Contributions with Long-Term Targets (NDC-LTT)" scenario: This scenario represents an ambitious decarbonisation pathway by incorporating countries' LTTs, even when concrete policy measures to achieve them remain undefined. The NDC-LTT scenario builds upon countries' stated 2030 emission targets pledged in their NDCs, applied in addition to existing climate policies. For countries/regions that have formulated LTTs, such as net-zero commitments or other goals for 2050 or beyond, whether legally binding, outlined in policy documents, or simply announced, the scenario imposes emission constraints that decline linearly from the 2030 NDC levels towards the specified LTT. In regions without declared LTTs, post-2030 emissions follow the same trajectory as in the NDC-EI scenario.

The current policies used in the scenarios are retrieved from the updated climate policy database of IAM COMPACT which currently includes a total of 333 recent national and regional policies/ targets for reducing emissions in different sectors (van de Ven et al., 2024). The NDC emission reduction targets and LTTs announced by each country that are used in the scenarios are taken from another IAM COMPACT database compiled in the first policy response mechanism cycle (PRM-1) (Mittal & van de Ven, 2024).

6.4.4 Results

Figure 28 presents the projected share of electricity in final energy consumption for the residential and commercial sectors across major world regions in 2030 and 2050, based on the "*CP-EI*" and "*NDC-LTT*" scenarios using results from the PROMETHEUS model. The results reveal a clear trend of rising electrification across all regions, with significantly higher electricity shares in the "*NDC-LTT*" scenario, particularly by 2050, driven by the increasing ambition of climate policies. Regions such as North America (NOAM), the Western Pacific (WPAC), China (CHN), and the EU-27 plus the UK (EU-28) are projected to reach electricity shares exceeding 75–90%, building on already high 2015 levels. Ambitious climate policies towards achieving net-zero targets in these regions help accelerate the transition.

Conversely, regions like India (IND), Emerging Markets (EMRG), and Energy-Producing Countries (EPROD) start from lower electrification baselines but also demonstrate strong growth under the "*NDC-LTT*" scenario. For example, India (IND) increases from approximately 23% in 2015 to over 70% by 2050. The Rest of the World (RESTW) shows the slowest progress, remaining below 20%, reflecting structural barriers such as low electricity access and continued reliance on traditional fuels like biomass, particularly in Sub-Saharan Africa.

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The pace of electrification between 2030 and 2050 varies significantly across regions, reflecting differences in policy ambition, decarbonisation options used, and socioeconomic conditions. When comparing based on the current regional policies, namely the "*CP_EI 2030*" with the "*CP_EI 2050*" results, all regions show some progress towards increasing electrification. Notably, the EU-27 plus the UK (EU-28), China (CHN), and India (IND) surpass the world average increase, while North America (NOAM), Western Pacific (WPAC), and Rest of the World (RESTW) lag behind. Regions such as Commonwealth of Independent States (CIS), Energy-Producing Countries (EPROD), and Emerging Markets (EMRG) fall near the global average. These trends highlight how even under current policies, progress is uneven and often constrained by regional circumstances.

When comparing the "*CP_EI 2050*" and "*NDC_LTT 2050*" scenarios, disparities in long-term climate policy ambition become more apparent. Regions like the EU-27 plus the UK (EU-28) appear on track to realise their full electrification potential, while others such as the North America (NOAM) and Western Pacific (WPAC) regions, despite high baseline levels, show limited additional progress under current policies, suggesting underutilisation of their decarbonisation potential.

Overall, the figure underscores the pivotal role of ambitious climate strategies in accelerating electrification, a cornerstone of the clean energy transition. While current policies yield incremental improvements, achieving substantial decarbonisation in the residential and commercial sectors requires stronger commitments and targeted support, especially in lagging regions. Tailored policy design, infrastructure development, and improved electricity access are essential for narrowing these regional disparities and ensuring a more equitable global energy transition.

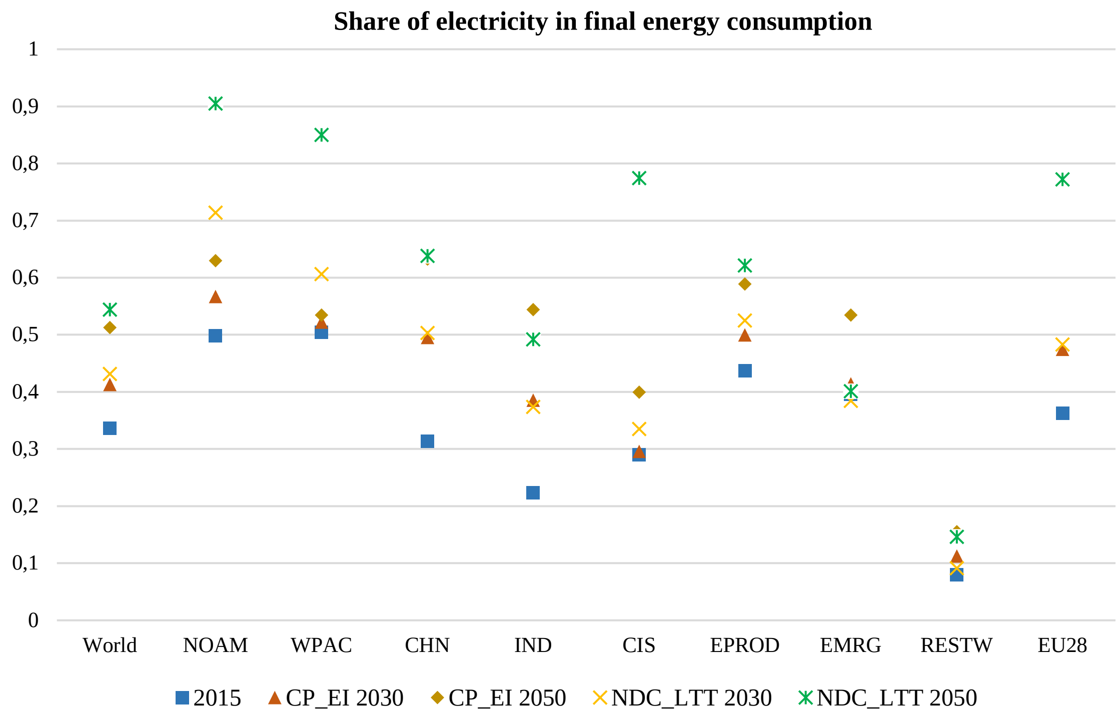

Figure 28. Share of electricity in the final energy consumption in the residential and the commercial sectors by 2030 and by 2050 across different world regions, compared to the 2015 electricity shares, under the "CP_EI" and the "NDC_LTT" scenarios. Regions: North America (NOAM), Western Pacific (WPAC), China (CHN), India (IND), Commonwealth of Independent States (CIS), Energy-Producing Countries (EPROD), Emerging Markets (EMRG), Rest of the World (RESTW), EU-27 countries plus the United Kingdom (EU-28 according to the model's nomenclature). Results are derived from PROMETHEUS.

Table 23 presents projected CO_2 emissions (in $MtCO_2$/yr) and their percentage change relative to 2015 levels in the residential and commercial sectors for the years 2030 and 2050, across multiple global regions. The projections are based on the "*CP-EI*" and the "*NDC-LTT*" scenarios, as simulated using PROMETHEUS.

Under the "*CP-EI*" scenario, global emissions are projected to slightly decrease by 9.4% in 2030, reaching 2,976 $MtCO_2$, and then further decline to 2,755.8 $MtCO_2$ by 2050 (a net 16.1% decrease from 2015). In contrast, the "*NDC-LTT*" scenario shows a much more ambitious reduction, with global CO_2 emissions from the residential and

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commercial sectors dropping to 2,468.5 $MtCO_2$ in 2030 (24.8% below 2015 levels) and plummeting to 1,686 $MtCO_2$ by 2050, a 48.6% reduction.

The most significant regional disparities occur in terms of both emissions levels and the pace of decarbonisation. North America (NOAM) and Western Pacific (WPAC) exhibit strong mitigation potential under "*NDC-LTT*". NOAM reduces emissions by a staggering 95.8% by 2050 compared to 2015 levels, while WPAC achieves a 93.5% reduction. These reductions reflect not only deep electrification of the residential and commercial sectors but also improvements in energy efficiency and fuel switching away from carbon-intensive sources. EU-27 plus the UK (EU-28) also shows very ambitious reductions under "*NDC-LTT*", with emissions nearly eliminated by 2050 (only 1.3 $MtCO_2$), representing a 99.8% cut. A similar trend is seen under "*CP-EI*", though to a lesser extent. These regions illustrate how high-income economies with mature infrastructure and strong institutional capacity can leverage technological innovation and policy coordination to achieve near complete decarbonisation of end-use sectors. Their trajectories serve as a benchmark for what is technically and economically feasible in the pursuit of net-zero emissions.

China (CHN) sees a modest emissions reduction under "*CP-EI*" (33% by 2050) and more aggressive cuts under "*NDC-LTT*" (53.9% by 2050), indicating the region's potential for emissions control with stronger policy interventions. India (IND) is showing increased emissions under "*CP-EI*" (up 107.5% by 2050) driven by increasing population, income and improved living standards, while even under "*NDC-LTT*" the emissions are increased by 90.1% by 2050, reflecting its continually growing energy demand in the building sector, as its population is expected to increase by 9% between 2030 and 2050 according to the updated SSPs' projections, thus highlighting the significant need for increased energy efficiency interventions in the residential and commercial sectors. The Commonwealth of Independent States (CIS) presents a complex pattern. Emissions slightly increase under the "*CP-EI*" scenario by 8.5% by 2050, indicating limited policy ambition, continued reliance on cheap natural gas, or structural inertia. However, under the "*NDC-LTT*" scenario, emissions fall by 82.8% compared to 2015 levels, suggesting significant mitigation efforts or structural transformation in line with international climate goals.

Energy-Producing Countries (EPROD) and Emerging Markets (EMRG) show increasing emissions under "*CP-EI*", with rises of 62.4% and 49.5% respectively by 2050, driven by their high population and income growth combined with lack of ambitious climate policies and increased cooling needs. Under "*NDC-LTT*", increases are more moderate, 48% for EPROD and 20.3% for EMRG, implying that while mitigation is feasible, these regions face greater challenges in curbing emissions due to growing energy demand (especially for cooling) and structural dependencies on fossil fuels. Rest of the World (RESTW) also exhibits a pronounced increase in emissions under both scenarios, indicating that even with long-term targets, this region, which comprises several developing and low-income countries, could experience growth in demand that outweighs policy-driven reductions, unless stronger interventions are implemented.

This comparison illustrates the stark difference in outcomes between a continuation of current trends ("*CP-EI*") and a globally coordinated mitigation effort aligned with NDCs and LTTs ("*NDC-LTT*"). While "*CP-EI*" results in marginal reductions or increases in emissions across several regions, "*NDC-LTT*" enables much deeper decarbonisation, particularly in developed regions and China. However, the feasibility of achieving such ambitious reductions, especially the near-zero levels projected for the EU-27 plus the UK, North America, and the Western Pacific, will depend on substantial technological breakthroughs, effective policy implementation, and widespread behavioural shifts. The contrasting trajectories in rapidly developing economies such as India and Rest of the World underscore the importance of addressing global equity, ensuring financial support, and accelerating technology transfer to ensure inclusive and effective climate action.

Table 23. CO_2 emissions (in $MtCO_2$/yr) and changes ("+": increases, "-": decreases) in CO_2 emissions (%) compared to the 2015 levels in the residential and the commercial sectors in 2030 and 2050, across different world regions, under the "CP_EI" and the "NDC_LTT" scenarios. Regions: North America (NOAM), Western Pacific (WPAC), China (CHN), India (IND), Commonwealth of Independent States (CIS), Energy-Producing Countries (EPROD), Emerging Markets (EMRG), Rest of the World (RESTW), EU-27 countries plus the United Kingdom (EU-28 according to the model's nomenclature). Results are derived from PROMETHEUS.

	CO_2 emissions ($MtCO_2$/yr) & Changes (%) compared to the 2015 levels

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	"CP-EI"		"NDC-LTT"	
	2030	**2050**	**2030**	**2050**
World	2,976 (-9.4%)	2,755.8 (-16.1%)	2,468.5 (-24.8%)	1,686 (-48.6%)
NOAM	533.5 (-17.4%)	385.6 (-40.3%)	249.0 (-61.4%)	27.4 (-95.8%)
WPAC	202.0 (-5.5%)	169.3 (-20.8%)	127.3 (-40.4%)	13.8 (-93.5%)
CHN	603.0 (-16.3%)	482.2 (-33%)	584.2 (-18.9%)	331.9 (-53.9%)
IND	211.3 (+26.6%)	346.3 (+107.5%)	211.3 (+26.6%)	318.5 (+90.1%)
CIS	304.1 (+6.6%)	309.4 (+8.5%)	262.1 (-8.1%)	49.2 (-82.8%)
EPROD	272.3 (+15.3%)	383.8 (+62.4%)	245.9 (+4.0%)	349.7 (+48%)
EMRG	361.9 (+11.7%)	484.5 (+49.5%)	337.9 (+4.3%)	390.0 (+20.3%)
RESTW	121.7 (+36.4%)	193.4 (+116.8%)	99.0 (+10.9%)	204.3 (+128.9%)
EU28	366.1 (-39.1%)	1.3 (-99.8%)	351.8 (-41.5%)	1.3 (-99.8%)

6.5 Regional scale: European Union plus the United Kingdom

6.5.1 Context

The EU leads global decarbonisation efforts, with buildings representing a central pillar in this transition. Since 1990, greenhouse gas (GHG) emissions from the EU's buildings sector have steadily declined, from 735 $MtCO_2eq$. to 489 $MtCO_2eq$ in 2022 (European Environment Agency, 2024), driven by improvements in energy efficiency, the greater use of renewable energy for heating, and the adoption of heat pumps and district heating systems. Despite this progress, buildings still account for 40% of the EU's final energy consumption and 36% of its energy-related GHG emissions. Moreover, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock remains energy-inefficient and requires renovation by 2030 to meet climate targets (European Commission, 2024a). Natural gas remains the dominant energy source for space heating in the residential sector, contributing roughly 39% of consumption, while oil and coal account for 11% and 3%, respectively.

The EC recommends an overall GHG emissions reduction target of 90% by 2040 compared to the 1990 levels, with the buildings sector expected to deliver an even higher reduction of 92% (Hesse & Braungardt, 2024). This target falls within the range of the current sectoral scenario estimates, which project GHG reductions of 88% to 99% by 2040. Achieving these reductions will rely largely on phasing out fossil fuel-based technologies and significantly improving energy efficiency through higher renovation rates. However, according to Member States' 2023 national projections, current policies are expected to reduce building-related GHG emissions by only 42% below 1990 levels by 2030 and by 53% by 2040, reaching 62% if additional measures are implemented (European

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Environment Agency (EEA), 2023; Hesse & Braungardt, 2024).

This gap between the EC's climate ambition and Member States' actual transition realities underscores that the buildings sector is still far from being on track to meet its 2030 and 2050 climate targets (European Commission, 2024b). Key indicators, including CO_2 emissions reduction, final energy consumption, renewable energy share, and renovation investments, remain more than 40% below the required trajectories for these targets (Buildings Performance Institute Europe (BPIE), 2024). Specifically, between 2015 and 2022, emissions fell by just 14.7%, well below the required reduction of 27.9%, leading to a total of 367 $MtCO_2$eq. in avoidable emissions, had the target pathway been met. Over the same period, final energy consumption in households and services declined by only 2.8%, less than half the necessary reduction of 6.5%. Similarly, the share of renewable energy in buildings rose by just 6.3%, far short of the 18% increase needed. Cumulative investments in buildings' renovation during the period 2015–2022 totalled €2,629 billion, only 60.6% of the €4,335 billion required, indicating that overall progress remains substantially off track (Buildings Performance Institute Europe (BPIE), 2024).

The EU has long pursued buildings' decarbonisation, establishing a series of regulations and ambitious targets (Voïta, 2025); the Energy Performance of Buildings Directive (EPBD)- first adopted in 2010 and revised in 2024- alongside the Energy Efficiency Directive (EED)- introduced in 2012 and updated in 2023- form the core of the EU's policy framework. In 2020, the EU launched the "Renovation Wave" strategy under the "European Green Deal", aiming to at least double the buildings' renovation rate by 2030 and promote deep renovations through a comprehensive action plan of regulatory, financial, and supporting measures (Buildings Performance Institute Europe (BPIE), 2020). Furthermore, in recent years, attention to buildings' performance has intensified, driven by two key events: first, the COVID-19 pandemic, which confined many Europeans to their homes and exposed widespread issues such as poor indoor air quality; and second, the energy crisis, exacerbated by Russia's invasion of Ukraine, which caused a sharp rise in energy prices and deepened energy poverty, now affecting 8 to 16% of the European population (Maier & Dreoni, 2024).

The unexpected and extreme events of the past five years have raised serious concerns about high energy prices and energy security across the EU. In response, the EU introduced the "REPowerEU" plan (European Commission, 2022), alongside the "Fit-for-55" package (European Commission, 2021a), both underscoring the urgency of phasing out fossil fuels, particularly oil products and natural gas, in the EU's buildings sector. These policy plans primarily aim to: (i). reduce the EU's reliance on Russian natural gas, (ii). improve energy efficiency, (iii). gradually phase out fossil-fuel boilers, and (iv). implement a parallel Emissions Trading System (ETS_2) for heating fuels in buildings, which will further incentivise investment in fossil-free alternatives such as heat pumps (European Commission, 2021a, 2022). This evolving policy landscape is shaping Member States' energy transition strategies, including updates to their National Energy and Climate Plans (NECPs) and National Building Renovation Plans (NBRPs, former Long-Term Renovation Strategies- LTRSs).

The energy crisis appears to have marked a turning point for residential gas demand in Europe. In 2022, residential and commercial gas consumption fell by over 15% compared to the previous year (IEA, 2023a). While ~40% of this decline was due to weather-related factors, specifically reduced heating needs during a mild winter, a significant portion resulted from deliberate gas-saving measures (IEA, 2023b). These measures included fuel switching, behavioural changes, energy-efficiency improvements, such as buildings' retrofits, and heat pump installations. Additionally, high energy prices forced some households and businesses to cut their energy use involuntarily (IEA, 2023b). This downward trend continued into 2023, with overall gas demand in the European member countries of the Organisation for Economic Co-operation and Development (OECD Europe) dropping an estimated 9% in the first three quarters compared to the same period in 2022. These developments indicate that gas demand in Europe's buildings sector is likely to decline moderately but persistently in the years ahead (IEA, 2023g).

The "Fit for 55" package also added a Social Climate Fund that supports the most vulnerable population and small businesses in the overall energy transition process (beyond just buildings) (European Commission, 2024a). Reflecting the increasing recognition of the building sector's importance in the energy transition, the 2024 – 2029 EC has added the housing sector to the prerogatives of the Energy Commissioner (Voïta, 2025). This demonstrates that building renovation can no longer be considered without its social dimension anymore, i.e., the promotion of

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affordable and/or social housing and the fight against energy poverty. New initiatives also include the EC's 2025 Task Force on Housing, in charge of developing a European Affordable Housing Plan. Renovation is critical even when considering service buildings that play a social role, typically for schools or hospitals (Psatha, 2024). Renovation is now part of broader infrastructure upgrade projects, with considerations about heating systems and adaptation to extreme weather events such as heat waves. These developments create new challenges for local governments. They must adjust their skills, acquire new ones, and find the right renovation policies that benefit affordable housing.

6.5.2 Stakeholder feedback

During the stakeholder workshop, participants emphasised the critical role of the recently revised EPBD, adopted in May 2024. They highlighted that the directive mandates the gradual installation of PV systems on both new and existing buildings between 2026 and 2030. In addition, Articles 7 and 11 of the EPBD introduce Zero Emission Building (ZEB) standards, requiring all new public buildings to meet zero-emission criteria by 2028 and all other new buildings by 2030.

A key infrastructure priority identified was the urgent need for distribution grid upgrades to accommodate rising electricity demand at the household level. Stakeholders noted that approximately two-thirds of total grid investments should be directed towards the distribution network, with the remaining one-third allocated to transmission systems. However, participants also pointed to the potential of self-consumption, energy storage, and smart building technologies to ease pressure on grid infrastructure by enabling decentralised energy solutions and reducing dependency on large-scale grid expansions.

Concerns were also raised regarding the slow progress in the buildings sector. The stakeholders referred to the insights provided by the "EU Buildings Climate Tracker", indicating that the sector is falling significantly behind on key decarbonisation indicators, including CO_2 emissions, energy consumption, renewable energy share, and renovation investments, lagging by over 40% relative to 2030 and 2050 target pathways. Stakeholders stressed that addressing this performance gap is essential to aligning the sector with the EU's climate neutrality objectives.

6.5.3 Scenario design and model parameterisation

6.5.3.1 Aalto-EU-TIMES

Details about the scenario design and parametrisation of Aalto-EU-TIMES are provided in Section 5.2.3.

6.5.3.2 EnergyPLAN

This analysis models and compares two future energy system scenarios for EU27+UK. The EC's "Baseline 2050" scenario, developed as part of the PRIMES "A Clean Planet for All" programme (European Commission, 2018), and the "Smart Energy Europe 2050" scenario first presented in Thellufsen et al. and developed based on Smart Energy System Principles (Thellufsen et al., 2023).

The "Baseline 2050" scenario was developed to reflect the EU decarbonisation trajectory towards 2050 based on agreed policies and policies proposed by the EC. The "Baseline 2050" scenario thus reflects macro-economic projections, fuel price projections, and technology assumptions. Hence, this scenario represents a relatively modest renewable energy expansion and integration effort, resulting to some extent in a transition scenario rather than a fully renewable and integrated energy system scenario.

The "Smart Energy Europe 2050" scenario, representing a 100% renewable energy system is based on smart energy system principles which emphasise energy efficiency first, the modernisation and expansion of heating systems including district heating, and the electrification of transport, among other measures.

The models exhibit a notable degree of harmonisation, with EnergyPLAN estimating total primary energy consumption at 12.51 PWh for the "Baseline 2050" scenario, and 10.92 PWh for the "Smart Energy Europe 2050" scenario, closely matching the 11.98 PWh projected by Aalto-EU-TIMES, thereby supporting consistency in the energy system assessment. However, the "Smart Energy Europe 2050" scenario assumes a 100% renewable

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energy system, which naturally results in lower total energy consumption due to the exclusion of less efficient fossil fuels such as gas, oil, and coal, which remain part of the Aalto-EU-TIMES scenario. In this variant of EnergyPLAN, updated costs and efficiencies for variable renewable energy (VRE) and electrolysis have been incorporated.

Considering that in previous modelling applications, the “Baseline 2050” and “Smart Energy Europe 2050” scenarios included very little demand side flexibility from the residential and industry/service sector, in this analysis, we explore the energy system impacts from extensive implementation of flexibility in electricity consumption across households, industries, and EV charging, aiming to quantify the potential positive effects of such flexibility. Specifically, for the residential sector (SN1: Flexible household energy consumption), we examine key flexibility potentials EVs, and the adaptability of general electricity use and appliances. The system also includes means of supply side flexibility, e.g., from power to heat technologies combined with thermal storage in the district heating sector, or from power-to-X (PtX) fuels and storage such as electrolysers combined with hydrogen storage. Consequently, the demand side flexibility modelled is in addition to the other and mostly more established forms of flexibility.

In this modelling application, EnergyPLAN enables modelling of 1-day, 1-week, and 4-week flexible electricity demands, i.e., demands that are flexible within the specified time frame and thus available for demand shifting based on what is preferable from a system perspective. Within the temporal constraint specified by the user, EnergyPLAN seeks to reduce the fuel consumption of the system, e.g., by shifting electricity consumption to periods with high VRE generation to avoid periods of low VRE generation and thus reduce the operation of power plants.

The scenario matrices below provide an overview of the modelled scenarios, including a reference scenario without any demand flexibility in the residential and industrial sectors. **Table 24** and **Table 25** presents a set of scenarios exploring varying levels of flexibility in electricity demand shifting across three different timeframes: 1 day, 1 week, and 4 weeks. For each timeframe, the flexibility potential is gradually increased from 0% (no flexibility) up to 100% (full flexibility) in 10% increments, allowing for a systematic assessment of the impact of demand-side flexibility on the energy system under different temporal resolutions. All scenarios are modelled both for the “Smart Energy Europe 2050” and “Baseline 2050” scenarios.

Table 24: Modelled scenarios considering residential and industrial electricity as flexible demands.

Electricity demands	1-day flexibility	1-week flexibility	4-week flexibility
-Residential demand -Industrial electricity demand	0%	0%	0%
	10%	10%	10%
	20%	20%	20%
	30%	30%	30%
	40%	40%	40%
	50%	50%	50%
	60%	60%	60%
	70%	70%	70%
	80%	80%	80%
	90%	90%	90%
	100%	100%	100%

Table 25: Modelled scenarios considering residential, industrial, and electric vehicle consumption as flexible demands.

Electricity demands	1-day flexibility	1-week flexibility	4-week flexibility
-Residential demand	0%	0%	0%
	10%	10%	10%
	20%	20%	20%

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-Industrial electricity demand	30%	30%	30%
	40%	40%	40%
	50%	50%	50%
-Electric vehicle consumption	60%	60%	60%
	70%	70%	70%
	80%	80%	80%
	90%	90%	90%
	100%	100%	100%

Results from the analysis will first and foremost compare fuel consumption of the energy system in the different scenarios, as an indicator on how system efficiency is influenced by increasing demand side flexibility. This is relevant for further discussions on the relevance and extent to which implementation of such measures should be prioritised in future energy systems. Secondly, results on the annual system costs are analysed for a comparison of potential cost savings from such demand side flexibility. Finally, critical excess electricity production (CEEP) is evaluated, providing insights into how the increased flexibility can contribute to reducing VRE curtailment. Altogether, this assessment contributes to the ongoing discussions on the technical and economic feasibility (from a holistic energy system perspective) of establishing measures and market principles incentivising exploitation of demand side flexibility.

6.5.4 Results

6.5.4.1 Residential and commercial sector energy transition in the EU-27 plus the UK region

Figure 29 illustrates the evolution of final energy consumption by fuel type in the residential and commercial sectors of the EU-27 plus the UK region for the years 2016, 2030, and 2050 under the CP_EI and NDC_LTT scenarios, based on the results of Aalto-EU-TIMES.

A prominent trend observed across both scenarios is the substantial increase in electricity consumption. From approximately 32% in 2016, electricity's share rises to around 45% in 2030 and reaches nearly 68% by 2050 in both scenarios. This reflects ongoing electrification in heating, cooling, and appliances, as well as progress in decarbonising electricity generation.

Fossil fuels, particularly natural gas and oil, experience significant declines. Fossil gas, which accounted for roughly 36% of energy consumption in 2016, drops to 8% in the CP_EI scenario and 6.5% in the NDC_LTT scenario by 2050. Oil use becomes negligible by mid-century, dropping from 12% in 2016, to 9% in 2030, and 0% in 2050, while coal, already marginal in 2016 at around 2%, sees a complete phase-out. These reductions are consistent with EU policy objectives to phase out fossil fuels and enhance energy efficiency in buildings.

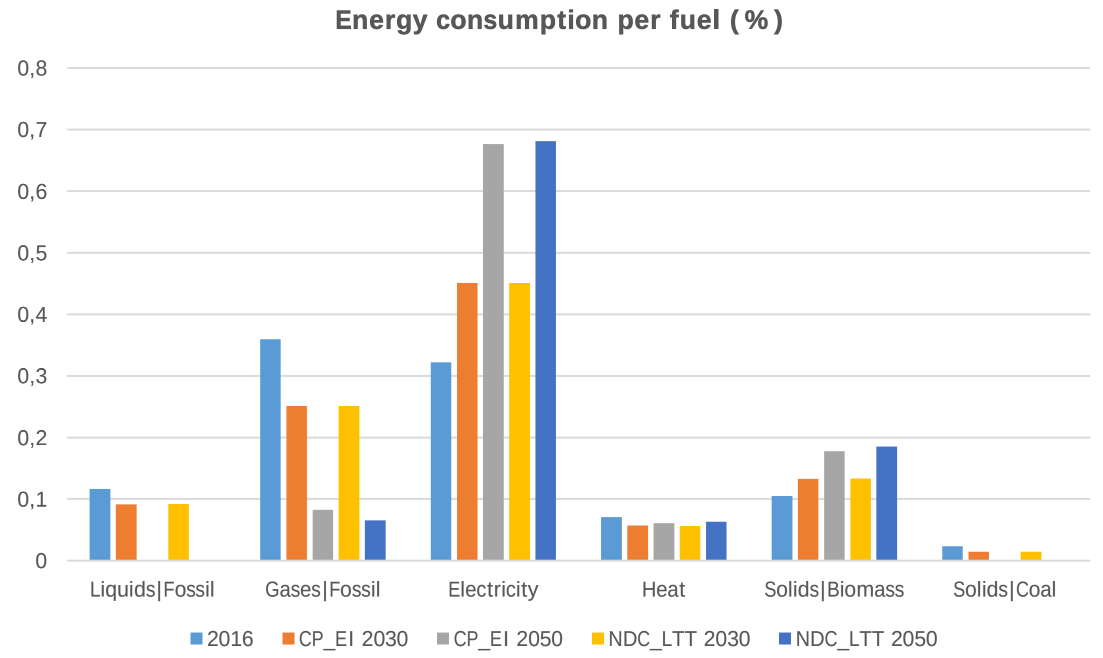

Figure 29. Final energy consumption by fuel type (%) in 2016, 2030, and 2050, in the residential and the commercial sectors in the EU-27+UK region, under the "CP_EI" and the "NDC_LTT" scenarios. Results are derived from Aalto-EU-TIMES.

The share of biomass increases steadily from 2016 levels, rising from about 10% in 2016 to approximately 18% by 2050. This indicates its continued role in off-grid and rural heating applications, especially in areas where electrification is constrained by infrastructure or affordability. However, its long-term sustainability depends on feedstock availability and emissions accounting. District heating remains a stable share throughout the period, ranging from 5–7%, suggesting continued relevance in urban heating networks, particularly in Northern and Eastern Europe.

Overall, the comparison between the CP_EI and NDC_LTT scenarios reveals that both lead to similar long-term outcomes, particularly by 2050. While NDC_LTT shows a slightly faster transition away from fossil fuels, the two scenarios converge over time, implying that market trends, technology adoption, and infrastructure shifts will be critical alongside formal policy in shaping the future energy mix of the EU-27 plus the UK region to avoid carbon lock-in and stranded assets.

Table 26 presents the projected CO_2 emissions and percentage reductions for the residential and commercial sectors in the EU-27 plus the UK region for the years 2030 and 2050, compared to 2016 levels, under the CP_EI and NDC_LTT scenarios, based on the results of Aalto-EU-TIMES.

In the residential sector, CO_2 emissions are expected to decline significantly under both policy scenarios. By 2030, emissions drop by 44.8% under CP_EI and 45.7% under NDC_LTT, reaching 199.8 $MtCO_2$/yr under CP_EI and 196.7 $MtCO_2$/yr under NDC_LTT. This early-stage reduction reflects the impact of short-term high-efficiency improvements and increased electrification. By 2050, the residential sector achieves even more substantial reductions: emissions decrease by 94.4% under CP_EI and 95.5% under NDC_LTT, compared to 2016 levels.

The commercial sector follows a similar trajectory but at a slightly slower pace. In 2030, emissions are reduced by 45.6% under CP_EI and 44.9% under NDC_LTT, levels similar to the residential sector, indicating early adoption of energy-saving technologies and electrification of heating and cooling loads in commercial buildings. However, by 2050, emissions decline by 81.2% in the CP_EI scenario and by 86.1% under NDC_LTT, reaching 28 $MtCO_2$/yr and 20.7 $MtCO_2$/yr, respectively. The slower decline compared to the residential sector, show higher retrofit complexity and capital intensity in commercial buildings stock.

Across both sectors, the results show that CO_2 emissions can be reduced by 81–96% by 2050 compared to 2016 levels. The convergence of outcomes in the residential sector between the two scenarios suggests a strong influence of structural decarbonisation drivers, such as the widespread adoption of heat pumps, electrification, and improved building standards. In contrast, the greater divergence in the commercial sector indicates that achieving deeper emissions reductions there may require more targeted and ambitious measures, including tailored retrofitting strategies for diverse building typologies and stricter building performance regulations for commercial real estate.

Table 26. CO_2 emissions (in $MtCO_2$/yr) and changes in CO_2 emissions (%) from the residential and the commercial sectors in 2030 and 2050 in the EU-27+UK region, compared to the 2016 levels, under the "CP_EI" and the "NDC_LTT" scenarios. Results are derived from Aalto-EU-TIMES.

CO_2 emissions ($MtCO_2$/yr) & Changes (%) compared to the 2016 levels				
	"CP-EI"		**"NDC-LTT"**	
	2030	**2050**	**2030**	**2050**
Residential	199.8 (44.8%)	20.3 (94.4%)	196.7 (45.7%)	16.1 (95.5%)
Commercial	81.2 (45.6%)	28 (81.2%)	82.3 (44.9%)	20.7 (86.1%)

6.5.5 Deep dive in the residential sector's energy transition in the EU-27 plus the UK region

Simulation results confirm more than a doubling in the share of electricity in the final energy consumption in the residential sector across EU-27 plus the UK from 2016 to 2050 (**Fig. 30a**). The share grows from 24.6% in 2016 to 55% in 2050, with the largest increase taking place during the decade 2030-2040. This increase is driven by the EU's climate policies and targets, including electrification of heating and cooking, growing use of electric appliances, and the shift to cleaner electricity while fossil fuels are being phased out. This trend is reinforced by the decarbonisation of the power sector and the implementation of EU-wide building renovation strategies under the "Fit-for-55" policy package.

Electrification leads to a corresponding decline in households' use of fossil fuels, which by mid-century accounts for only a minor share of the final energy consumption in most countries' residential sector. In 2016, natural gas, heating oil, liquified petroleum gas (LPG), and coal cover 37.5%, 7.2%, 5.2%, and 3.2% of the residential fuel basket, respectively. Coal is phased out before 2035 due to regulatory bans and declining economic viability, heating oil and LPG are phased out before 2040 and by 2050, respectively, as a result of fuel-switching incentives, while natural gas covers 6.5% of households' energy mix by 2050 mostly in legacy systems or hybrid heating configurations, highlighting the need for targeted phase-out policies and infrastructure repurposing.

- **Key finding**: By 2050, nearly half (13 out of 28) of the European countries under study (EU-27 plus the UK) surpass the 50% electrification threshold in their households' fuel basket, while biomass emerges as the second most consumed fuel across the region, accounting for 30.4% of the residential energy mix.

Residential sector's CO_2 emissions fall sharply in parallel with electrification and the phase-out of fossil fuels (**Fig. 30b**). From 2016 to 2050, households' emissions decrease by 94.4%, also reflecting the lower overall energy use due to significant gain from energy-efficiency measures, i.e., the total final energy consumption is reduced by 50.5% from 2016 (11.2 PJ) to 2050 (5.5 PJ). The latter highlights that sectoral emissions reduction is not only a function of switching fuels but also of achieving energy savings through improving the EU buildings' performance.

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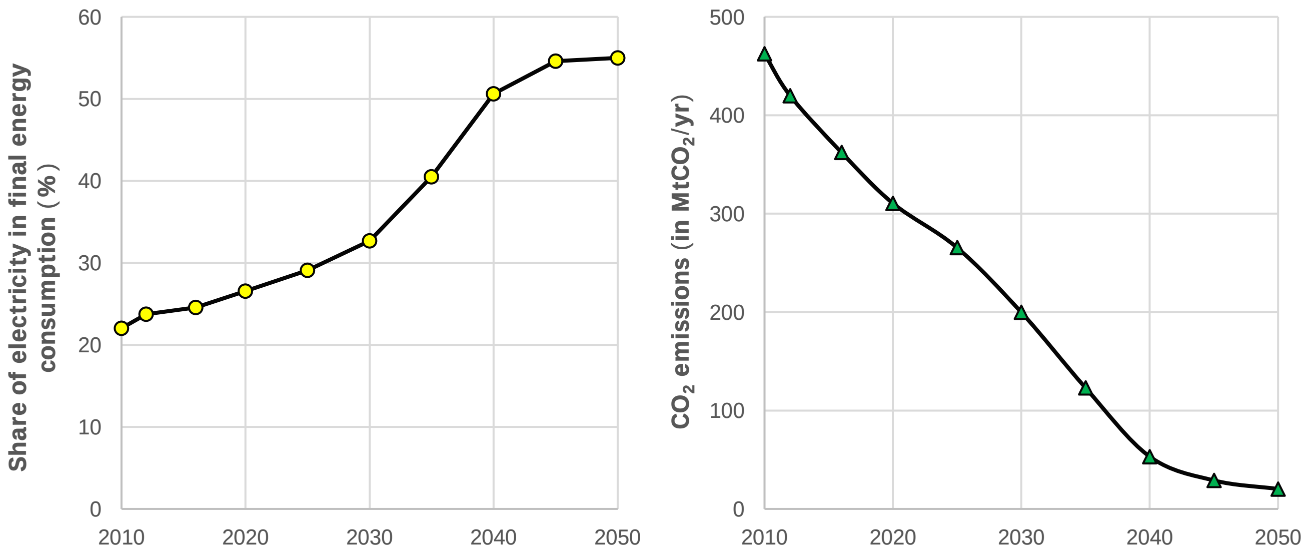

Fig. 30. (**a**)**.** Share of electricity in the residential sector's final energy consumption (%) in the EU-27 plus the UK, under the "CP-EI" scenario. (**b**)**.** CO_2 emissions (in $MtCO_2/yr$) in the residential sector in the EU-27 plus the UK, under the "CP-EI" scenario. Results are derived from Aalto-EU-TIMES.

6.5.6 Demand-side flexibility impacts on the European energy system

The simulations of the "Smart Energy Europe 2050" and the "Baseline 2050" scenarios indicate significant potential for increasing system efficiency and thus reducing total fuel consumption in the European energy system, as illustrated in **Figure 31**. This figure presents total fuel savings compared to the reference scenario with 0% flexibility in the residential, industrial, and EV electricity demands. These fuel savings mainly occur as a result of reduced power plant operation, particularly gas and coal, due to increased utilisation of VRE and reduced curtailment. This saves fuel that would otherwise have been used for the operation of the power plants and increases the utilisation of the systems VRE technologies. The total fuel savings achieved amount to upwards 660 TWh (5.8% of total energy demand), in the "Smart Energy Europe 2050" scenario and 200 TWh (1.6% of total energy demand) in the "Baseline 2050" scenario.

The potential for achieving fuel savings depend on several factors and energy system characteristics. Firstly, perhaps not surprisingly, a prerequisite is a substantial flexible electricity demand, i.e., demand that can be shifted in time. This is further underlined when also including the EV electricity demand as potential flexible demand in addition to the residential and industrial electricity demand, where the potential fuel savings increase both in the "Smart Energy Europe 2050" and "Baseline 2050" scenarios. The results demonstrate that while it is naturally preferable to have the freedom to shift demands over longer time horizons, i.e., 1 week is better than 1 day, and 4 weeks even more so, most of the energy savings can be achieved with only 1 day flexibility or 1 week flexibility. Having demand that is flexible over a 4-week period is only a marginal improvement compared to 1 week. Also, in all scenarios it is seen how most of the potential is realised at only 30% implementation of flexible demand which underscores the non-linear relationship between flexibility penetration and system benefits. In other words, the earlier amount of flexible demand is much more impactful than later further additions.

Secondly, the potential for fuel savings depends on the energy system having substantial installed VRE capacities. A system dominated by power plants, that are easily regulated up and down will have limited benefits from flexibility on the demand side, while on the contrary, a system with large VRE capacities such as wind and solar will have significant benefits from any source of flexibility as this will allow for improved utilisation of the variable resources. This is also demonstrated in these results, where the "Smart Energy Europe 2050" scenario has large VRE capacities installed, while the "Baseline 2050" scenario relies much less on renewable energy and more so on traditional power plants and nuclear energy.

Finally, the realised fuel savings depend on the extent to which other means of flexibility, either on the supply or

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demand side, exist in the energy system. This could be large power-to-heat capacities such as electric boilers and heat pumps coupled with thermal storage in district heating, or electrolysis capacity, which are both present in large scale in the "Smart Energy Europe 2050" scenario, thus limiting the effect of further flexibility measures, as implemented in this analysis on the demand side in the residential, industrial, and EV sectors.

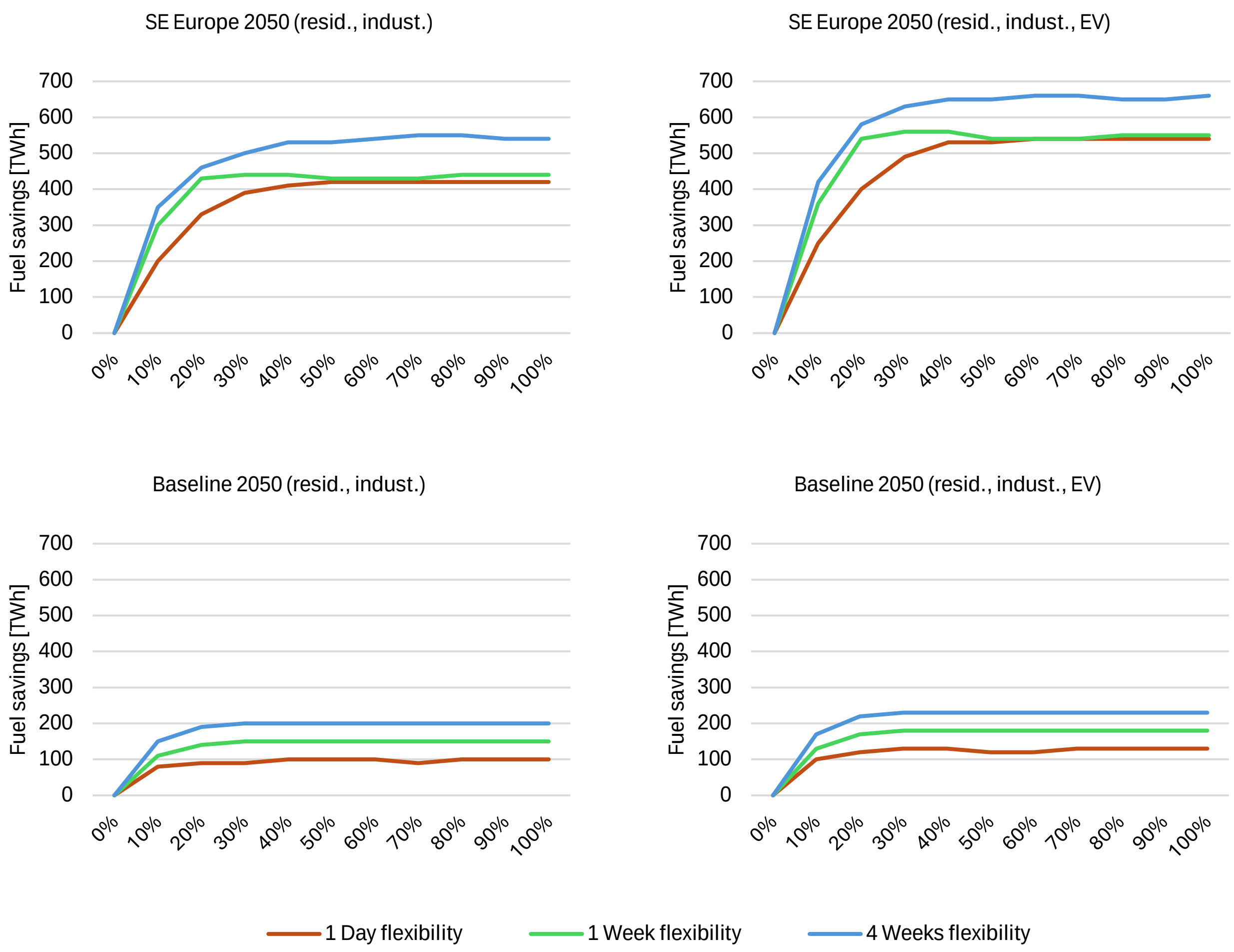

Figure 31. Total fuel savings in "Smart Energy Europe 2050" and "Baseline 2050" scenarios with increasing flexible demand.

Figure 32 illustrates the total cost savings achieved in the energy system through the implementation of flexible electricity demands. The most substantial savings are observed in the "Smart Energy Europe 2050" scenario with a 4-week flexibility window, which aligns with the scenario's highest fuel savings, fuel costs being the primary driver of total system cost reductions. In this scenario, total system costs amount to €1976 billion, including cost savings of €24 billion (1.2% of the total system cost). In the "Baseline 2050" scenario, total system costs amount to €2019 billion, including savings of approximately €8 billion (0.4% of the total system cost).

It is important to note that the supply side of the energy system remains unchanged across all simulations; the installed capacities of power plants and VRE technologies are held constant. However, increased system flexibility, particularly on the demand side, could enable strategic adjustments to the supply side. For instance, reduced reliance on dispatchable power plants could lower the need for backup capacity, while enhanced flexibility could support higher shares of VRE integration. These changes could further reduce both investment and operational costs, thereby amplifying the overall cost savings.

Nonetheless, such adjustments must be approached with caution. Reducing dispatchable generation capacity may compromise system security and resilience, especially in the face of unforeseen events, emergencies, or extreme weather conditions. While the system may appear technically feasible under the conditions of a single reference year, long-term reliability and robustness must be carefully considered in future planning.

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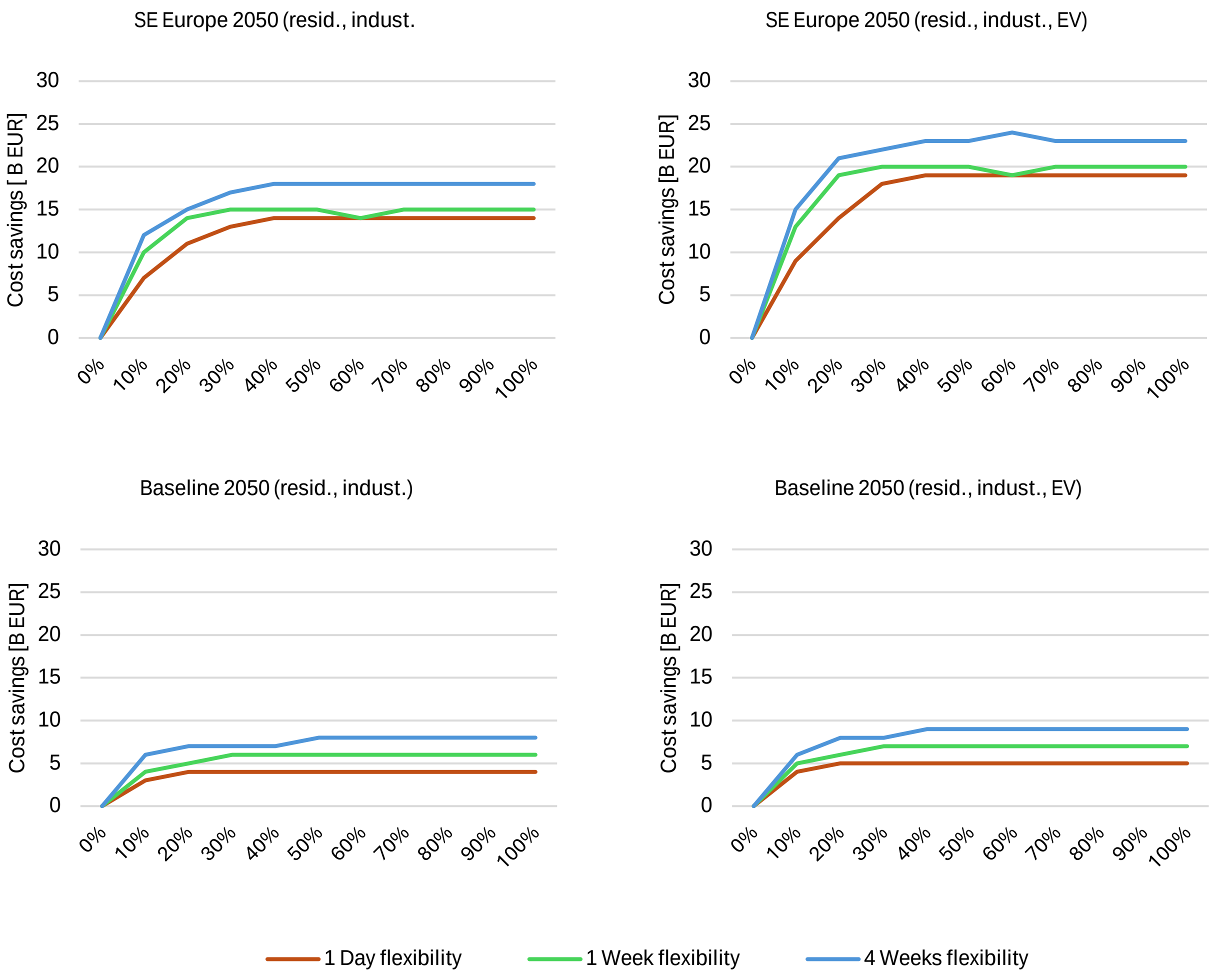

Figure 32. Total cost savings in "Smart Energy Europe 2050" and "Baseline 2050" scenarios with increasing flexible demand.

In EnergyPLAN, *Critical Excess Electricity Production* (CEEP) refers to electricity generated within the system that cannot be utilised domestically or exported. This typically arises from surplus production by VRE sources such as wind and solar. In a real-world energy system, such excess electricity would generally be curtailed to maintain grid stability and prevent frequency imbalances. Therefore, CEEP serves as an indicator of a system's ability to effectively integrate VRE.

High levels of CEEP suggest either limited system flexibility or an overcapacity of VRE relative to the system's ability to absorb and distribute it. **Figure 33** presents the CEEP levels across the simulated energy system scenarios. The most significant reductions in CEEP are observed in the "Smart Energy Europe 2050" scenario, indicating improved system efficiency through enhanced VRE integration. However, these reductions should be interpreted in the context of the scenario's substantially higher installed VRE capacity, which inherently increases both the potential for excess production and the opportunity for flexible demand to mitigate it.

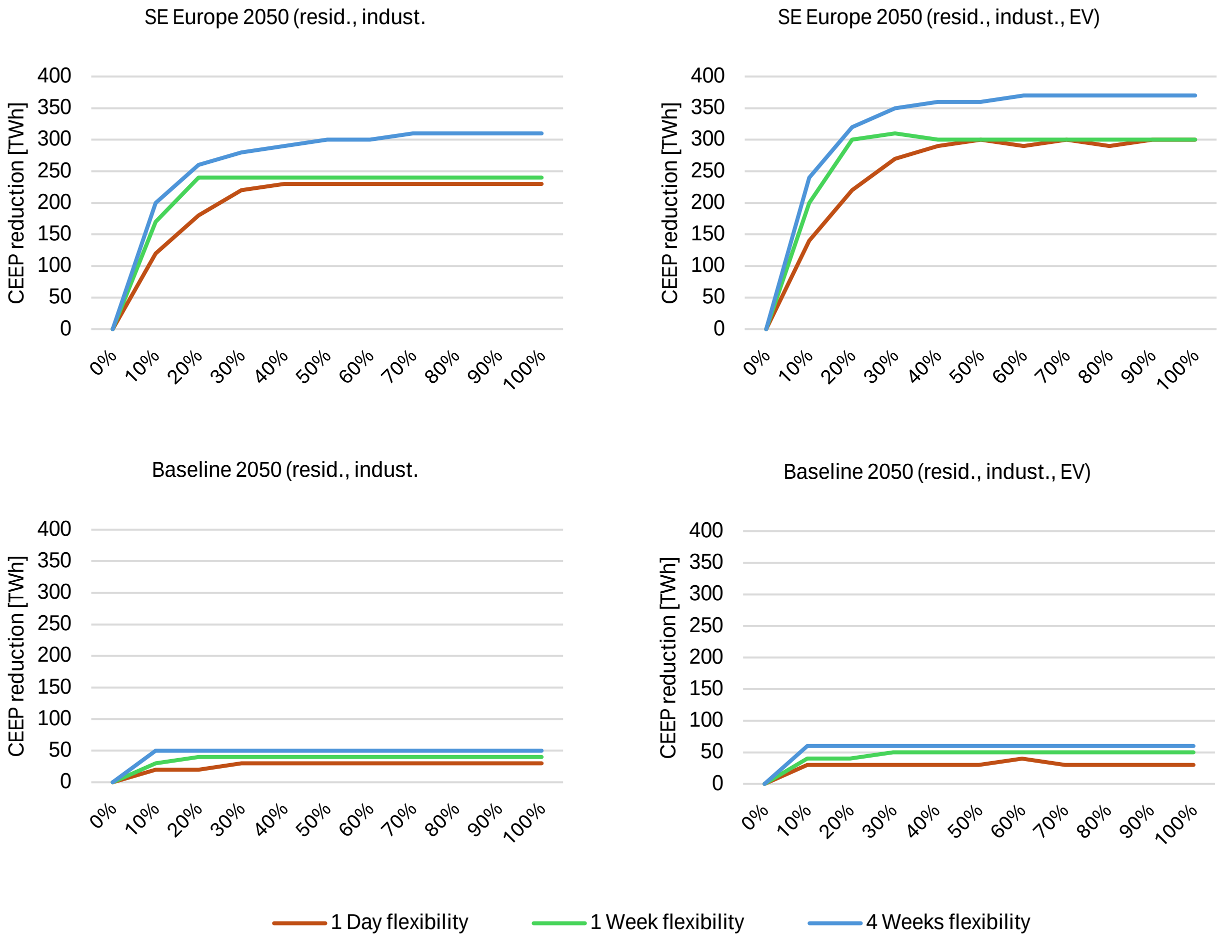

Figure 33. Reduction of Critical excess electricity production (CEEP) in "Smart Energy Europe 2050" and "Baseline 2050 scenarios" with increasing flexible demand.

Figure 34 and **Figure 35** depict the hourly operation of the simulated energy systems during the first week of January for both the "Smart Energy Europe 2050" and "Baseline 2050" scenarios. Each scenario is shown under two conditions: with 0% flexible demand and with 100% flexible demand over a 4-week horizon, considering residential, industrial, and EV electricity demands.

As illustrated, the "Baseline 2050" scenario exhibits a generally lower electricity demand, reflecting its lower level of electrification and, consequently, reduced total electricity consumption. This scenario also relies more heavily on dispatchable electricity generation, such as conventional power plants, CHP units, and nuclear energy, and features a comparatively smaller installed VRE capacity.

In both scenarios, EnergyPLAN shifts electricity consumption to align with periods of high VRE generation, primarily coinciding with periods of PV production. However, due to the significantly larger VRE capacity in the "Smart Energy Europe 2050" scenario, this system is better equipped to take advantage of demand-side flexibility. Conversely, during periods of low VRE output, electricity consumption is minimised wherever possible to reduce reliance on dispatchable generation.

The result, as shown for the example week, display remarkable contrast in system operation. The "Baseline 2050" scenario continues to rely substantially on power plants, CHP units, and nuclear energy, while the "Smart Energy Europe 2050" scenario avoids their use entirely during the same period. This outcome highlights the combined impact of high VRE penetration and demand-side flexibility (alongside other supply side flexibility measures) in enhancing system efficiency and reducing reliance on conventional generation.

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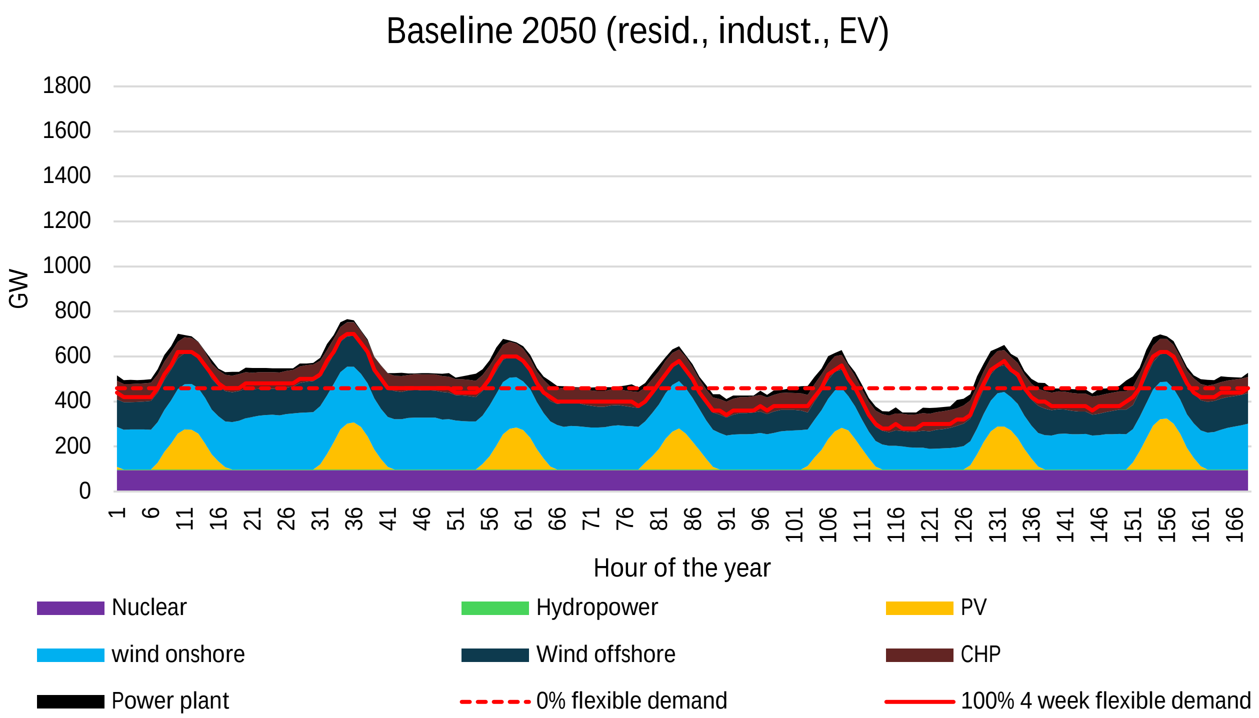

Figure 34: Temporal distribution of electricity demand and production for the first week of January in the "Baseline 2050" scenario with 0% and 100% 4-week flexible electricity demand.

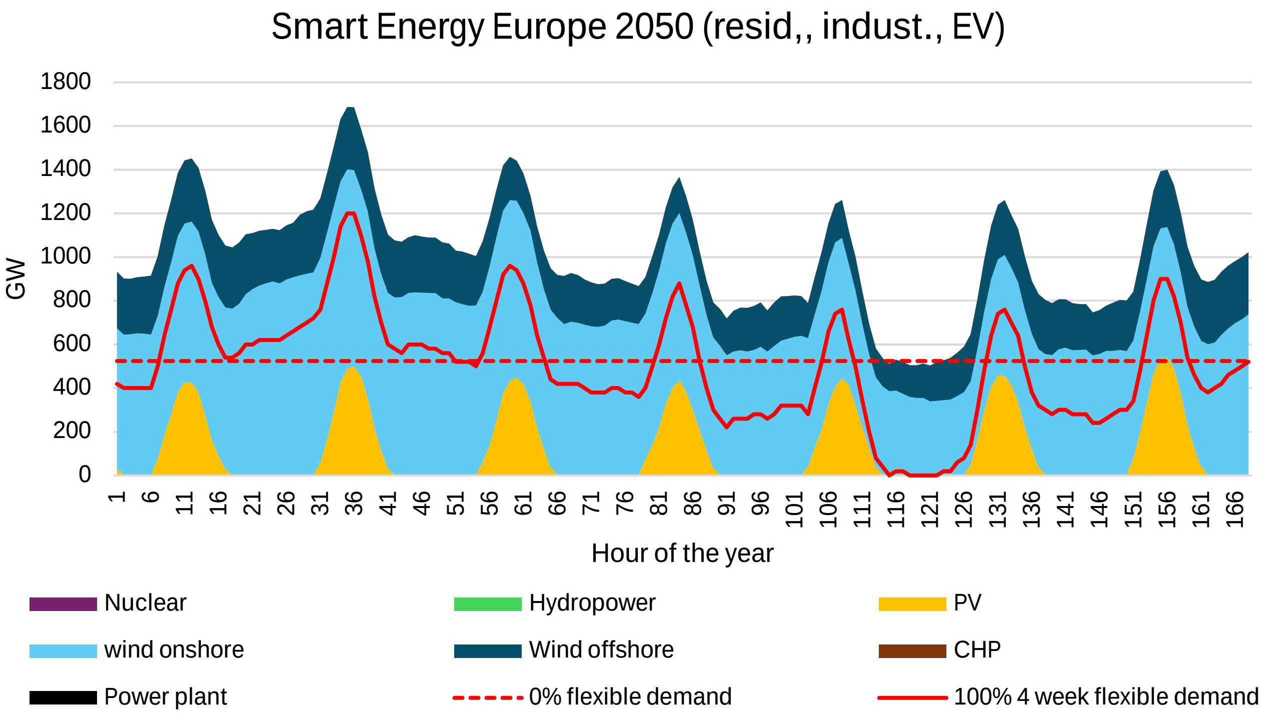

Figure 35: Temporal distribution of electricity demand and production for the first week of January in the "Smart Energy Europe 2050" scenario with 0% and 100% 4-week flexible electricity demand.

The results highlight the significant potential of demand-side flexibility from a system-wide perspective. Technically, such flexibility enables improved energy efficiency by enhancing the integration of VRE and reducing reliance on dispatchable generation. Economically, it contributes to notable reductions in total system costs, primarily through fuel savings and more efficient utilisation of existing infrastructure.

However, when viewed in the context of the large-scale energy system modelled, covering the EU-27 plus the UK, the overall impact of demand-side flexibility is relatively modest, with fuel savings reaching up to approximately 6% of total energy demand in the most ambitious scenario. This underscores the importance of complementing demand-side measures with other forms of system flexibility.

Large-scale energy storage, district heating systems, and PtX technologies such as electrolysis play equally, if not more, critical roles. These technologies offer substantial flexible energy consumption and storage capacities, which are essential for balancing supply and demand in systems with high shares of VRE. In particular, their ability to absorb excess electricity and provide sector coupling opportunities makes them critical for achieving deeper decarbonisation and long-term energy system resilience.

In conclusion, while demand-side flexibility is a valuable and necessary component of a future sustainable energy system, it should be viewed as part of a broader portfolio of flexibility solutions. Maximising system efficiency and cost-effectiveness will require an integrated approach that leverages the synergies between flexible demand, VRE deployment, and complementary technologies across all sectors of the energy system.

6.6 National scale

6.6.1 India

6.6.1.1 Context

Temperatures have been steadily rising in India, bringing the onset of summer forward by at least one month, combined with more frequent and intense heatwaves. From 1981 to 2022, heat extremes in India have increased linearly, contributing to major heatwaves over the last decade (Prabhu & et al., 2025). The El Niño-year 2023 saw multiple heatwaves, starting with the hottest February on record in the country (BBC News India, 2023), while average mean and maximum temperatures in August were the hottest ever recorded due to large rainfall deficiency and weak monsoon (Euractiv, 2023). About 57% of Indian districts, home to 76% of the country's population, are currently at high to very high risk from extreme heat (Prabhu & et al., 2025). Many heat-exposed and vulnerable sections of the community, with limited ability to stay indoors and access cooling, make up over half of the country's labour force employed in sectors such as agriculture, mining, and construction (IEA, 2023b).

More frequent and prolonged heatwaves, such as those experienced in northern India in 2023, have highlighted the growing importance of efficient cooling and thermal comfort, priorities emphasised under India's G20 presidency in the G20 Voluntary Action Plan and Strategic Plan for Advancing Energy Efficiency Across Demand Sectors by 2030 (Bureau of Energy Efficiency, 2023b). This global focus was expected to continue at 'Cool COP28' in Dubai, with the introduction of a Global Cooling Pledge (UNEP & Cool Coalition, 2023). However, India has not signed the pledge to reduce cooling-related emissions at COP28, citing the need to ensure affordable cooling for its population, the largest in the world (UNEP & Cool Coalition, 2024). The pledge aims to cut cooling-related CO_2 emissions by at least 68% by 2050 compared to 2022 levels. It should be noted that India's climate policies have saved 0.44 $GtCO_2$ from 2015 to 2020 and are projected to save in total 3.95 $GtCO_2$ during 2020-2030, 22.67 $GtCO_2$ during 2030-2050, and 44.07 $GtCO_2$ during 2050-2070 (Chaturvedi et al., 2024).

Supported by rapid economic expansion and increasing electrification, electricity demand in India grew 5.8% y-o-y in 2024 amid strong economic growth (IEA, 2025). While good interconnections among states and the operation of thermal power plants allow Indian utilities to cover demand in energy terms throughout the year, more frequent and prolonged heatwaves are thus placing immense pressure on electricity grids by driving up peak demand for cooling (IEA, 2025). These, without adequate demand-side management, can lead to power outages, leaving people without the ability to restore healthy levels of thermal comfort and to keep food and medicines at appropriate temperatures (IEA, 2023b). Peak electricity load in India has shown strong growth in recent years, rising from 148 GW in 2014 to 250 GW (+68%) in 2024, led higher by the rapid expansion of its

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industry, development of agriculture, enhanced electricity access and increased use of air conditioning and appliances in the residential and commercial sectors. As a result, electricity demand in these sectors rose by around 60-65% between 2014 and 2024. Under current policy conditions, peak electricity demand is expected to rise around 60% from 2022 levels by 2030, with cooling will account for almost half of this increase (IEA, 2023b).

Together, the building and construction sectors are responsible for nearly one-third of India's greenhouse gas emissions, stemming from both operational energy use and embodied emissions in materials and construction processes (Al Khourdajie et al., 2025). As such, decarbonising these sectors is essential for India's transition to a net zero future. Specifically, India's building sector accounts for 33% of total final energy consumption, with demand projected to increase by approximately 8% annually. This demand growth is driven by factors such as rising housing needs, increased ownership of household appliances, greater access to modern cooking fuels, and, notably, the surge in space cooling demand, which has become a major driver of peak electricity load in the country (IEA, 2023f). Although access to air conditioning remains relatively low, ownership is growing rapidly. Prior to 2019, only 1 in 10 households owned an air conditioner (Ministry of Environment Forest & Climate Change of India, 2019), but by 2021, 24% of households had acquired either an evaporative cooler or an air conditioner (Ministry of Health and Family Welfare of India, 2022).

Electricity consumption due to space cooling increased 21% between 2019 and 2022, and in 2023 nearly 10% of electricity demand came from space cooling requirements (IEA, 2023i). Even though less than 20% of households in India are equipped with an air conditioner, the contribution of cooling to total peak load is estimated at 60 GW in 2024, as sales reached a new record of 14 million AC units sold in 2024 (IEA, 2024). This is 27% more than in 2023, when 11 million units were sold. By 2030, cooling equipment is expected to contribute one-third to the peak electricity load in India, potentially reaching 140 GW (IEA, 2023i). This would be more in line with trends in advanced economies such as the United States, where cooling demand currently takes 50% of total peak load on the warmest days in Texas. Data shows that for each incremental degree in daily average temperature, daily peak demand in India increased by more than 7 GW in 2024, twice the increase observed in 2019. By 2027, this value could surpass 11 GW per degree (IEA, 2025), while data on daily electricity loads in the summer months of May and June 2023 showed that every 1°C increase in the average daily temperature above 24°C drives a 2% rise in electricity demand (IEA, 2023f).

Several demand response programmes are currently being piloted to reduce peak demand. Tata Power Delhi Distribution and Auto Grid launched a pioneering AIenabled smart energy management system focusing on the behavioural demand response for residential customers in Delhi in 2021, which was expanded to Mumbai in 2023. It aims to engage 55,000 residential consumers and 6,000 large commercial and industrial customers to achieve up to 200 MW of peak capacity reduction by 2025 (IEA, 2023b). Flagship programmes of India's Bureau of Energy Efficiency under the Ministry of Power, including Standards and Labelling (S&L) of appliances, the Energy Conservation Building Code (ECBC), and Eco-Niwas Samhita (ENS), are instrumental in managing rising energy demand in India (IEA, 2023b). A mandatory S&L programme for air conditioners has been in place since 2009, requiring a 24°C default temperature setting for all room air conditioners since 2020 as an important measure to induce behaviour change. MEPS and labels for air conditioners now cover 100% of residential space cooling consumption, up from only 37% in 2009 (IEA, 2023b).

6.6.1.2 Stakeholder feedback

The workshop underscored the pivotal role of the building sector in achieving India's Net Zero 2070 target. Key recommendations emerging from the discussions included the need to strengthen policy frameworks, advance green building practices, enhance financial mechanisms, and promote cross-sector collaboration. Participants emphasised the importance of resource efficiency, the acceleration of retrofitting efforts, and the adoption of effective demand-side management strategies. A strong sense of urgency was expressed regarding the rising energy demand in the building sector, highlighting the need for closer collaboration between government, industry stakeholders, and the construction sector. Such collaboration is essential to address persistent challenges around the deployment of energy-efficient appliances and to ensure the development of sustainable, low-carbon building solutions. Additionally, several stakeholders pointed to a significant policy gap, both in the design and

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implementation of decarbonisation strategies for the building sector. This was identified as a major barrier to progress. Furthermore, participants noted a lack of scientific and peer-reviewed literature on net zero pathways for India's residential buildings, underlining the need for more targeted research to inform action toward the country's updated NDC commitments to the UNFCCC by 2030.

6.6.1.3 Scenario design and model parameterisation

India has a target to be a developed nation by 2047 and is committed to be net zero by 2070. The building sector in India consumes more than 30% of the total electricity generation, 38% of primary energy use, and is one of the major contributors to GHG emissions at 25% (including direct (5-7%) and indirect emissions from electricity). The current building stock consists of around 80% residential and 20% commercial space. Its floor area is projected to increase more than 2.5 times, i.e., from 16 billion m^2 in 2015 to 58 billion m^2 in 2050. The increase in floor space will add to its current stock of air conditioners from 30 million units in 2018 to 240 million units in 2030 and more than 1,100 million units in 2050. This will offer emerging opportunities to leapfrog to advanced building energy codes. In this case, providing thermal comfort and reliable electricity to all citizens in India will be a key challenge which will require technological solutions such as net-zero buildings, low-energy cooling innovations, smart appliances, and energy-efficient technologies (Bureau of Energy Efficiency, 2023a).

The model application will focus on estimating the energy demand and associated CO_2 emissions from the buildings sector in India and the additional energy demand required due to the policies of the India's Cooling Action Plan (2017-18). It is assumed that India's population will increase by 328 million in 2027 and 386 million in 2037, with the share of households owning air conditioners expected to rise from 21% in 2027–28 to 40% in 2037–38, highlighting a significant surge in future space cooling demand. Two scenarios have been developed based on feedback received from stakeholder engagement workshop in India:

- **Baseline/Business as Usual (BAU) scenario**: BAU scenario assumes the continuation of policies or measures implemented before 2015. It is not intended to be a prediction of the future, but rather a counterfactual construction that can serve to highlight the level of emissions that would occur without further policy effort.
- **Net Zero scenario (NZS)**: The NZS scenario captures the planned policies (including updated NDC) and ratcheted implemented policies in addition to the policies mentioned in India's LTS. Both ambitions and pledges are considered in this scenario. Specifically, NZS focuses on increasing the share of energy-efficient appliances, i.e., super-efficient air conditioners, energy-efficient ceiling fans, LED lights, clean cooking appliances, other energy-efficient appliances, etc. in the buildings sector of India.

6.6.1.4 Results

Figure 36 shows direct CO_2 emissions from each of the energy sectors (i.e., power, industry, transport, buildings, and agriculture) in BAU and NZS, covering the period from 2020 to 2070. Under the BAU scenario, total emissions rise steadily from approximately 2 $GtCO_2$/yr in 2020 to a peak of more than 5 $GtCO_2$/yr by 2050. Following the peak, emissions decline only modestly, remaining at ~4.5 $GtCO_2$/yr through 2070. The power sector is the largest contributor throughout the period, followed closely by industry, both of which experience sustained emissions across the 50-year span. Emissions from the transport and buildings sectors grow moderately but do not dominate the overall profile. Agricultural emissions, while relatively stable, remain persistent and represent a consistent baseline of emissions under BAU.

In contrast, the NZS envisions a significant transformation of the energy system, with total CO_2 emissions peaking around 2050 at more than 4 $GtCO_2$/yr and then rapidly declining to ~1 Gt CO_2/yr by 2070. The largest reductions are observed in the power sector, which reaches near-zero emissions between 2050 and 2060. Emissions from industry, transport, and buildings also decrease substantially during the same period, reflecting improvements in energy efficiency, electrification, and clean fuel adoption. The buildings sector (including residential and commercial sectors) emissions achieves the largest percentage reduction among all end-use sectors. In fact, residential sector achieves net zero; however, residual emissions from the commercial sector were observed in

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the NZS. Notably, agriculture remains the primary source of residual emissions post-2060, while, by 2070, agricultural emissions are almost half of the remaining CO_2 emissions under the NZS.

The comparison of these two pathways illustrates the impact of policy ambition on sectoral emissions. While the BAU scenario locks in high emissions well beyond mid-century, the NZS scenario demonstrates that deep decarbonisation is achievable, especially in the power, industrial, and residential sectors, if transformative actions are taken.

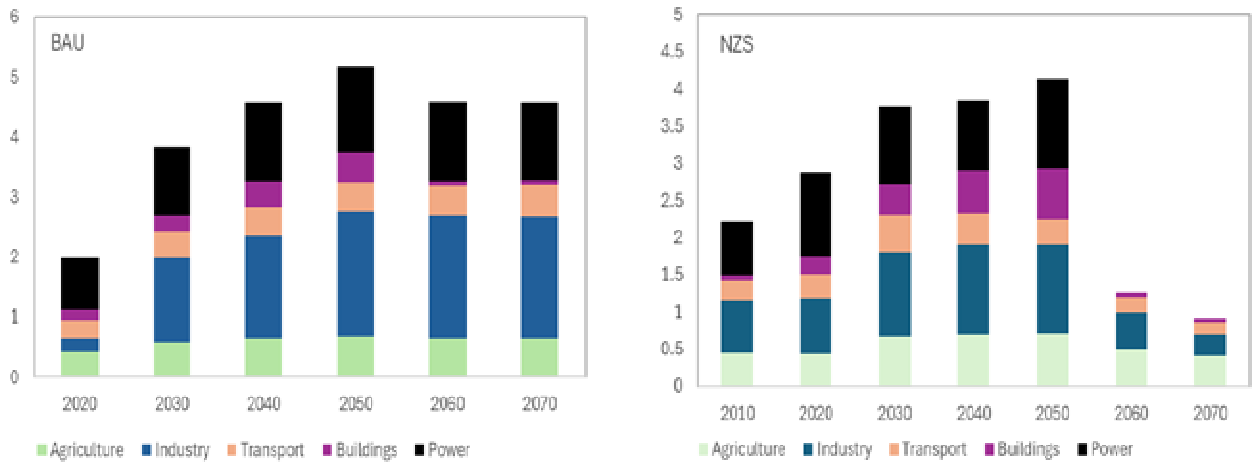

Figure 36. CO_2 emissions (in $GtCO_2$/yr) across energy sectors for the BAU and NZS scenarios between 2020 and 2070.

Figure 37 provides the evolution of buildings' energy demand by fuel type between 2020 and 2070 under the BAU and the NZS scenarios.

Under the BAU scenario, total energy demand in buildings increases steadily through mid-century, reaching a peak of approximately 14 EJ/yr by 2050. This rise is primarily driven by a sharp increase in the consumption of electricity, especially by 2050, which becomes the dominant energy carrier. Biomass maintains a relatively stable share, while oil and gas continue to contribute significantly, especially between 2040 and 2050. Although total energy demand declines after 2050, phasing biomass and natural gas out of the buildings energy mix, oil remains embedded in it until 2070, due to the LPG distribution in the systems.

The NZS scenario shows a similar growth trajectory in total demand through 2050, but with a different composition. Electricity again emerges as the dominant energy source, but with much lower shares of fossil fuels, since biomass retains a consistently larger share in the fuel basket by 2050, serving as a transitional or complementary energy source. By 2070, biomass and gas are phased out and oil consumption declines substantially, highlighting a clear shift toward clean electrification and energy-efficient technologies.

Despite comparable levels of total energy use in both scenarios, the NZS scenario achieves higher CO_2 reductions by altering the structure of energy demand, rather than just reducing overall demand. It should be noted that energy consumption in the residential sector is determined by the behaviour of households, the ownership of various assets and appliances, and the amount of energy used by each appliance, while energy consumption in the commercial sector depends on the evolution of floor space. In the BAU scenario, the rate of ownership of electric, cooling, and heating appliances is increased due to rapid urbanisation and rising household incomes. In the NZS scenario, increased technical efficiencies, energy efficiency, and building improvements lead to a slight decrease in energy demand in 2070 when compared with the BAU scenario.

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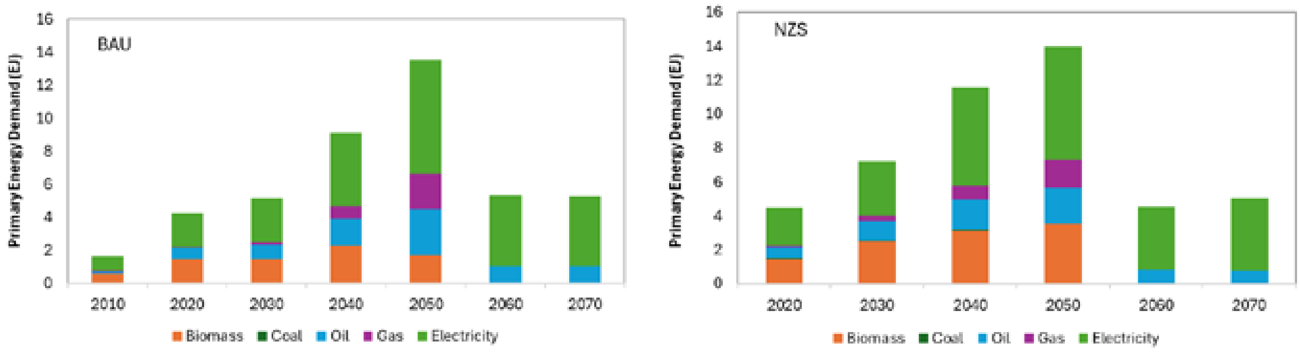

Figure 37. Building energy demand (in EJ/yr) for the BAU and NZS scenarios between 2020 and 2070.

6.7 European Union plus the United Kingdom

Despite the shared regional targets, the European countries under study (EU-27 plus the UK) follow distinct transition pathways due to differences in economic conditions, starting points in the energy transition, and policy ambition levels.

6.7.1 Context

In several regions in Europe, particularly the Nordic European countries, heat pumps already hold a considerable market share due to their favourable total life-cycle cost (Wemhoener, 2016); in Norway, for example, 60% of buildings are equipped with heat pumps (IEA, 2022h), with Sweden (Jonasson, 2019) and Finland (Hirvonen, 2021) exceeding 40%, undercutting the argument that heat pumps are unsuitable for cold climates; France has also seen significant adoption (Durier, 2023).

Russia's invasion of Ukraine accelerated the adoption of heat pumps across the EU, as surging natural gas and electricity prices prompted consumers to shift towards more energy-efficient heating technologies. In response to the energy crisis, the EC announced in 2022 its intention to double the deployment rate of heat pumps (European Commission, 2022), as initially proposed in the IEA's 10-Point Plan to Reduce the EU's Reliance on Russian Natural Gas (IEA, 2022a). As a result, nearly 3 million heat pumps were sold across Europe that year, an increase of almost 40% compared to 2021 (IEA, 2023d). The EU market grew by approximately 35%, with countries such as Poland, the Netherlands, Italy, and Austria recording sales in the first half of 2022 that were roughly double those of the same period in the previous year (IEA, 2022h). Emerging markets like Poland and the Czech Republic saw their markets double in size, while Italy, France, and Germany together accounted for nearly half of all the European heat pump sales. In the Nordic countries, where heat pumps are an already well-established heating solution, nearly five times as many units were sold per household compared to the rest of the Europe (IEA, 2023d).

Strong sales growth continued into the first half of 2023, with heat pump sales rising by 75% in Germany, the Netherlands, and Sweden combined. However, a slowdown took place in other markets, including Italy, Finland, and Poland, where sales declined in 2023 (Azau, 2023). In light of this mixed outlook, the European Heat Pump Association (EHPA) has called for stable and consistent long-term policy frameworks to provide clarity for investors and consumers and to accelerate a green transition in the European residential sector (IEA, 2023b). According to the guidelines of the EPBD, several European countries have either implemented or announced bans on the installation of boilers powered exclusively by fossil fuels (IEA, 2023d). As of 2022, the UK, Norway, and seven EU countries, together responsible for 80% of Europe's residential gas use, had introduced or planned such bans for new or existing buildings (IEA, 2022b). In 2023, several governments clarified their phase-out timelines and minimum energy performance standards (MEPS) for heating systems, though others postponed their plans due to concerns over public acceptance and implementation challenges (IEA, 2023b).

In France, gas boiler installations have been banned in new buildings since 2022 and the government

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has considered to phase out gas boilers in existing buildings from 2026 onwards (French Ministry of Territorial Planning and Decentralisation, 2023). However, in September 2023 the French president ruled out a ban on gas boilers in existing buildings (Samuel, 2023). France also prohibits buildings with very low energy efficiency levels (above 450 kWh/m²) to be rented full-time (French Ministry of Territorial Planning and Decentralisation, 2024). Requirements will become more stringent with a prohibition to be rented long-term for buildings with Energy Performance Certificate (EPC) class G from 2025, class F from 2028 and class E from 2034 (IEA, 2023b). In France, heat pumps outsold fossil fuel boilers in buildings for the first time in 2022, coinciding with the first year of a national ban on gas boilers in new buildings. While demand for fossil fuel boilers is declining in other major European countries, they still have a higher market share than heat pumps (IEA, 2023d).

The German government has proposed that from 2024 onwards new heating systems in both new and existing buildings must run on at least 65% renewables (German Ministry for Economic Affairs and Energy, 2023a). After months of negotiations, the German parliament passed an amendment to this Buildings Energy Act, which sets the 2024 requirement only for buildings in new development areas, while for installations in all other new and existing buildings the deadline has been extended to 2026 in larger cities and 2028 elsewhere (German Ministry for Economic Affairs and Energy, 2023b). In Germany, there were twice as many fossil fuel boilers sold than heat pumps in 2022. At the same time, there are proposals to phase out the most polluting technologies and fuels.

The UK initially planned to ban new oil, LPG and gas boilers in new-built homes from 2026, and new gas boilers in existing buildings from 2035. However, these plans have been pushed back to 2035 and the ban on new gas boilers in existing properties will have 20% of households exempted (UK Government, 2023). The UK has directly linked efficiency and heating system performance through the Boiler Upgrade Scheme, a government financial incentive programme designed to promote the replacement of fossil fuel heating systems with a heat pump or biomass boiler.

The Netherlands has banned gas boiler installations in new buildings since 2018. In 2022, the Dutch government announced a new standard from 2026 requiring a (hybrid) heat pump to be installed in buildings when an existing gas boiler needs to be replaced (IEA, 2023b). The updated energy savings obligation mandates hybrid heat pumps for space heating for businesses under certain conditions from 2023 (Netherlands Enterprise Agency, 2024).

The Danish government has had a ban on gas and oil boilers in new buildings in place since 2013 and plans to replace all fossil fuel boilers by 2029 through district heating and heat pumps (IEA, 2023b).

Luxembourg announced a phase-out of fossil heating when replacing an existing boiler as well, but initially on a voluntary basis (Luxemburg's Ministry of the Environment Climate and Biodiversity, 2024).

6.7.2 Stakeholder feedback

During the stakeholder workshop, participants emphasised that Member States must prioritise decarbonisation in heating and cooling systems by applying the Energy Efficiency First (EE1st) principle as a means to accelerate the phase-out of fossil fuels by 2040. Achieving this will require a clear focus on deep retrofitting and the transition to net zero buildings to ensure climate neutrality by 2050.

Stakeholders also stressed the importance of integrating insights from NECPs, which offer clarity on Member States' 2030 interim targets, even if they are less detailed regarding 2050 climate neutrality goals. These intermediate milestones are seen as crucial for assessing progress and aligning national policies with longer-term decarbonisation pathways.

The complex role of EU policymaking and funding mechanisms was also discussed, particularly the challenges faced by Distribution System Operators (DSOs). Many DSOs are small-scale, lack sufficient staff and access to finance, and operate at a local level where the actual implementation of grid investments occurs. This creates a mismatch between EU-level ambition and on-the-ground capacity. For example, grid congestion in the Netherlands was cited as a barrier to further PV deployment, underscoring the need to align European targets with local delivery capabilities.

Stakeholders stressed that national differences in electrification levels and building quality must be properly reflected in modelling scenarios. They noted significant regional variation in energy consumption profiles, such as the dominance of electricity in France and coal use in parts of Eastern Europe. These variations affect the pace and nature of the energy transition and should guide country-specific policy designs and projections.

When shaping national renovation pathways, stakeholders identified energy efficiency, renewable energy integration, and regulatory clarity as key factors. While the EPBD sets overall targets for Member States, it leaves flexibility on how these targets should be met, which can result in inconsistent national approaches. Additional focus is needed on skills development, public awareness, and education to ensure the workforce and society are prepared for the scale of renovations required.

Finally, participants emphasised the importance of accounting for the tenant-owner dynamic in assessing the renovation potential of the national pathways. Countries with a high share of rental housing, such as Germany, may face distinct challenges compared to those with higher owner-occupancy rates, influencing the adoption rate and depth of building renovations.

6.7.3 Scenario design and model parametrisation

For this modelling application, policies listed in the Climate Policy Database (van de Ven et al., 2024) including the recent updates related to the Emissions Trading System (ETS), Effort Sharing Regulation (ESR), share of renewables in final energy, energy efficiency, and Land Use, Land-Use Change, and Forestry (LULUCF) targets have been implemented (European Commission, 2021b). In this variant, Aalto-EU-TIMES uses the updated datasets for the costs of power generation, hydrogen production, and carbon capture, storage, and utilisation technologies (European Commission: Directorate-General for Mobility and Transport, Directorate-General for Climate Action, Directorate-General for Energy, De Vita, A., Capros, P. et al., 2021). Furthermore, PROMETHEUS provides Aalto-EU-TIMES with the information on global fuel prices and costs of power generation technologies. For the model harmonisation, the cost assumptions for EVs and heat pumps in Aalto-EU-TIMES are also updated to match the dataset used in PROMETHEUS (European Commission: Directorate-General for Mobility and Transport, Directorate-General for Climate Action, Directorate-General for Energy, De Vita, A., Capros, P. et al., 2021). We also harmonise the two models based on their final energy consumption in the buildings sector. To do so, since the demand assumptions of Aalto-EU-TIMES significantly differ from those of PROMETHEUS, we constrain the primary energy consumption from 2030 to 2050 for Aalto-EU-TIMES based on the corresponding values in the results from PROMETHEUS, using a linear interpolation. This constraint, along with the use of demand elasticity in Aalto-EU-TIMES, helps us to change the demands automatically and consequently harmonise the final energy consumption. As a result, a below 10% deviation for the final energy consumption is observed. We also ensured a high degree of consistency across historical emissions.

To evaluate energy transition pathways in the EU's residential sector based on current trends and policies in place, the "*Current Policy (CP)*" scenario is assessed. The CP scenario builds on the existing suite of emission-reduction measures and credible policy targets in place through 2030 across both EU and non-EU countries (European Commission, 2021b), assuming that, after 2030, climate policy ambition remains at its current level without further strengthening. Specifically, the annual rate of decline in CO_2 emissions per unit of GDP observed between 2020 and 2030 is projected to continue unchanged beyond 2030, in line with Sognnaes et al. (Sognnaes, Ida, 2021). To prevent any backsliding on progress achieved, all policy targets established for 2030 are retained as binding floors after 2030, ensuring that improvements in emissions' intensity realised during 2020-2030 remain the baseline for subsequent decades. The CP scenario has been implemented in both PROMETHEUS and Aalto-EU-TIMES, and the mentioned information has been exchanged between the models. Here, we analyse results from Aalto-EU-TIMES, as the model provides a granular, country-level representation of the residential sector in EU-27 plus the UK, capturing a wide range of heating, cooling, and other service technologies across different housing types.

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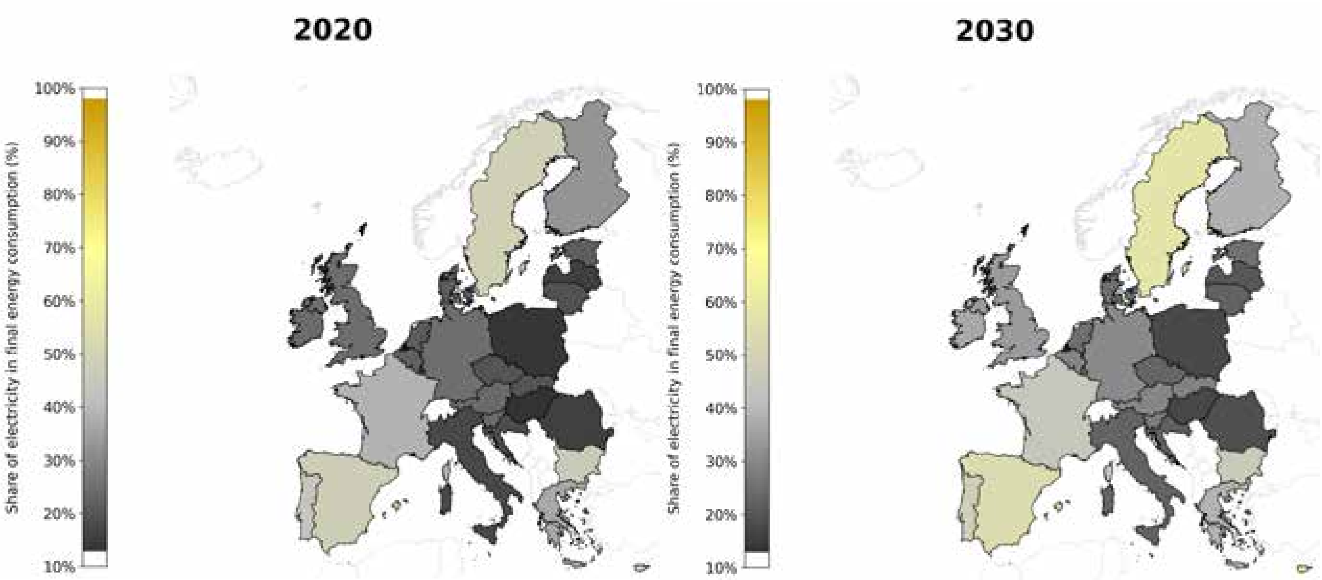
6.7.4 Results

6.7.5 Electrification rates by country

Because of these boundary conditions, the transition to electrification in the European residential sector follows different trajectories (**Figure 38**). *Electrification leaders* like **France**, **Portugal**, **Spain**, and **Sweden** attain a relatively high share of electricity in their households' fuel basket by 2030 (44%, 48%, 53%, and 58%, respectively). This increasing trend is further strengthened by 2050 for France, Portugal, and Spain (64%, 75%, and 69%, respectively), while the electrification trend in Sweden stabilises at around 58% between 2030 and 2050, due to increased gains from energy efficiency, which reduce total heating demand while electrification trends remain high. These countries benefit from established electric and biomass heating systems, or district heating systems in the case of **Sweden**. Their leadership in electrification is further underpinned by a combination of favourable policy environments, strong investment in renewable electricity infrastructure, and government incentives for clean heating technologies, such as heat pumps. In **Portugal** and **Spain**, the relatively mild climate significantly supports this transition: electric heating systems, particularly heat pumps, operate more efficiently and economically in warmer regions, where peak heating demand is lower and seasonal temperature fluctuations are less severe. Meanwhile, France leverages its low-carbon electricity mix, largely supplied by nuclear power, to advance clean heating, and Sweden builds on its mature district heating and biomass sectors as well as high energy-efficiency standards.

Fast adopters such as **the Netherlands**, **Germany**, **the UK**, and **Ireland** begin with lower electrification rates than the *electrification leaders* but are projected to make substantial gains, reaching 25%, 30%, 34%, and 37% in 2030, and 65%, 65%, 67%, 77% in 2050, respectively (**Figure 38**). Despite their lower baseline levels, stemming from an entrenched reliance on fossil fuels, such as natural gas, heating oil, LPG, and coal, which are all prevalent in the residential fuel baskets of **Germany**, **the UK**, and **Ireland**, *fast adopters* are making rapid progress, supported by a mix of regulatory reforms and targets. **The Netherlands** has taken a leading role by banning new gas connections in buildings and mandating hybrid heat pumps from 2026, supported by municipal-level heat transition plans. **Germany**'s Building Energy Act requires new heating systems installed to buildings in newly developed areas to source at least 65% of energy from renewables from 2024 onwards, complemented by federal support for local heat planning. **The UK** government has set an ambition to install 600,000 heat pumps per year by 2028, and to phase out the sale of most new fossil fuel boilers from 2035. Similarly, **Ireland** is providing policy support to replace fossil fuels in buildings, with a ban on the installation of new fossil fuel heating systems set to take effect after 2035.



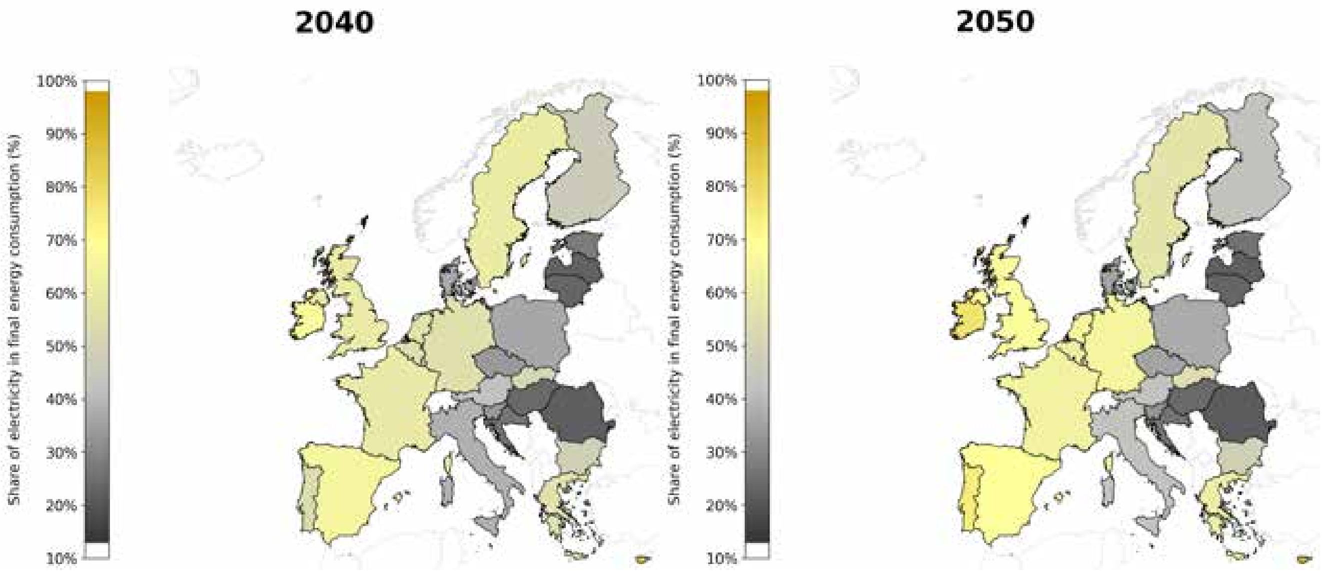


Figure 38. Share of electricity in the residential sector's final energy consumption (%) across the EU-27 plus the UK in 2020, 2030, 2040, and 2050, under the "Current Policy (CP)" scenario. Results are derived from Aalto-EU-TIMES.

While colder climates in these countries present additional challenges, such as higher peak heating demand and longer heating seasons, these are being addressed through expanding renewable electricity capacity, increased heat pump installations and improvements in their efficiency, and financial incentives to support household adoption. These efforts demonstrate a swift transition away from fossil-based heating, even in regions starting from a more carbon-intensive baseline.

Conversely, *slow adopters* including the **Baltic states** (**Estonia**, **Latvia**, and **Lithuania**), and **Romania** remain heavily reliant on biomass, district heating, and natural gas, with electricity comprising less than 26% of their residential energy use even by 2050 (**Figure 38**). This slower transition is largely due to worse economic conditions compared to the rest of the countries under study that limit investment in new technologies and infrastructure with high upfront investment costs, such as heat pumps. Moreover, these countries remain dependent on existing fossil-fuel infrastructure, such as extensive natural gas networks, which are costly and complex to replace. The latter creates a form of lock-in, making the shift to electrification more difficult and costly.

It is worth noting that **Denmark**, which plans to phase out all remaining fossil-fuel boilers by 2029 through the expansion of district heating and heat pumps, continues to rely primarily on district heating for residential energy demand until 2035. After this point, the energy mix shifts further, with biomass and electricity accounting for the largest shares by 2050.

6.7.6 CO_2 emissions reduction across countries

Emissions reduction trajectories in the residential sector also vary significantly across the countries under study, reflecting underlying differences in starting points, energy system structures, policy ambition, and the pace of electrification (**Figure 39**). *Decarbonisation frontrunners* include the **Nordic countries** (**Finland** and **Sweden**), which are projected to reduce residential emissions by 87% and 97%, respectively, until 2035, compared to the 2016 levels. Both countries achieve deep reductions between 2030 and 2035; this is largely the result of an already low-carbon energy mix, the widespread use of district heating and biomass, high energy-efficiency standards, and the rapid deployment of electric heating systems. Nevertheless, the two countries accounted for only 0.4% of the total CO_2 emissions in the European of the EU-27 plus the UK region's residential sector in 2016, so their impact on the overall EU's targets is relatively limited despite their ambitious trajectories.

Major emitters (i.e., **Belgium**, **Germany**, **France**, **Italy**, **the Netherlands**, **Poland**, **Spain**, and **the UK**) achieve gradual yet substantial drops, reaching over an 80% of CO_2 emissions reduction in the residential sector by 2040, following more incremental improvements over time (**Figure 16**). These countries begin with higher levels of fossil-fuel use in residential heating, which makes their transition more complex. However, their

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decarbonisation targets are mainly driven by a combination of long-term climate targets, increasing carbon prices associated with the full implementation of ETS2 in 2027, and robust policy packages to support electrification. As a result, these countries are making strong progress in shifting their residential energy mix towards electricity, primarily through the expansion of renewable energy and the further deployment of heat pumps.

Conversely, *lagging countries*, like **Luxembourg** and **Romania,** are projected to reach only 67% and 86% reductions by 2050, respectively (**Figure 39**). These outcomes show limited ambition, suggesting structural and policy-related barriers. In Romania, for instance, slower electrification reflects lower income levels, limited access to clean heating alternatives, and reliance on heating systems that are difficult to modernise, while Luxembourg's slow progress is partly driven by its higher energy consumption per capita compared to the average levels in the EU-27 plus the UK region.

It is important to note that some countries, such as **Portugal**, start with lower total CO_2 emissions compared to the region's average, which means their potential for further reductions is naturally more limited. However, this does not imply a lack of progress; rather, it reflects a slower pace of reduction while maintaining a strong overall position in terms of decarbonisation.

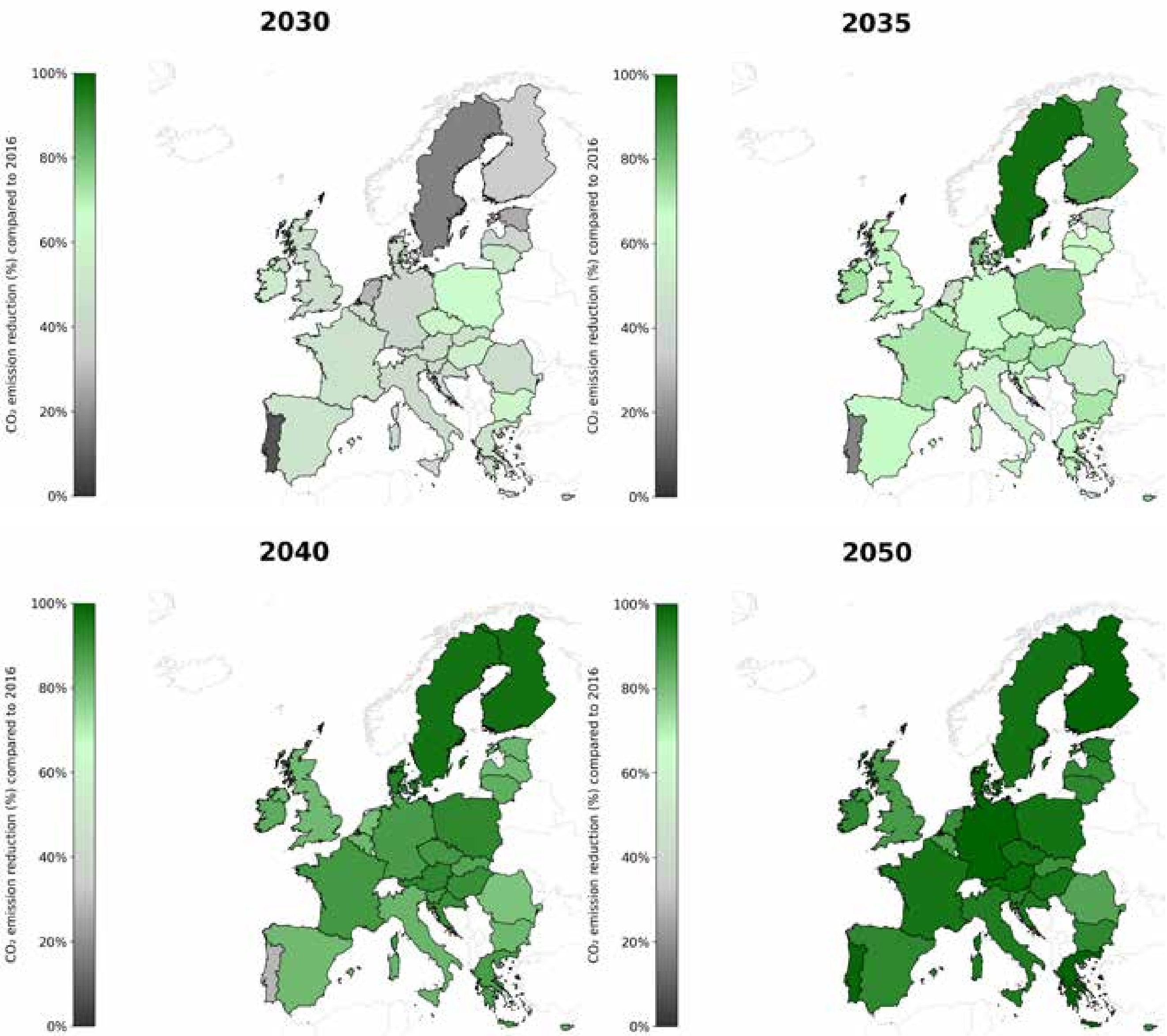

Figure 39. CO_2 emissions reduction in the residential sector across the EU-27 plus the UK region in 2030, 2035, 2040, and 2050, under the "Current Policy" scenario (compared to the 2016 levels). Results are derived from Aalto-EU-TIMES.

Overall, the variation in emissions reduction levels is closely tied to the speed and the scale of electrification in

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each country. *Fast adopters* expect better progress, while countries with greater fossil-fuel dependency, infrastructure inertia, or limited financial capacity are expected to progress more slowly. These differences stem from a mix of climatic, structural, and socioeconomic factors. For example, the design and the condition of national housing stocks affect their retrofit potential, while climate variability affects the attractiveness of technologies like heat pumps. Cultural habits and attitudes towards energy use also shape adoption rates. Policy coherence is crucial, yet fragmented governance often hinders progress. Disparities in fiscal and institutional capacity limit the ability of less affluent Member States to finance public investments, or support household upgrades, slowing their progress. These combined factors lead to uneven progress and underscore the importance of context-sensitive policies to enable all countries to contribute effectively to the European residential sector's transition.

6.8 Greece

Greece is a country with a significant renewable energy potential and presents a case of a significant shift in planning for its future energy system's development.

6.8.1 Context

Greece's annual mean temperature has been rising since 1960 and is expected to increase by 3-4.5 ^{o}C above 1961-1990 levels (IEA, 2022c). In recent years, Greece has made notable progress in reducing fossil fuels dependency, primarily due to the decrease in the lignite use (Kontochristopoulos et al., 2021). However, Greece's reliance on fossil fuel imports, particularly natural gas, underscores the urgency to transition to cleaner energy forms in alignment with the EU objectives (Stavrakas et al., 2021).

The Greek residential sector accounts for 24% of the total final energy consumption with heating and cooling accounting for 71% of this figure (IEA, 2023e). The energy transition of the Greek residential sector is expected to be driven by a substantial increase in the electrification of heating systems. Heat pumps, in particular, offer the opportunity to reduce energy consumption and carbon emissions. Specifically, replacing a gas boiler with an electric heat pump in Greece reduces carbon emissions by almost 47% (JRC, 2024). Also, compliance with the National Climate Law will further support this transition, with new oil boilers prohibited from installation after 2025 and mandates for a 30% bio-diesel blend in oil by 2030. Additionally, integrating the buildings sector into the ETS scheme will gradually increase the cost of using fossil fuels, further incentivising the shift to sustainable heating systems (Hellenic Ministry of the Environment and Energy, 2024).

However, high electricity prices pose a significant barrier to the adoption of heat pumps. Rising energy costs have burdened households, with 18.7% unable to keep their home adequately warm and 34.1% having arrears on their utility bills. To electrify the residential building stock, a favourable electricity-gas ratio and available subsidies are essential (JRC, 2024). For this reason, a significant proportion of the Recovery and Resilience fund resources in combination with the Partnership Agreement and other European funds, support multiple cycles of national programs promoting energy efficiency renovations and the installation of energy efficient heating systems. Targeted energy upgrades, particularly for older buildings, will further support the transition (Hellenic Ministry of the Environment and Energy, 2024).

The revision of the NECP-2019 was not only an obligation under EU legislation but an opportunity to adapt the national strategy to the new circumstances that have emerged in recent years. In this context, the NECP-2024 has been designed to adapt to current trends and dynamics, focusing on the policies necessary to achieve emission reductions by 2030, while advancing towards climate neutrality by 2050 (Hellenic Ministry of the Environment and Energy, 2024). A key component of the NECP-2024 will be the National Building Renovation Plan (former Long-Term Renovation Strategy), which will be monitored and evaluated through the integrated national NECP reporting (Hellenic Ministry of the Environment and Energy, 2024). The aim of these plans is to ensure that the national building stock is renovated into a high energy-efficient and zero-emission building stock (European Commission, 2025b). The National Building Renovation Plan should be designed to align with the targets set by the NECP and provide detailed analysis to support these objectives.

A key priority of NECP-2024 is the energy efficiency upgrade of the building sector. This involves the installation

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of insulation and new appliances, as well as a shift to cleaner forms of energy for heating and cooling (i.e., heat pumps) and accelerating both the pace and depth of renovation. The plan also emphasises smart management of energy consumption and behavioural changes to reduce energy requirements. Specifically, the NECP-2024 targets 68,000 buildings envelope renovations annually for residential buildings from 2025 to 2030. According to the NECP projections, this figure will decrease slightly to 64,000 renovations per year between 2031 and 2040 but then will significantly rise to 83,000 renovations per year during the period 2041-2050. In total, over a period of 25 years, the plan anticipates around 1,880,000 building renovations in the residential sector. These measures aim to improve energy performance, alleviate energy poverty, and promote a green and just energy transition.

Furthermore, the plan sets clear targets for the reduction of final energy consumption in the residential sector by 2050. The average primary energy use in residential buildings is set to drop 16% by 2030 and 20-22% by 2035. Key measures include gradual phasing out of oil and gas boilers and a significant increase of heat pump installations by 2030. Additionally, according to data obtained from the Ministry of Environment and Energy, in 2022 the share of heat pumps in the final energy consumption for heating is 8% and is expected to reach 24% in 2030. The NECP-2024 sets ambitious targets for advancing the energy efficiency of the residential sector.

Considering the above, further modelling work is necessary to enable a comprehensive analysis of the NECP-2024 targets, quantifying their environmental impact through the calculation of the evolving environmental footprint and assessing the economic benefits of the energy transition in the residential sector by 2050. Such analysis will provide critical and actionable insights into the specifics of the energy transition in Greece's residential sector, addressing energy efficiency, energy poverty, and the promotion of cleaner energy forms, and serve as a valuable tool for policymakers to design and implement strategies that align with both national decarbonisation and energy independence goals, as well as broader EU objectives.

6.8.2 Stakeholder feedback

Stakeholders highlighted several economic, technical, and socio-cultural factors that must shape the national pathways toward building decarbonisation.

Participants emphasised that the feasibility and pace of technology deployment depend on critical parameters such as upfront investment costs, deployment rates, skills availability, and access to clean technologies. In particular, they noted that high upfront costs and long payback periods can deter households from adopting energy-efficient solutions, underlining the importance of ensuring that renovation measures remain cost-optimal and market-realistic.

Participants emphasised that the feasibility and pace of technology deployment are closely tied to key factors such as upfront investment costs, deployment rates, skills availability, and access to clean technologies. They highlighted that high initial costs remain one of the main barriers preventing households from adopting energy-efficient solutions. Moreover, they stressed that the assumed payback periods for renovation measures must realistically reflect market conditions and technology performance in each country. If payback times are too long or misaligned with consumer expectations, this could discourage investment. Participants also noted that while certain materials and technologies can offer superior energy performance, their higher costs may limit uptake unless financial incentives or cost-reduction strategies are in place to support their deployment.

Flexibility solutions, such as battery energy storage systems, were identified as essential to support the wider uptake of distributed renewables like solar PV, particularly at the household level. However, financial constraints, insufficient information, a lack of skilled installation companies, and even cultural preferences remain significant barriers to the adoption of technologies such as heat pumps and solar panels.

Participants also pointed to the socio-cultural dimension of the energy transition, noting that perceptions of renewable technologies may be shaped by broader societal or political attitudes. This cultural resistance to change -though difficult to quantify- was seen as a potentially important barrier to technology adoption in some regions and should not be overlooked in scenario modelling or policy design.

Overall, the stakeholder needs for a modelling application focused on the Greek residential sector are driven by the necessity to evaluate and support effective decarbonisation strategies aligned with national and EU climate

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targets. Stakeholders require robust tools to assess whether current national planning, as outlined in the Greek NECP, is sufficient to achieve full decarbonisation by 2050. Additionally, they seek insights into how projected developments in the residential sector translate into quantifiable environmental impacts and economic outcomes. A critical need is the ability to compare the effectiveness and cost-efficiency of various intervention pathways, particularly building envelope renovations versus technology replacements such as heat pumps, to inform investment priorities and policy support mechanisms.

6.8.3 Scenario design and model parameterisation

In this study, we have considered the country's recent climate commitments and key data projections for the residential sector, as these have been articulated in the NECP-2024. The scenario space for simulating the NECP-2024 aligned scenario was developed as outlined in **Table 27** and **Figure 40**.

In this regard, we further develop and apply the DREEM model to simulate a scenario aligned with the revised NECP-2024 by 2050. More specifically, we parameterise the DREEM model using data acquired from the Greek Ministry of Environment and Energy on energy consumption and technology penetration for the reference year (i.e., 2022) and the targets and the specifications of the revised NECP-2024. The model simulated the energy consumption mix for the reference year, which served as the baseline for setting the targets for following years. The targets for the following years were designed to ensure that the consumption and penetration of different heating systems follow the energy transition trends outlined in the NECP-2024. **Table 27** presents the adjusted energy consumption targets for the different heating systems up to 2050.

Table 27. Adjusted energy consumption targets in the Greek residential sector for the reference year, the milestone years, and the target year, according to the bottom-up methodology followed.

Consumption per fuel (ktoe)	2022	2025	2030	2035	2040	2045	2050
Oil	1,874	1,200	422	296	98	0	0
Natural gas	457	535	489	288	132	85	69
Bioenergy / Biomethane / Biodiesel	673	849	1,040	1,092	1,193	1,160	1,150
Electricity	1,603	1,803	1,871	1,888	1,964	2,002	1,978

Figure 40 illustrates the projected evolution of heat pumps' penetration in the final energy mix in the Greek residential sector up to 2050.

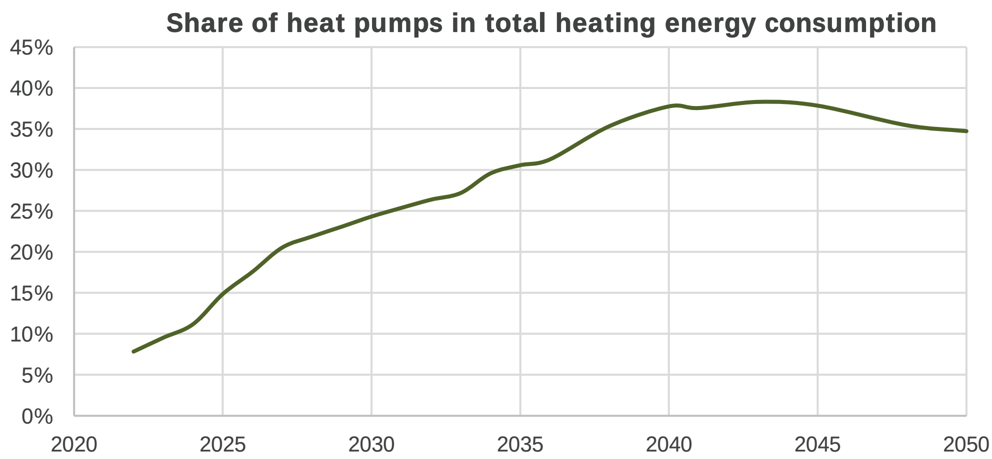

Figure 40. Evolution of the share of heat pumps in final heating energy consumption by 2050 in the Greek residential sector (Source: Hellenic Ministry of Energy).

For this study, energy upgrade interventions are simulated following three (3) types and combinations of energy saving interventions:

- **Replacement of heating systems**: These interventions refer to the replacement of oil or gas boilers with heat pumps, aiming to improve energy efficiency.
- **Building envelope renovations**: These include renovations of the building envelope, energy upgrading of windows, windows frames, etc. In this study, these interventions referred to installation of exterior wall insulation and window upgrades for dwellings build before 1981 and installation of exterior wall insulation for dwellings constructed during the period 1981-2000.
- **Combination of interventions**: These include the simultaneous implementation of heating system replacement and building envelope renovation, as defined above.

In all cases, priority is considered to be given to houses built before 1981.

Finally, the scenario space is further enhanced with projections on the evolution of different useful exogenous variables to extract meaningful and policy-relevant conclusions. For this analysis, all prices and future monetary flows are discounted using Greece's discount rate of 4% (European Commission, 2025a). More specifically, for energy prices, two different cases are explored. As shown in **Table 28**, the first one follows the estimated price trends provided by the NECP-2024, while the second one follows the projected price trends from PROMETHEUS. The price evolution of bioenergy, biodiesel and biomethane, which is collectively referred to as biomass, is assumed to be the same in both cases and was derived from market research conducted for Greece, taking into account their projected share in the energy mix through 2050. Fuel costs for the years prior to 2025 were determined using real-word data. Electricity costs were based on data from the "Independent Power Transmission System Operator"[34], while natural gas prices were sourced from "Eurostat" data[35] specific to Greece. The cost of heating oil was calculated based on the fuel price overview sheets published by the Ministry of Development and Competitiveness[36].

Table 28. Projections on the potential future evolution of fuel prices by 2050 in Greece.

Year	2022	2025	2030	2035	2040	2045	2050
"NECP-2024 price evolution" case							
Heating oil (€/MWh)	118	111	111	111	118	127	143
Natural gas (€/MWh)	82	38	38	38	38	38	38
Electricity (€/MWh)	304	145	139	125	117	108	95
Biomass (€/MWh)	51	51	63	62	56	52	53
"PROMETHEUS model price evolution" case							
Heating oil (€/MWh)	118	117	120	129	131	129	131
Natural gas (€/MWh)	82	77	66	69	74	74	78

[34] https://www.admie.gr/agora/statistika-agoras/kyrioi-deiktes-dashboard/mesostathmiki-timi-agoras
[35] https://ec.europa.eu/eurostat/databrowser/view/ten00118/default/table?lang=en
[36] https://www.fuelprices.gr/deltia.view

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Electricity (€/MWh)	304	120	123	125	122	114	109
Biomass (€/MWh)	51	51	63	62	56	52	53

The analysis also includes projections on the future evolution of technological costs by 2050, i.e., the costs to be paid by end-users for the implementation of the measures foreseen in the transition scenarios, e.g., natural gas/ heat pump installations, buildings envelope upgrades, etc. The projections presented in **Table 29** are based on trends in retail price per kW for each technology (De Vita, A., Capros, P., Paroussos, L., Fragkiadakis, K., Karkatsoulis, P., Höglund-Isaksson, L., Winiwarter, W., Purohit, P., Gómez-Sanabria, A., Rafaj, P., Warnecke, L., Deppermann, A., Gusti, M., Frank, S., Lauri, P., ... Kalokyris, T. (2021). De Vita, A, 2021) and their corresponding nominal capacity (Sakellariou et al., 2023). The renovation costs were derived from the study "Definition of cost-optimal levels of minimum energy efficiency requirements for buildings and building elements & preparation of a national plan to increase the number of buildings with near-zero energy consumption", provided by the Ministry of Environment and Energy (not published yet).

Table 29. Projections on the future evolution of the unit cost of a heating technology or building intervention by 2050 in Greece.

Unit cost per technology/intervention	2022	2030	2050
Natural gas boilers (€)	2,124	2,752	2,472
Heat pumps (€)	6,821	7,736	3,848
Biomass boilers (€)	10,250	14,850	11,708
Building envelope renovations (€)	13,912	13,912	13,912

Furthermore, the Emission Trading System (ETS)-relevant costs are quantified based on their expected evolution (€/tn). According to the NECP-2024, the ETS is expected to start in 2027 and will initially be applied to buildings at reduced rates with full integration beginning in 2031. The Ministry of Environment and Energy provided the ETS prices as shown in **Table 12**.

Table 30. Projections on the potential future evolution of the ETS costs by 2050 in the building sector.

Year	2022	2030	2035	2040	2045	2040
Carbon price (€/tn)	0	60	140	290	430	490

For the calculation of CO_2 emissions, the projection of the emission factor for electricity was based on data from the NECP-2024, which were used to calculate its evolution over time (**Table 31**). For heating oil and natural gas, the respective emission factors are kept constant by 2050 and were derived from other sources[37] of the Ministry of Environment and Energy.

Table 31. Projections on the future emission factors for electricity, heating oil, and natural gas.

Electricity	
Year	*Emission factor (tnCO₂/ktoe)*
2022	4,205

[37] https://ypen.gov.gr/wp-content/uploads/2023/12.pdf

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2025	2,201
2030	770
2035	222
2040	160
2045	95
2050	96
Heating oil	
Year	*Emission factor (tnCO₂/ktoe)*
(2022-2050)	3,089
Natural gas	
Year	*Emission factor (tnCO₂/ktoe)*
(2022-2050)	2,335

6.8.4 Results

Simulation outcomes indicate a significant reduction in total final energy consumption in the Greek residential sector, as shown in **Figure 41**. The total consumption drops from approximately 4,608 ktoe in the reference year (2022) to around 2,678 ktoe in 2050, representing a reduction of nearly 42%. This significant decrease is primarily driven by building envelope renovations and the transition to more energy-efficient heating systems (i.e., heat pumps).

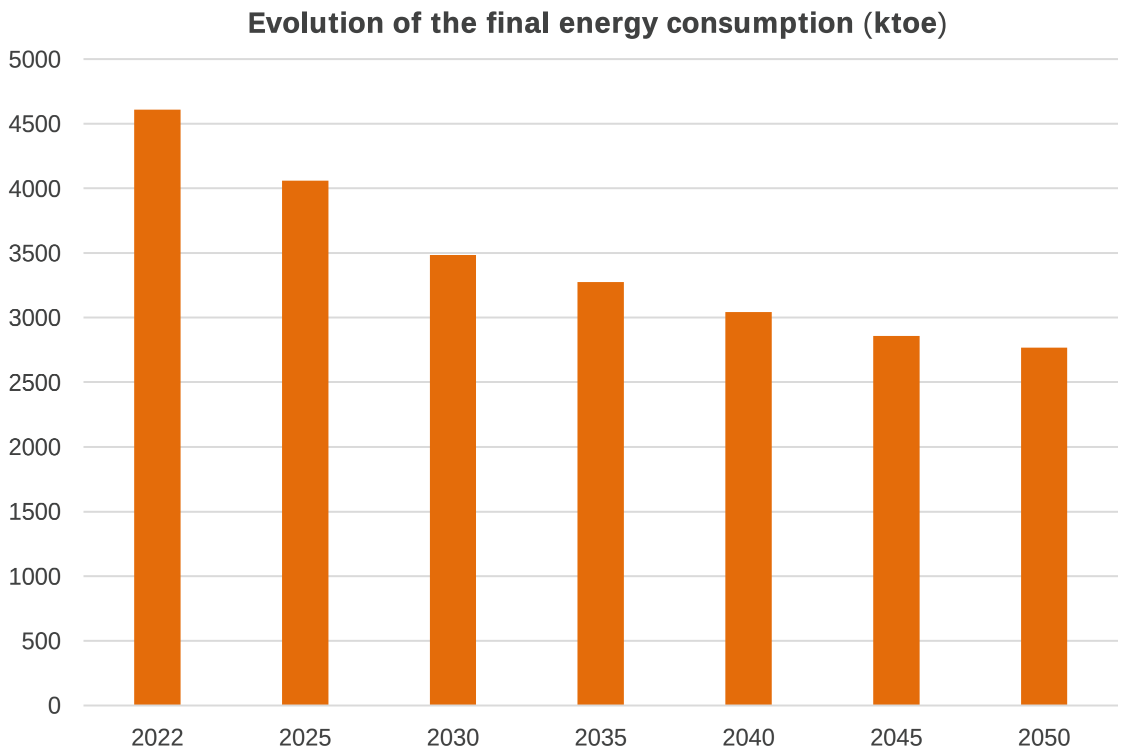

Figure 41. Evolution of the total final energy consumption (in ktoe) in the Greek residential sector by 2050, under a scenario aligned with the NECP-2024. Results are derived from DREEM.

Figure 42 provides a detailed view of to the evolution of the energy mix. The gradual phase out of fossil fuels is evident, with oil being eliminated from the energy mix by 2045. Natural gas increases in the first few years up until 2025 and then drops significantly. Although not fully phased out in 2050, its consumption reduces from 529 ktoe in 2025 to almost 59 ktoe in 2050 which accounts for 2% of the total final energy consumption in 2050.

In contrast, electricity plays an increasingly prominent role in the energy mix, rising from 1,603 ktoe in 2022 to 1,757 ktoe in 2040, largely replacing the use of fossil fuels. This increase corresponds to 35% of the total final energy consumption in 2022 and 58% of the total final energy consumption in 2040 and is largely driven by the widespread adoption of heat pumps. By 2050, electricity sees a slight reduction to 1,695 ktoe, attributed to the impact of energy efficiency renovations. Additionally, bioenergy and biofuels are playing an enhanced role in the energy mix, rising from 673 ktoe in 2022 to 1,014 ktoe in 2050.

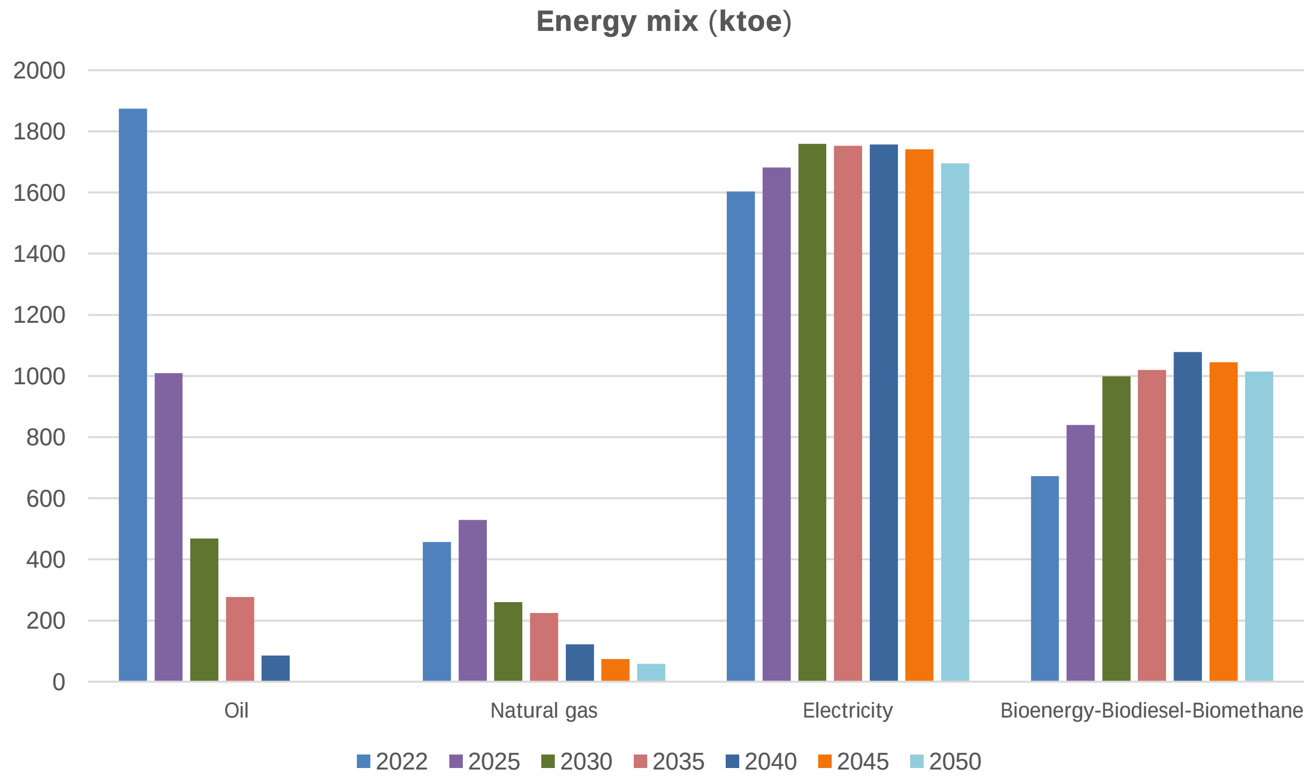

Figure 42. Evolution of the final energy mix (in ktoe) in the Greek residential sector by 2050, under a scenario aligned with the NECP-2024. Results are derived from DREEM.

The critical role of energy saving measures, such as upgrade of heating systems and building renovations, underscored by the significant reduction in CO_2 emissions. **Figure 43** depicts the annual and cumulative CO_2 emissions up to 2050, along with the total emissions avoided due to the measures foreseen by the NECP-2024.

In 2022, total annual CO_2 emissions in the Greek residential sector are estimated at around 13.6 Mt CO_2, while by 2050, they are reduced to around 0.35 Mt CO_2, representing a total reduction of around 97%. Furthermore, a comparison of cumulative CO_2 emissions for the current state of the Greek residential stock with the scenario aligned with the revised NECP-2024, reveals that these interventions will prevent the release of 142 Mt CO_2 by 2050. This major reduction in emissions, and the substantial volume of avoided emissions can be attributed to household electrification, through the gradual installation of heat pumps and the phase-out of fossil fuel-based boilers, as well as to energy-efficient building renovations.

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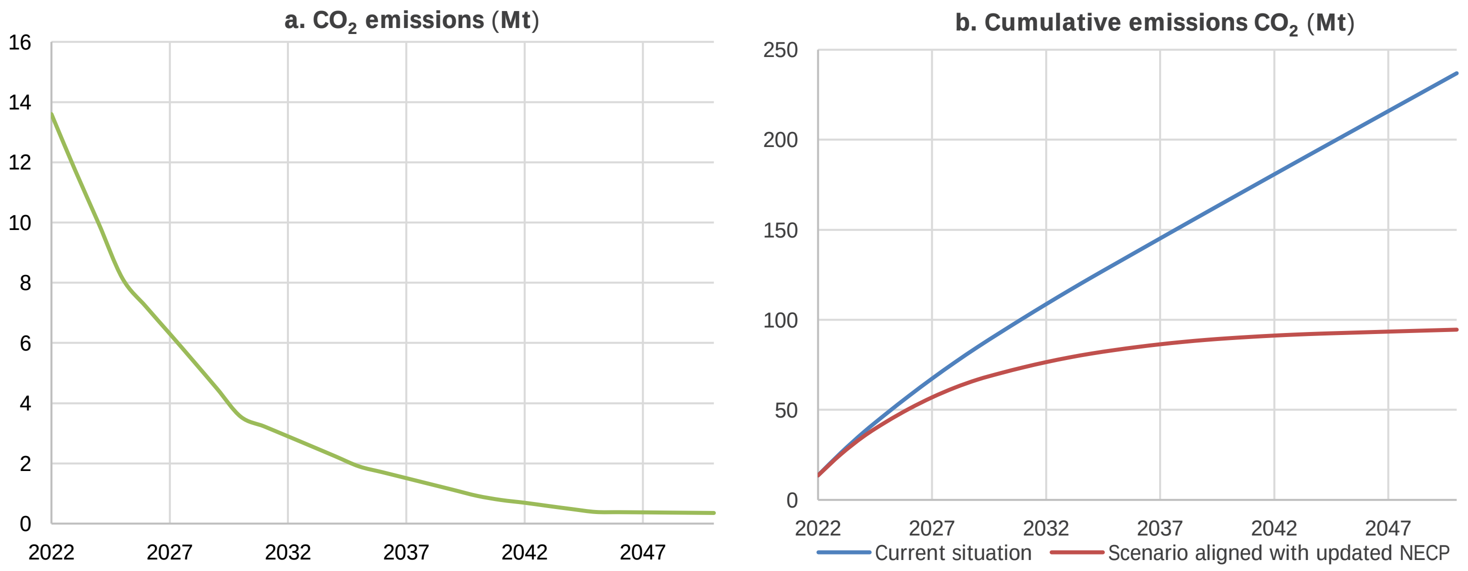

Figure 43. a. CO_2 emissions (in $MtCO_2$/yr) by 2050 in the Greek residential sector, under a scenario aligned with the NECP-2024, **b.** Total emissions avoided (in $MtCO_2$/yr) by 2050 compared to the current situation. Results are derived from DREEM.

To achieve the aforementioned final energy consumption and emission reduction, 4.36 million total interventions are required to be implemented. **Figure 44** depicts the progression of each type of intervention up to 2050, including heating system replacements, buildings envelope renovation and combined renovation with heating system replacement. The majority of these interventions concern the replacement of heating systems, reaching 2.39 million in 2050, due to their significant impact in energy consumption and relatively low cost. Building envelope renovation show a gradual and steady increase reaching 1.85 million by 2050. In contrast, combined interventions appear to be implemented in only a small number of households (113,068 in 2050), due to their high cost.

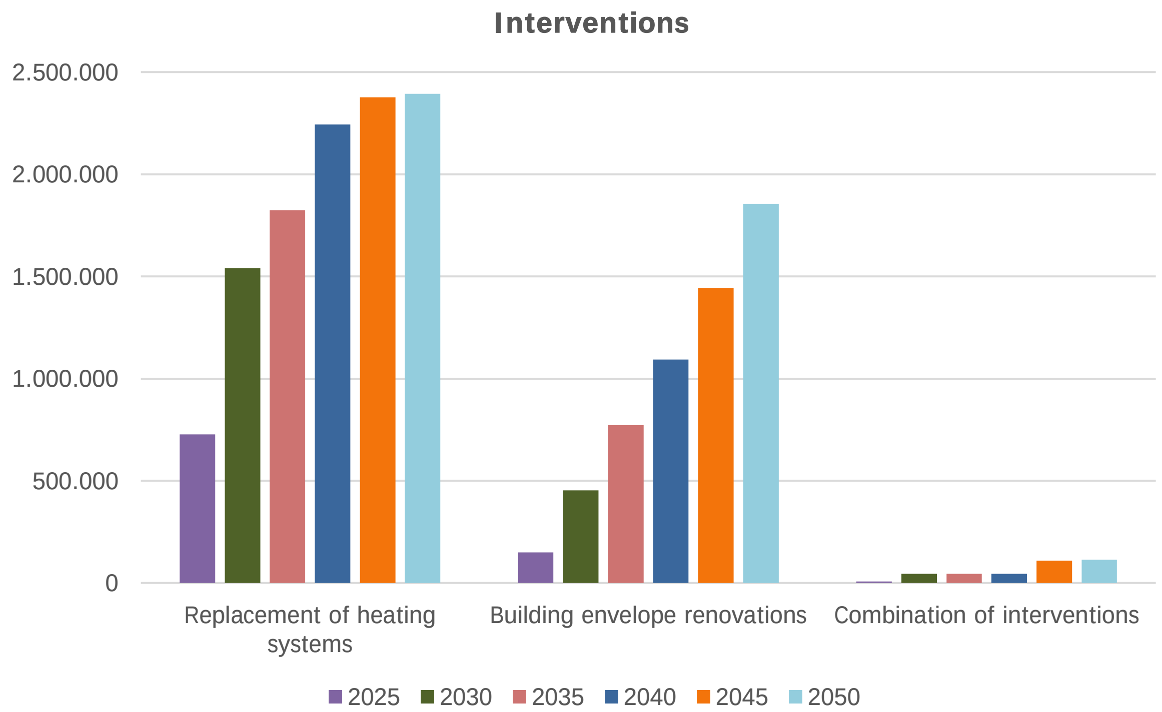

Figure 44. Progression of the interventions needed in the Greek residential sector by 2050 to meet the objectives outlined in the NECP-2024. Results are derived from DREEM.

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Simulation results provide information on the economic implications of the energy transition by 2050 in the Greek residential sector for the scenario aligned with the NECP-2024. All results from the economic analysis are presented in discounted terms. **Figure 45** presents the evolution of discounted fuel costs (i.e., costs paid by consumers for household heating, cooling, and use of appliances) by 2050 and the total discounted fuel costs in 2050 for the two price evolution cases under study.

Overall, it is evident that in both cases the annual fuel costs are significantly reduced in 2050 compared to 2022. This reduction is driven by the complete phase-out of oil from the energy mix, declining electricity prices, and reduced energy consumption. In the case of the price trends derived from PROMETHEUS, even when energy prices increase, overall fuel costs still decline due to substantial reduction in energy consumption. By 2050, discounted annual fuel costs are estimated at around €1.1 billion for fuel price trends provided by PROMETHEUS and around €0.99 billion for the fuel prices of NECP-2024 in 2050. The total discounted fuel cost for the full energy transition period (2022-2050) is around €79 billion for the PROMETHEUS price scenario and around €78.6 billion for the NECP-2024 price scenario.

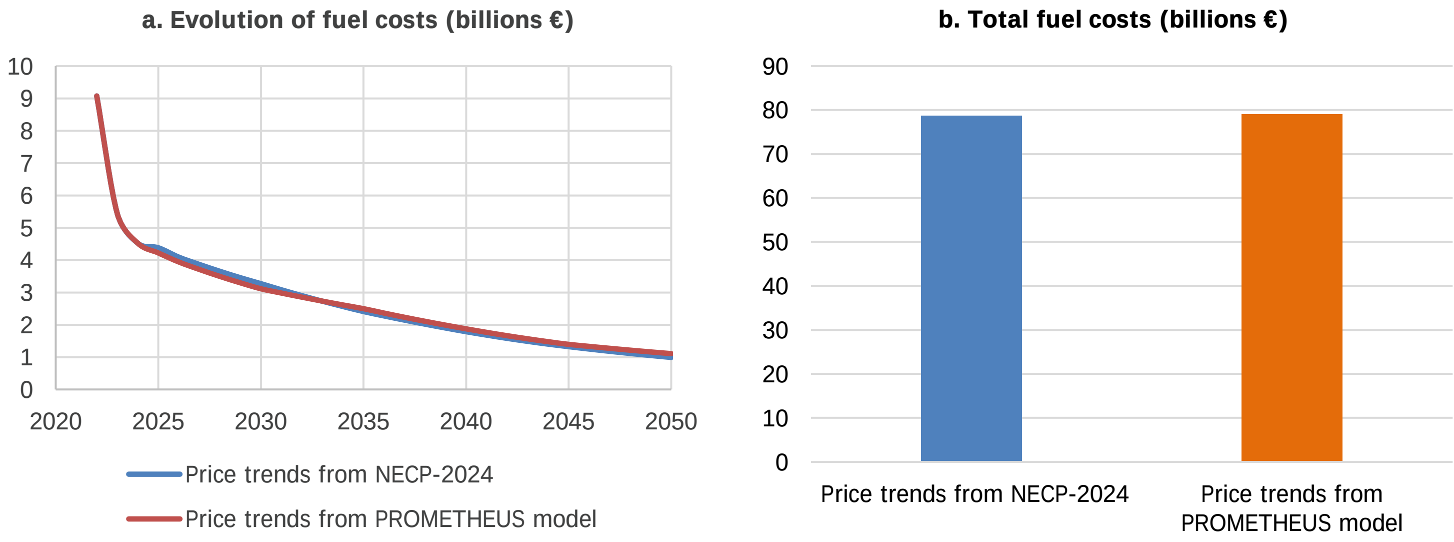

Figure 45. a). Annual evolution of discounted fuel costs (in billions of €) by 2050, and **b**). Total discounted fuel costs (in billions of €) by 2050 in the Greek residential sector for the two price evolution scenarios.

To supplement the economic analysis, simulation results also provide information on the discounted cost of interventions, based on the evolution of technological costs. As presented in **Figure 46**, the total cost of interventions fluctuates over time, influenced by changes in renovation rates and technology adoption. The first few years, as more extensive actions in a narrower time span are required, the total cost of interventions is higher. Between 2025 and 2030, when the annual renovation rate is 68,000 households, the annual cost declines from approximately €1.69 billion to €1.16 billion, mainly driven by the phase-out of natural gas, thus the discontinuation of new natural gas boilers installations and the declining electricity prices. By 2040, the annual cost drops further to around €554 million, corresponding to a lower renovation rate of 64,000 per year. After 2040, the renovation rate increases to 83,000 per year, causing the cost to rise to around €619 million. However, due to the slower clean technology penetration rate and lower cost of heat pumps, the annual cost declines to around €391 million by 2050. Overall, the total discounted cost for building envelope renovations and heating system replacements throughout the energy transition period is estimated at approximately €23 billion.

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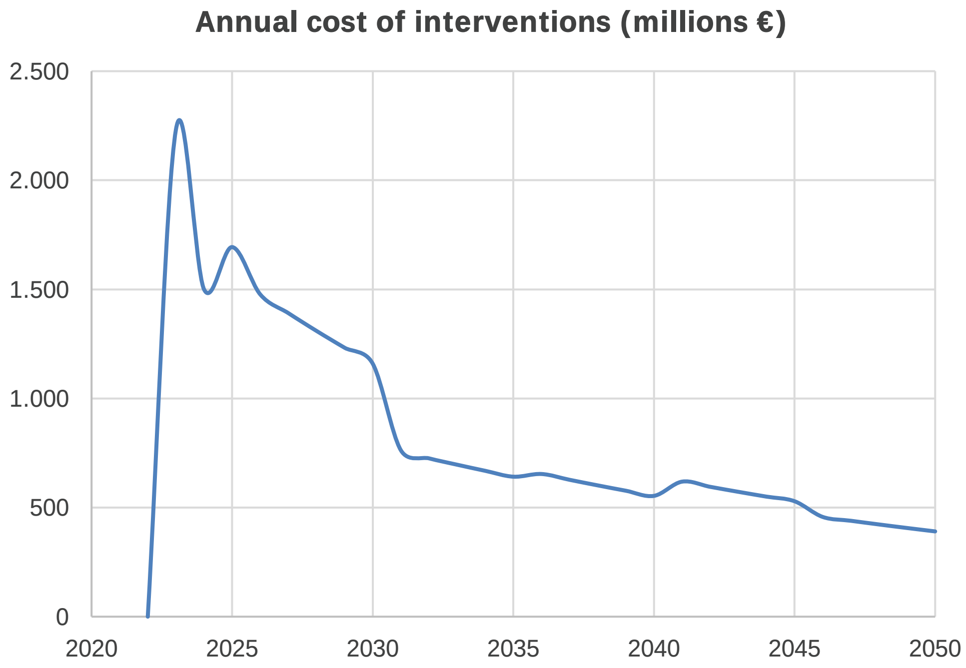

Figure 46. Evolution of the discounted annual cost of interventions by 2050 (in millions of €).

Moreover, simulation results further supplement the economic analysis with the quantification of the discounted costs related to the inclusion of the EU's building sector in ETS. It is important to note that household electricity consumption is excluded from additional ETS charges, as these costs are integrated at the electricity generation level of the supply side.

Figure 47 presents the evolution of the discounted annual ETS-related costs by 2050 for the scenario aligned with the NECP-2024 and compares the total discounted ETS-related costs in 2050 under this scenario with the discounted costs of the current situation of the building stock. Due to the initially low ETS rates and the fossil-fuel boiler phase-outs, ETS-related costs decrease from approximately €170 million in 2027 to €94 million in 2030. However, despite the ongoing emission reduction, the higher ETS rates introduced after 2030 lead to an increase in costs, which peak at around €128 million by 2036. After 2036, the level of the cost savings due to emissions reduction becomes significant enough to outweigh the effect of ETS prices, resulting in a decline in ETS-related costs to around €26 million by 2050.

The significance of the energy transition is outlined by the great difference in discounted cumulative ETS-related costs. By 2050, the scenario aligned with NECP-2024 results in total ETS-related costs of around €2.1 billion, compared to approximately €37 billion under the current building stock conditions.

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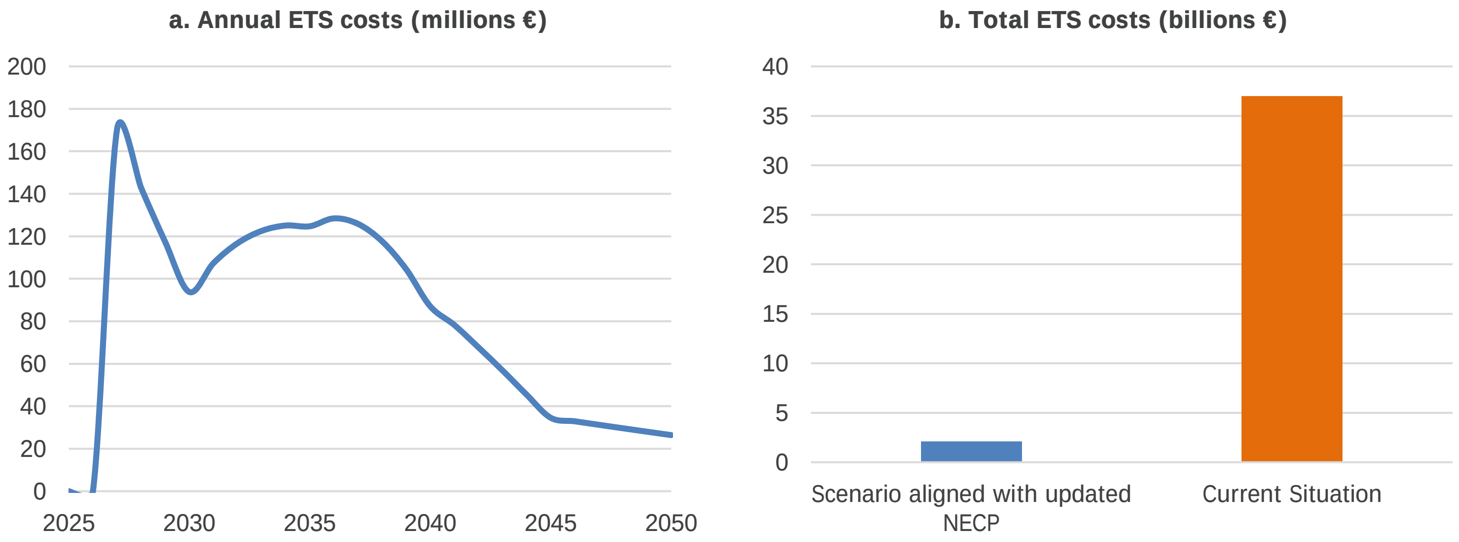

Figure 47. a). Evolution of the discounted annual ETS-related costs by 2050 (in millions of €) under a scenario aligned with the NECP-2024, and **b**). Evolution of the total discounted ETS-related costs in 2050 (in billions of €) compared to the current situation of the building stock.

By calculating all the individual costs above, this study seeks to provide policy implications related to the economic impacts of the energy transition in the Greek residential sector by 2050. Assuming that these discounted cumulative costs are equally divided among all the households in Greece, it is feasible to scale down costs at the household level and quantify the expected annual charges of the energy transition for consumers.

Figure 48 shows the evolution of discounted annual and cumulative costs by 2050 at the household level in Greece based in the scenario aligned with the NECP-2024 and the current state of the building stock, using the fuel price projections from the NECP-2024. Due to the upfront cost of interventions, the NECP-2024 aligned scenario results in slower reduction of the annual costs until 2027. However, after 2036, the rising ETS-related costs and the higher fuel consumption in the scenario without interventions lead to an increase in household costs. By 2050 the annual household cost under the NECP-2024 aligned scenario is €325, compared to €931 under the scenario without interventions. In terms of cumulative costs, the scenario aligned with the NECP-2024 becomes more economical in 2035 onward, with total savings reaching €9,985 by 2050.

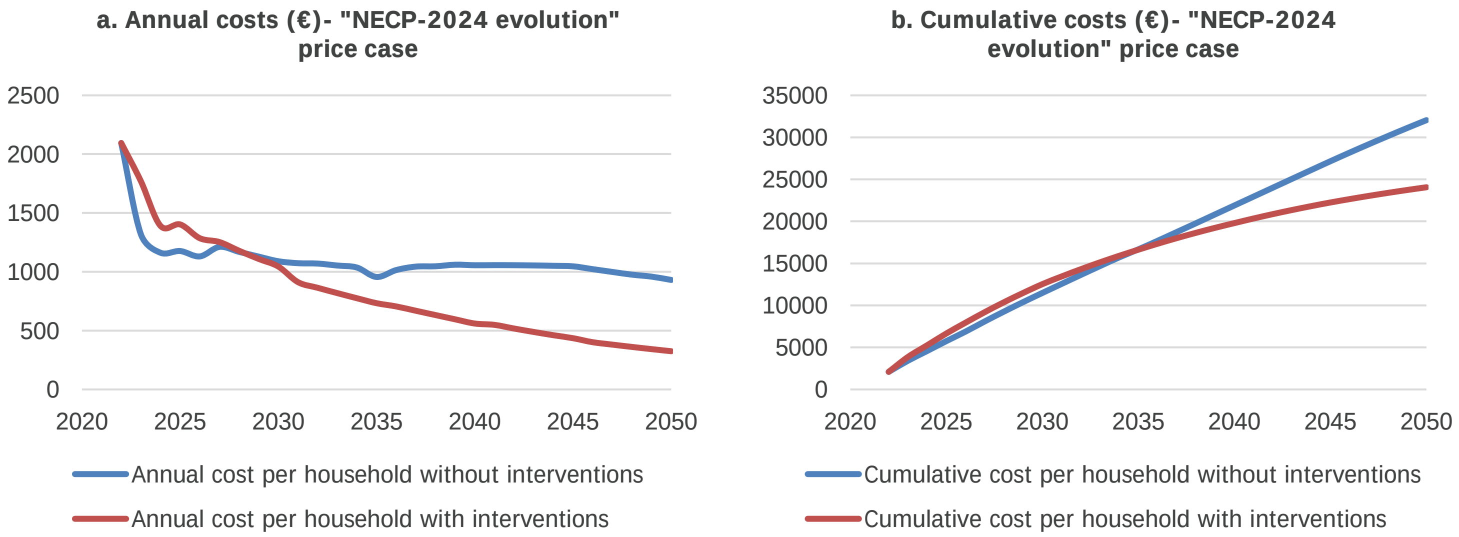

Figure 48. a). Evolution of discounted annual costs per household in Greece by 2050 under the scenario aligned with the NECP-2024 and the scenario reflecting the current state of the building stock, using the NECP-2024 fuel price projections, and **b**). Evolution of discounted cumulative household costs under the same two scenarios.

Figure 49 also shows the evolution of discounted annual and cumulative costs by 2050 at the household level in Greece based in the scenario aligned with the NECP-2024 and the current state of the building stock, using the fuel price projections from the PROMETHEUS model. In this case, the annual cost under the NECP-2024 aligned scenario becomes lower starting in 2028. By 2050, the annual household cost is €352 under the NECP-2024-aligned scenario, compared to €947 under the scenario without interventions. Regarding the cumulative costs, the NECP-2024 aligned scenario becomes more cost-effective from 2034 onward with total household savings reaching €8,758 in 2050.

Even with two different fuel price projections, the interventions required for the energy transition scenario aligned with the NECP-2024, ultimately benefit the consumer. While these interventions may involve high upfront costs, they lead to lower discounted annual and cumulative household energy expenses over time, especially as ETS-related costs rise.

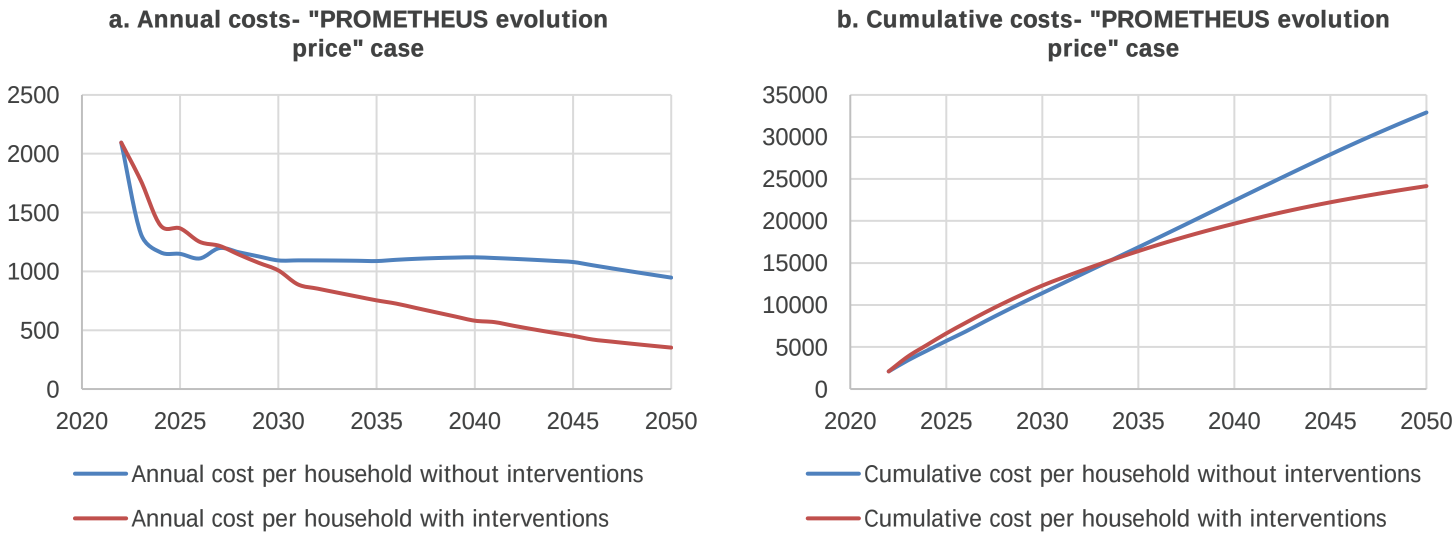

Figure 49. a). Evolution of discounted annual costs per household in Greece by 2050 under the scenario aligned with the NECP-2024 and the scenario reflecting the current state of the building stock, using the PROMETHEUS model's fuel price projections, and **b**). Evolution of discounted cumulative household cost under the same two scenarios.

To assess the impact of each type of intervention, discounted household cost saving under the two different fuel price evolution cases, as well as household emission savings up to 2050, were calculated. Households equipped with different heating technologies or state renovation shift between savings categories depending on the interventions implemented. For example, since oil is completely phased out by 2040, it is assumed that all households previously using oil boilers have transitioned to alternative heating technologies.

Table 32 presents the evolution of discounted annual cost savings per household for each type of intervention up to 2050 using the NECP-2024 fuel price projections. It is evident that replacing oil boilers with an alternative heating system leads to the highest cost savings, particularly when heat pumps are installed. Notably, in 2045 the annual household savings reach €1,012. Moreover, until 2035, replacing natural gas boilers with biomass boilers does not generate cost savings; however, after 2040, when ETS-related costs become more significant, this intervention becomes more economically viable and eventually lead to €250 annual savings in 2050. Cost savings from building envelope renovations are higher in households using oil boiler due to the higher reduction in consumption and the relatively high cost of heating oil. In contrast, renovations in households with heat pumps result in lower savings over time, since electricity is excluded from ETS and its price decreases. For these households, energy savings decline from €337 in 2025 to €83 in 2050.

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Table 32. Discounted annual household cost saving for each type of intervention up to 2050 using the NECP-2024 fuel price projections.

Annual Household Cost Savings (€)						
Intervention	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Building envelope renovation of household with oil boiler	467	438	420	454	-	-
Building envelope renovation of household with natural gas boiler	147	159	173	207	219	198
Building envelope renovation of household with heat pump	337	266	196	151	115	83
Building envelope renovation of household with biomass boiler	237	243	195	145	111	92
Replacement of oil boiler with heat pump	748	767	808	948	1012	971
Replacement of oil boiler with biomass boiler	575	491	565	773	878	844
Replacement of oil boiler with natural gas boiler	691	517	482	540	561	542
Replacement of natural gas boiler with heat pump	-	55	175	314	391	378
Replacement of natural gas boiler with biomass boiler	-	-221	-69	139	256	250

Table 33 presents the evolution of discounted annual cost savings per household for each type of intervention up to 2050 using the PROMETHEUS model fuel price projections. Also in this case, the most economically beneficial intervention is the replacement of oil boilers, especially with heat pumps, which reach €910 annual costs savings in 2050. The replacement of natural gas boilers with biomass boilers does not generate cost savings until 2035, with savings peaking at €410 in 2045. Among interventions that include building envelope renovations, those targeting households with oil boilers are the most profitable, achieving annual cost savings of €489 in 2025 and €483 in 2040. In contrast, building envelope renovations in households with heat pumps remain less cost-effective in this case as well, with lower annual savings over time.

Table 33. Discounted annual household cost saving for each type of intervention up to 2050 using the PROMETHEUS model fuel price trends projections.

Annual Household Cost Savings (€)						
Intervention	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Building envelope renovation of household with oil boiler	489	467	470	483	-	-
Building envelope renovation of household with natural gas boiler	298	248	253	284	283	256
Building envelope renovation of household with heat pump	280	234	196	157	121	95
Building envelope renovation of household with biomass boiler	237	243	195	145	111	92
Replacement of oil boiler with heat pump	875	877	932	1015	1015	910
Replacement of oil boiler with biomass boiler	630	561	689	847	888	797
Replacement of oil boiler with natural gas boiler	747	587	606	614	572	495
Replacement of natural gas boiler with heat pump	-	311	369	493	536	504
Replacement of natural gas boiler with biomass boiler	-	-4	126	326	410	391

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In terms of annual household emission savings for each type of intervention, as presented in **Table 34**, the replacement of oil boilers with heat pumps or biomass boilers results in the highest level of emission reduction. For interventions that don't involve electricity, emission savings remain constant throughout the years due to the fixed emission factors. The lowest emission savings are observed in the case of household renovation equipped with heat pumps, which is attributed to the continuous decline in the electricity emission factor over the years.

Table 34. Discounted annual household emissions savings for each type of intervention up to 2050 under the scenario aligned with the NECP.

Annual Household emission savings ($tnCO_2$)						
Intervention	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Building envelope renovation of household with oil boiler	1.25	1.25	1.25	1.25	-	-
Building envelope renovation of household with natural gas boiler	0.87	0.87	0.87	0.87	0.87	0.87
Building envelope renovation of household with heat pump	0.49	0.17	0.05	0.04	0.02	0.02
Replacement of oil boiler with heat pump	2.52	2.92	3.07	3.09	3.11	3.11
Replacement of oil boiler with biomass boiler	3.13	3.13	3.13	3.13	3.13	3.13
Replacement of oil boiler with natural gas boiler	1.01	1.01	1.01	1.01	1.01	1.01
Replacement of natural gas boiler with heat pump	-	1.91	2.06	2.08	2.10	2.10
Replacement of natural gas boiler with biomass boiler	-	2.13	2.13	2.13	2.13	2.13

6.9 Discussion

In this study, we assess energy transition pathways in the residential and the commercial sectors across different scales and contexts. Our work differentiates from existing studies by coupling top-down with bottom-up perspectives, not only capturing the macroeconomic implications and systemic constraints of electrification but also incorporating the technological detail and sector-specific dynamics necessary to assess realistic transition pathways. We combine knowledge embedded in stakeholders with a hybrid modelling ensemble, comprising an integrated assessment model, three energy system models, and a sectoral model focusing on the buildings sector, to simulate "current policy" and high-ambition scenarios from the global to the continental (European Union) scale, and from the continental scale to national case-specific studies to illustrate the analysis; namely, in a Global South country (India) and a European Union member state (Greece). Our results provide policy recommendations that reflect the technological, socioeconomic, and institutional conditions in each context, supporting targeted and effective electrification strategies at the global, regional, and national levels.

6.9.1 Global scale

Using PROMETHEUS, we examined energy transition pathways in the global buildings sector by 2050, and specifically scenarios covering different levels of climate policy ambition, including current policies and NDCs with LTTs. Overall, outcomes underscore the urgent need to enhance the ambition and implementation of NDCs by the Conference of the Parties of the UNFCCC (COP30). Our results highlight that current policies are insufficient to meet global climate goals, leading to modest global CO_2 reductions. In contrast, the combination of NDCs with LTTs can result in more than double emissions cuts by 2030 and 2050. Thus, we recommend that COP30 prioritise formal mechanisms to align NDCs with LTTs, encouraging countries to treat mid-century targets as drivers of near-term policy. This would require integrating sectoral pathways, especially for electrification and industry, into the 2035 cycle.

Our findings also show that each region has a specific role to play. The European Union and the United Kingdom

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are nearing their electrification and mitigation ceilings but must remain vigilant to ensure resilience, grid flexibility, and decarbonisation of hard-to-abate sectors. North America and Western Pacific regions, despite having the technical capacity and high baseline electrification, show minimal additional progress under current policies, a red flag that should be a core focus of COP30 discussions, promoting stronger national policy commitments, the removal of fossil-fuel subsidies and the scaling of clean energy incentives to fully harness the decarbonisation potential of these regions. India, Emerging Markets, and Energy-Producing Countries regions face steep emissions growth under current policies but show the potential for moderated growth with stronger support. The focus must be on clean infrastructure expansion and not on fossil lock-in. Special attention is needed for the Rest of the World region, where electrification remains below 20% by 2050. Especially in this region, structural barriers must be tackled through international climate finance, technology transfer, and tailored capacity building in order to meet equity and just transition goals.

6.9.2 Regional scale: European Union plus the United Kingdom

By harmonising primary energy consumption between Aalto-EU-TIMES and EnergyPLAN, we analysed different future energy system scenarios for the European Union and the United Kingdom region. Focusing on the EnergyPLAN application, we explored energy system impacts from the extensive implementation of flexibility in electricity consumption across households, industries, and electric vehicle (EV) charging, aiming to quantify the potential positive effects of flexibility. To do so, we compared a baseline scenario with a scenario developed based on smart energy system principles.

Our findings highlight the importance of a comprehensive approach to energy system flexibility, beginning with the promotion and incentivisation of demand-side flexibility. This includes encouraging the adoption of smart technologies, such as smart meters, home energy management systems (HEMS), and bidirectional EV chargers, that enable consumers to shift electricity use in response to system needs. This will require support of flexible electricity demand across all end-use sectors (i.e., residential, commercial, industrial, and transport) and can be further achieved through dynamic pricing, time-of-use tariffs, and demand-response programmes.

Enhancing consumer engagement and awareness is equally crucial, requiring tailored education about the benefits of flexible energy use for different consumer segments (e.g. homeowners, tenants, SMEs), alongside tools that help manage their consumption effectively. Behavioural change should also be encouraged through targeted campaigns and incentives that align individual choices and actions with system-wide efficiency goals.

At the same time, as shown by our results, it is important to acknowledge the limitations of demand-side flexibility, which, while beneficial, can only deliver modest system-wide gains in isolation. Therefore, broader system integration is needed, including investment in complementary flexibility solutions such as thermal storage, PtX technologies (e.g., green hydrogen, synthetic fuels), and district heating and cooling networks. These options offer significant energy-shifting potential and should be coordinated with the large-scale deployment of VRE and sector coupling to maximise the effectiveness of all flexibility measures across electricity, heating, transport, and industry.

6.9.3 National scale: European Union plus the United Kingdom

By harmonising the primary energy consumption between PROMETHEUS and Aalto-EU-TIMES, we performed a country-by-country analysis of the residential energy transition in the European Union and the United Kingdom region by 2050, looking into decarbonisation pathways that are compatible with the “Fit-for-55” policies and the EU Green Deal’s objectives. Our findings highlight that, while deep decarbonisation in the European residential sector through electrification is technically feasible and already underway in many parts of Europe, achieving equitable and timely progress requires a well-targeted and multi-level policy response. Our modelling underscores both regional successes and disparities that demand nuanced action.

First and foremost, the energy transition in Europe must be fair and tailored to national and regional contexts, particularly given the unique challenges faced by Southern and Eastern European countries that shape their electrification potential. These include climatic conditions leading to high seasonal variation in terms of heating and cooling needs, economic barriers such as high upfront investment costs, and structural constraints like limited

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availability of skilled installation companies. The divergence in electrification and emissions reduction trajectories between frontrunner and lagging countries underscores that a one-size-fits-all approach is inadequate. As such, we suggest that electrification strategies must be tailored to regional and national differences through flexible, context-sensitive policy instruments that ensure a fair and inclusive transition across all the European countries. Furthermore, EU-level funding mechanisms should be more responsive to these national contexts by prioritising support and allocating greater resources to countries facing limited fiscal capacity and higher transition costs.

Our findings highlight that accelerating electrification in European regions requires not only cleaner electricity but also robust infrastructure and institutional capacity. Upgrading the distribution grid is essential to accommodate rising household electricity demand. However, national governments should also significantly increase investments in self-consumption, storage, and smart-home technologies, while ensuring that the energy transition does not rely excessively on grid expansion alone.

It cannot be understated that a successful transition also hinges on a diversified and accelerated shift to renewable-based heating, which entails both scaling up clean energy solutions and phasing out fossil-fuel boilers. We recommend that Member States implement integrated, technology-neutral support schemes that encourage the adoption of a wider range of renewable-based heating and cooling solutions, including heat pumps and geothermal energy, to reduce reliance on bioenergy. In parallel, they should also set binding national deadlines for phasing out fossil-fuel boilers in existing buildings well before 2040. Successful coordination of these efforts will accelerate the transition to low-carbon heating systems across Europe.

Apart from electrification, to achieve a zero-emission building stock, renovation efforts should be intensified, and investment must be mobilised for an inclusive and large-scale “Renovation Wave”, focusing on deep and staged renovations. In this context, Member States should align higher levels of financial support with ambitious (staged) deep renovation projects that exceed minimum energy performance standard (MEPS) requirements, to prevent lock-in effects and maximise the impact of available funds. They must also ensure that public financial resources are used efficiently and distributed equitably, envisioning support for vulnerable and low-income households, to guarantee an inclusive “Renovation Wave” that leaves “no one behind” and accelerates the shift toward zero-emission buildings.

Finally, the effectiveness of targeted buildings sector policies depends on establishing local delivery capacity and empowering households, which involves overcoming barriers such as limited access to information about investments and addressing cultural preferences, including attitudes towards heat pumps and small-scale solar PV systems. In this regard, we suggest that EU and national programmes invest in training local authorities, offer subsidies, or low-interest loans for households, and launch information campaigns at the local level to boost technology uptake.

6.9.4 National scale: India

By harmonising the primary energy consumption between PROMETHEUS and AIM-Enduse India, we explored long-term energy transition pathways for India. Our results show that electrification and fuel substitution will play a critical role in India’s pathway to achieving net-zero emissions. This transition is particularly urgent in light of India’s escalating challenges, including the unprecedented growth of its building stock over the next three to four decades, combined with rising temperatures and intensifying heatwaves that are occurring more frequently and starting earlier in the year. In this context, prioritising electricity as the dominant energy source in the buildings sector becomes essential, as it aligns with the growing demand for efficient and sustainable cooling technologies. Given that buildings already contribute 25% of India’s total GHG emissions, a failure to shift towards clean electrification and energy efficiency strategies could significantly hinder India’s ability to meet its net-zero target by 2070.

Of course, future strategies must go beyond operational improvements like electrification and efficiency; they also need to address embodied emissions through the use of low-carbon materials and promotion of circular economy. While this study incorporates important elements related to lifestyle changes, energy efficiency, and renewable energy integration, it does not explicitly capture climate-resilient building design within its scenario design. This remains a critical area for further research and policy development, especially as climate extremes intensify and

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urban infrastructure rapidly expands. Moreover, the transition must address not only emissions but also consider the broader implications of energy use, equity, and access to thermal comfort. India's decision not to sign the Global Cooling Pledge at COP28 reflects the ongoing tension between ambitious climate targets and the imperative to provide affordable, accessible cooling for its population, especially for the most vulnerable. Balancing this social imperative with climate mitigation goals will require robust climate policies that simultaneously advance emissions reduction and human well-being.

6.9.5 National scale: Greece

Using DREEM and soft-linking it with PROMETHEUS, we also examined energy transition pathways in the Greek residential sector by 2050, based on the scenario aligned with the NECP-2024. We followed the renovation plan for the residential sector and the trends for the projection of energy consumption for each heating technology outlined in NECP-2024, along with the technology penetration of heat pumps according to data obtained from the Ministry of Enironment and Energy. We find that the energy transition by 2050 is projected to reduce energy consumption by 42% compared to 2022, primarily driven by phasing out oil and gas boilers and enhancing building envelope renovations. Electrification is expected to play a pivotal role in the energy transition, as energy consumption declines while electricity consumption increases, primarily due to the widespread adoption of heat pumps. Additionally, the amount of CO_2 emissions avoided (142 $MtCO_2$ in 2050) due to interventions, underscores the critical role of electrification and its significant contribution to achieving the overall national climate objectives.

Our findings provide policymakers with tailored policy recommendations that could help shape the NBRP of Greece. First, achieving Greece's ambitious energy-efficiency targets, as outlined in the NECP-2024, requires prioritising interventions that offer the greatest impact. Considering our results, priority should be given in the replacement of inefficient heating systems, particularly oil and gas boilers, which are widespread in the Greek residential sector. This should be followed by building envelope renovations. These interventions can significantly reduce final energy consumption, while also improving thermal comfort and overall living conditions for residents. In parallel, they lower household energy bills, delivering tangible financial benefits to consumers and reinforcing public support for the transition.

In addition to upgrading buildings, the decarbonisation of Greece's residential sector must be accompanied by a gradual restructuring of the national energy mix. This means phasing out oil heating entirely and sharply reducing natural gas use in favour of cleaner, renewable-based electrification. Aligning the energy supply with the consumption standards set by the NECP-2024 will be essential for ensuring that energy demand reductions are not undermined by continued reliance on fossil fuels.

Economic barriers, however, continue to pose significant challenges to the widespread implementation of building envelope renovations. To address this, Greece must scale up tailored financing mechanisms to make energy upgrades more accessible. Public funding should be strategically allocated to attract private investment and ensure that sufficient financial resources are available. Special emphasis must be placed on supporting vulnerable and low-income households, to guarantee an inclusive transition and actively combat energy poverty.

Finally, the success of the energy transition depends heavily on the engagement and participation of citizens. Increasing awareness of the long-term benefits of energy efficiency in the residential sector is critical. This includes not only awareness-raising actions and clear communication strategies but also the provision of substantial financial and fiscal incentives that can encourage behavioural change. Through targeted outreach and education, Greece can foster a culture of energy responsibility, reshape consumption habits, and build a culture of lasting public commitment to the goals of the energy transition.

6.10 Conclusions and cross-scale implications

Achieving decarbonisation of buildings demands a shift away from one-size-fits-all solutions towards multi-scalar action rooted in place, guided by robust data, and designed around the people and communities most affected by the transition. Our study demonstrates that while the technological solutions for decarbonising the buildings sector, such as heat pumps and energy-efficient renovations, are widely known and increasingly available, their

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deployment remains highly uneven across regions.

Cross-scale analysis reveals a complex landscape: the European Union continues to push forward with ambitious climate and energy targets, yet implementation is constrained by varying national capacities, housing stock characteristics, and socioeconomic conditions. Greece, for example, shows significant potential for impactful interventions such as replacing oil and gas boilers and improving building envelopes, but faces challenges around affordability, financing access, and public engagement. In India, the challenge is different: avoiding future carbon lock-in in rapidly urbanising areas while creating pathways for electrified, low-carbon housing aligned with rising demand.

These cases illustrate the critical importance of multi-level approaches. National strategies must provide the financial frameworks, regulatory clarity, and technical guidance needed to empower municipalities and local actors, who are often best placed to identify vulnerable populations, coordinate renovations, and ensure that social and climate goals align. At the same time, local delivery mechanisms need to be better integrated into national plans, supported with long-term funding and workforce development. Global policy ambition will fall short without on-the-ground implementation that is both equitable and adapted to local realities.

Moving forward, several areas require greater policy attention and further research. Financing mechanisms must be redesigned to overcome the persistent barrier of high upfront costs, especially for low-income households and small building owners. Strengthening workforce capacity, particularly through coordinated reskilling efforts for installers, auditors, and technicians, is essential to scale up renovations and clean energy deployment. In parallel, the development of high-resolution data and monitoring tools is needed to evaluate impact and ensure that energy poverty is addressed rather than exacerbated. Further research into sector-coupled systems, linking heat pumps with renewables, storage, and EVs, can help unlock additional efficiency gains and system flexibility.

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Wemhoener, C. (2020). *Field monitoring in nZEB with heat pump*.

ANNEX A

A1. An example of one Monte Carlo scenario

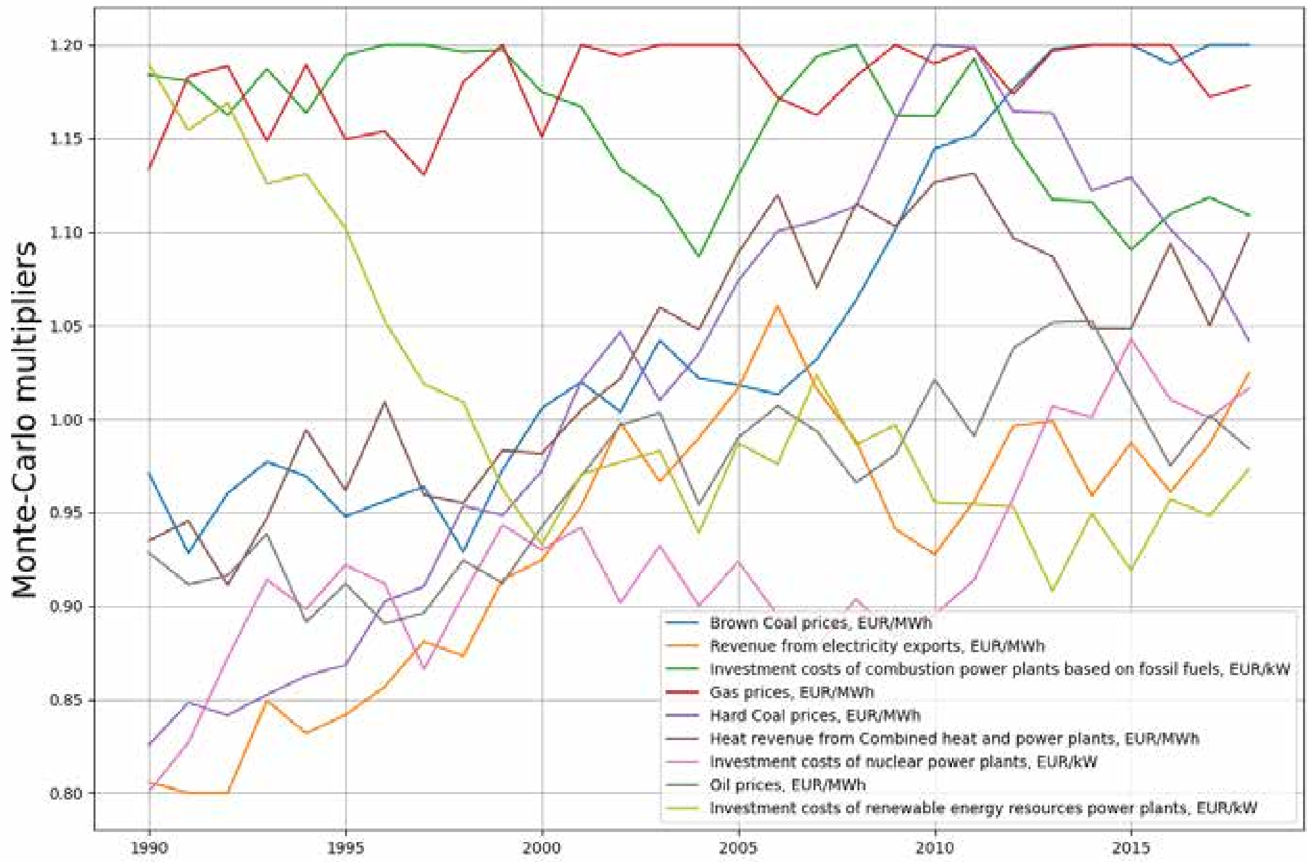

Figure A1. The Monte Carlo multipliers from the two-step draw of cost uncertainties as compared to the first Monte Carlo scenario.

A2. Results for single-year model

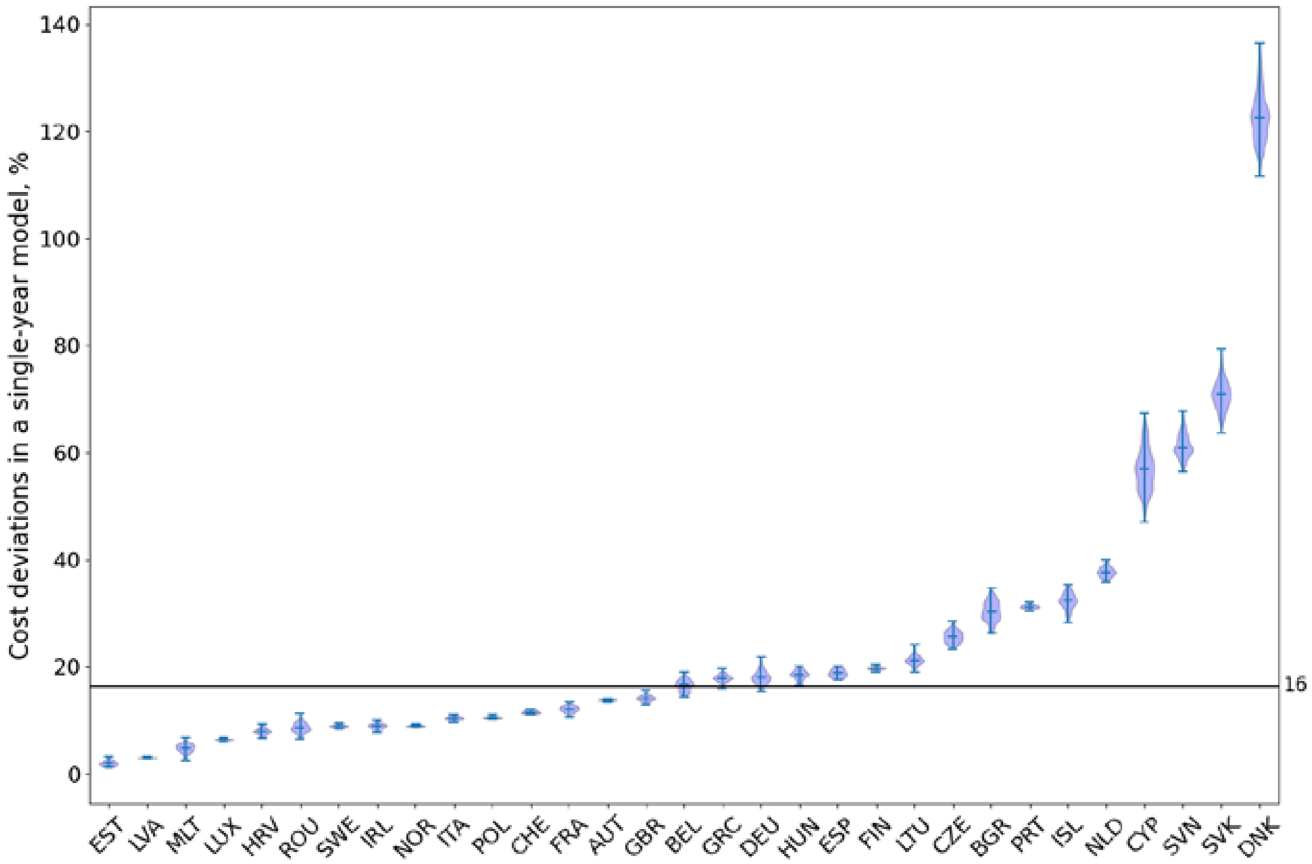

Figure A2-1. Distribution of cost deviations 10 years ahead (2000) for the 1.000 Monte Carlo runs for each of the 31 European countries. For each country, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution. Countries are sorted from lowest to highest median cost deviation. The black horizontal line shows the median value of 16% of all Monte Carlo runs and all 31 European countries.

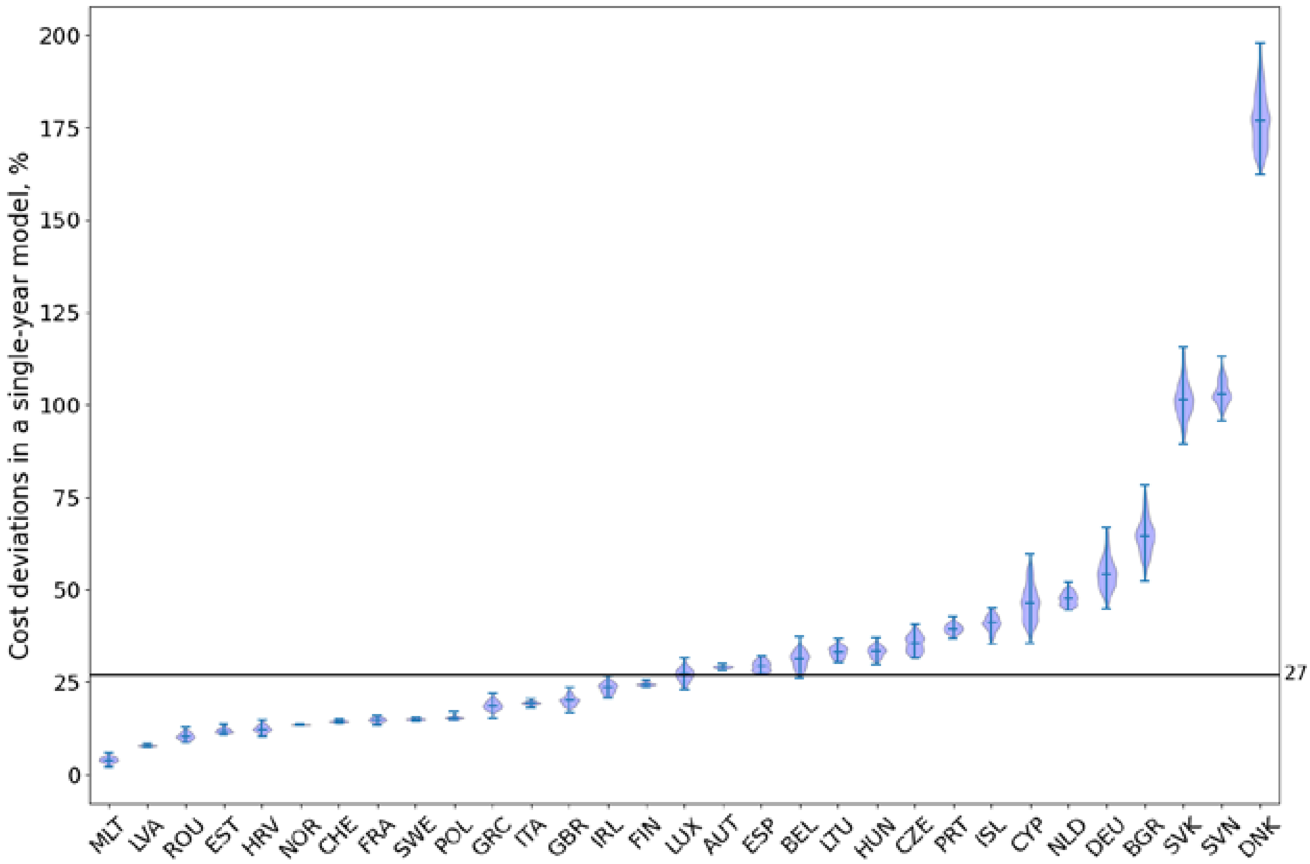

Figure A2-2. Distribution of cost deviations 15 years ahead (2005) for the 1.000 Monte Carlo runs for each of the 31 European countries. For each country, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution. Countries are sorted from lowest to highest median cost deviation. The black horizontal line shows the median value of 27% of all Monte Carlo runs and all 31 European countries.

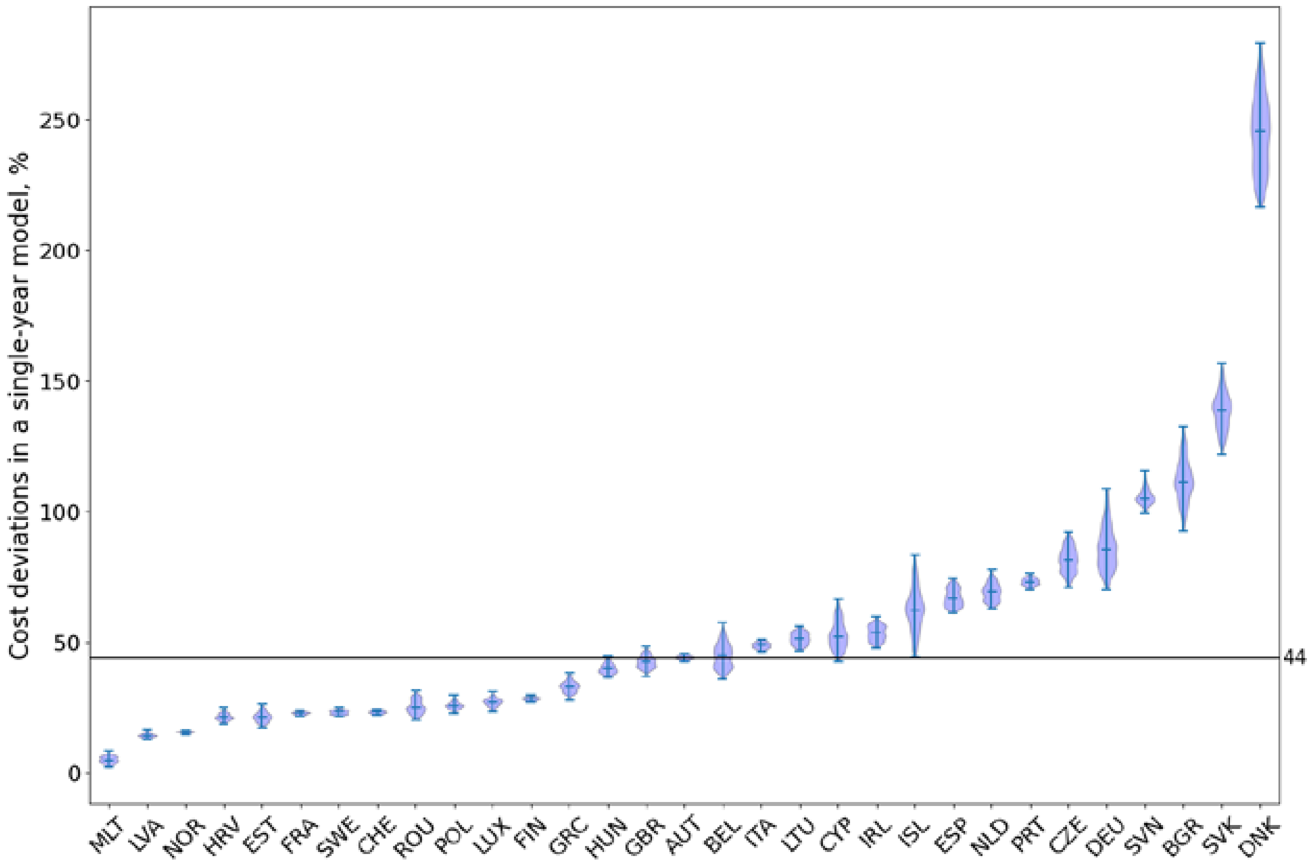

Figure A2-3. Distribution of cost deviations 20 years ahead (2010) for the 1.000 Monte Carlo runs for each of the 31 European countries. For each country, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution. Countries are sorted from lowest to highest median cost deviation. The black horizontal line shows the median value of 44% of all Monte Carlo runs and all 31 European countries.

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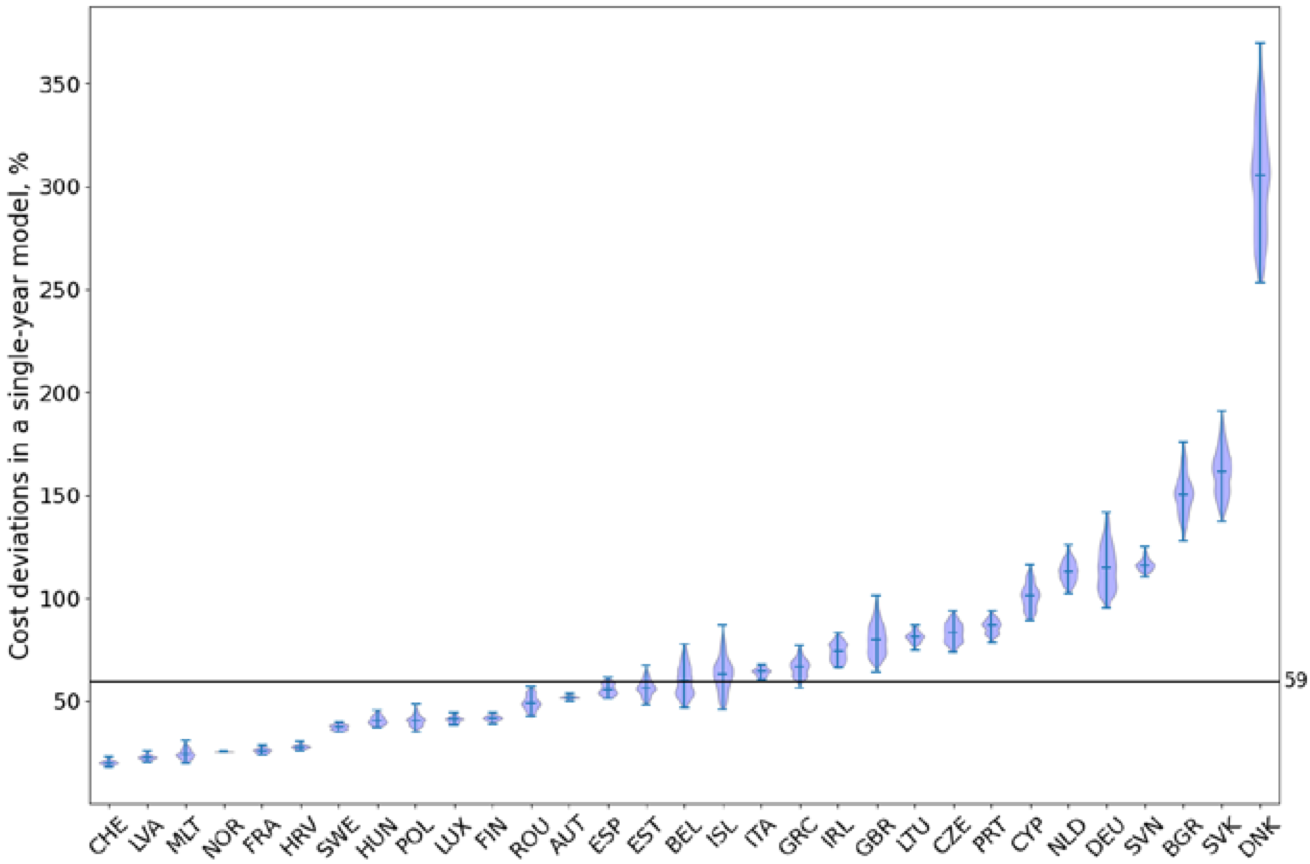

Figure A2-4. Distribution of cost deviations 25 years ahead (2015) for the 1.000 Monte Carlo runs for each of the 31 European countries. For each country, the minimum, maximum and median cost deviations are indicated by horizontal blue lines in the distribution. Countries are sorted from lowest to highest median cost deviation. The black horizontal line shows the median value of 59% of all Monte Carlo runs and all 31 European countries.

A3. Results per country

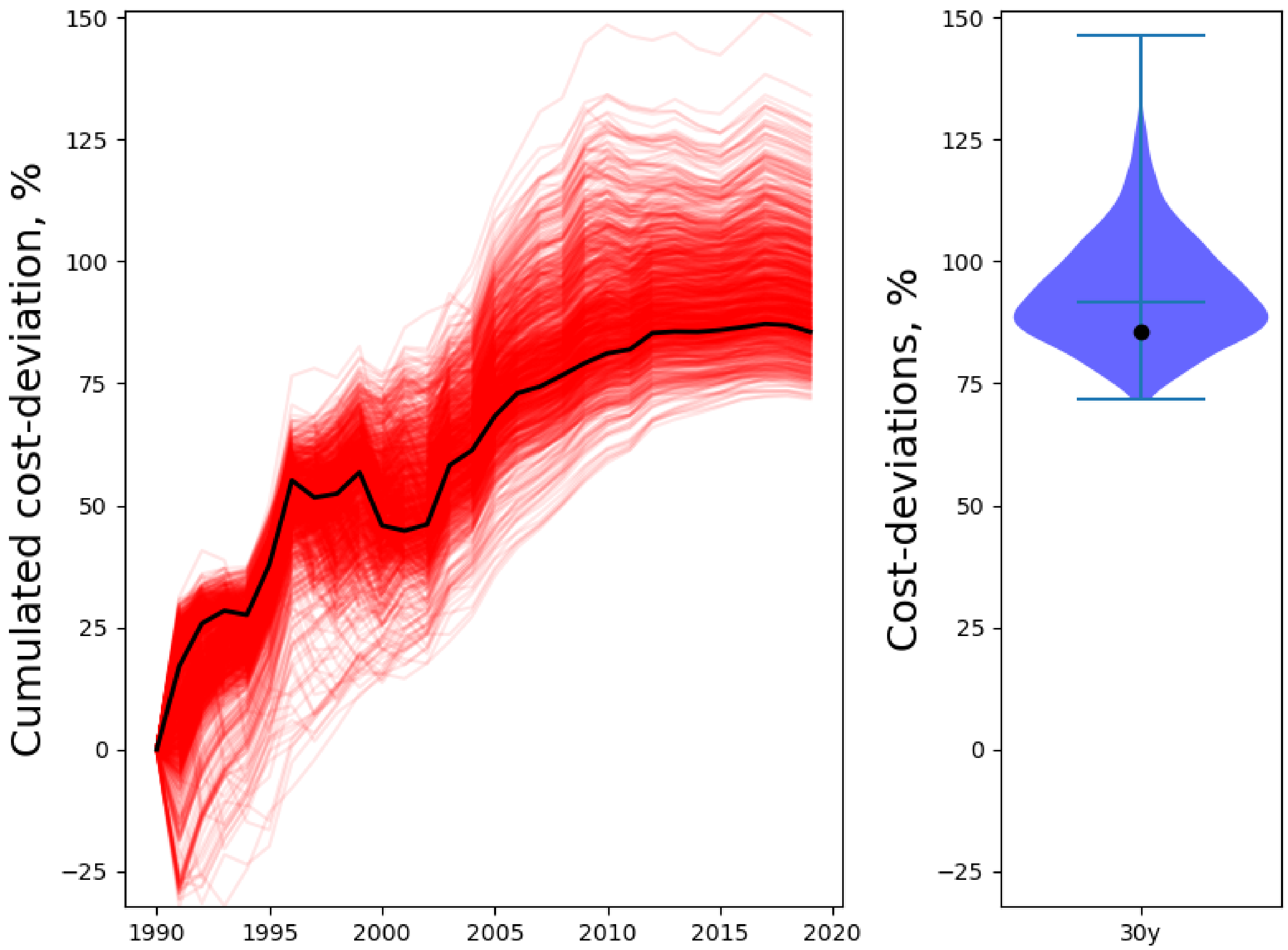

Figure A3-1. Evolution of cost deviations in Austria in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

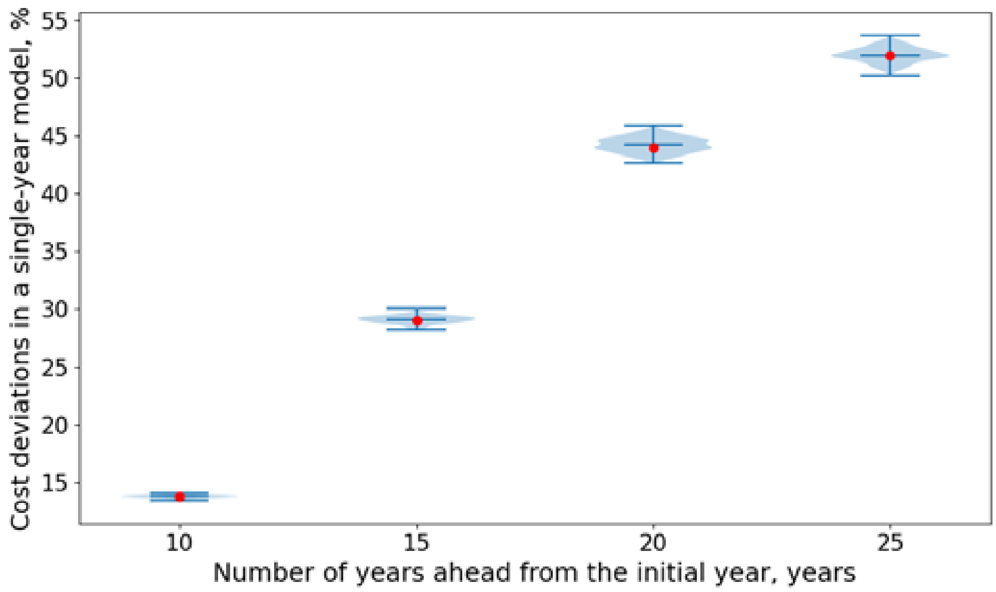

Figure A3-2. Distributions of cost deviations in Austria for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

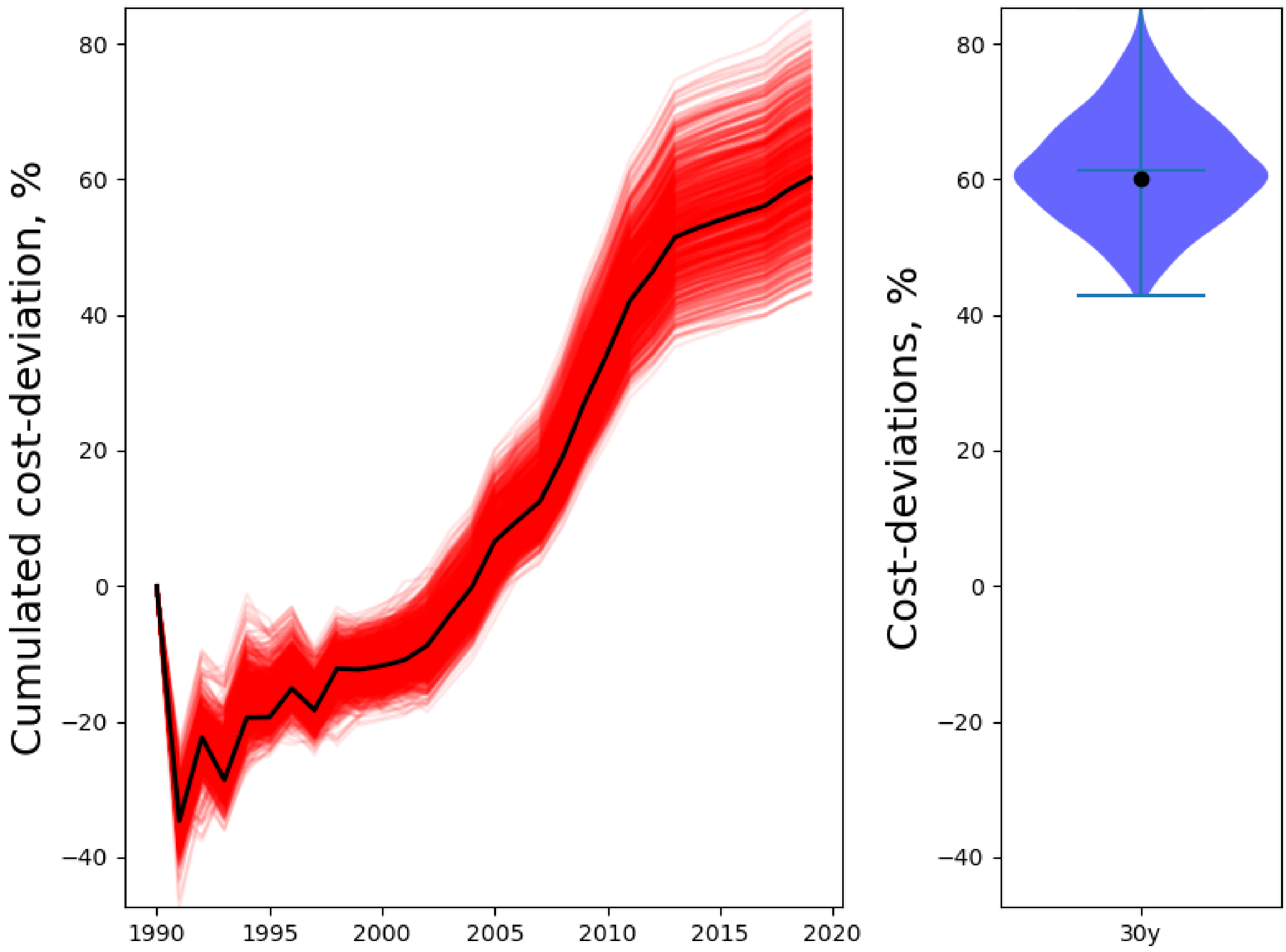

Figure A3-3. Evolution of cost deviations in Belgium in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

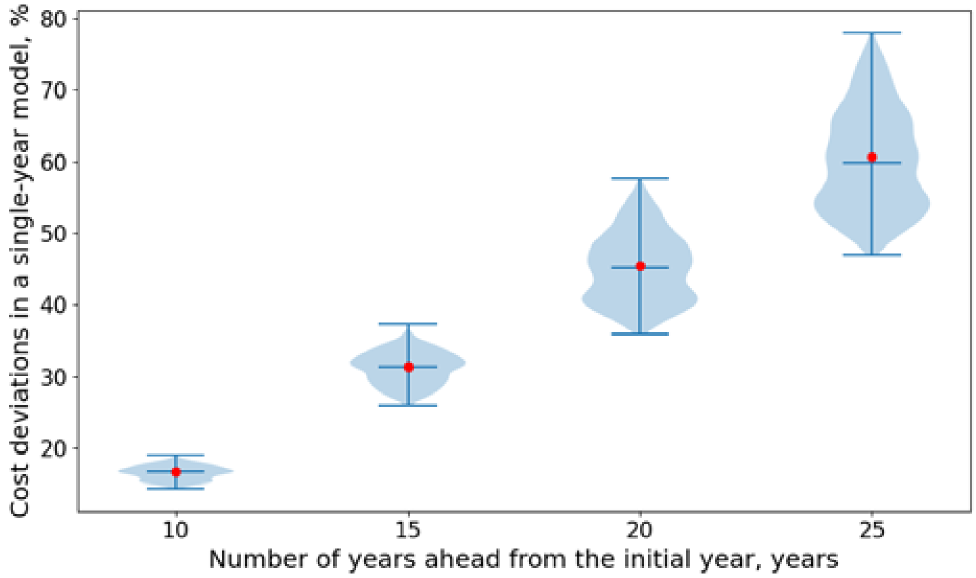

Figure A3-4. Evolution of cost deviations in Belgium for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

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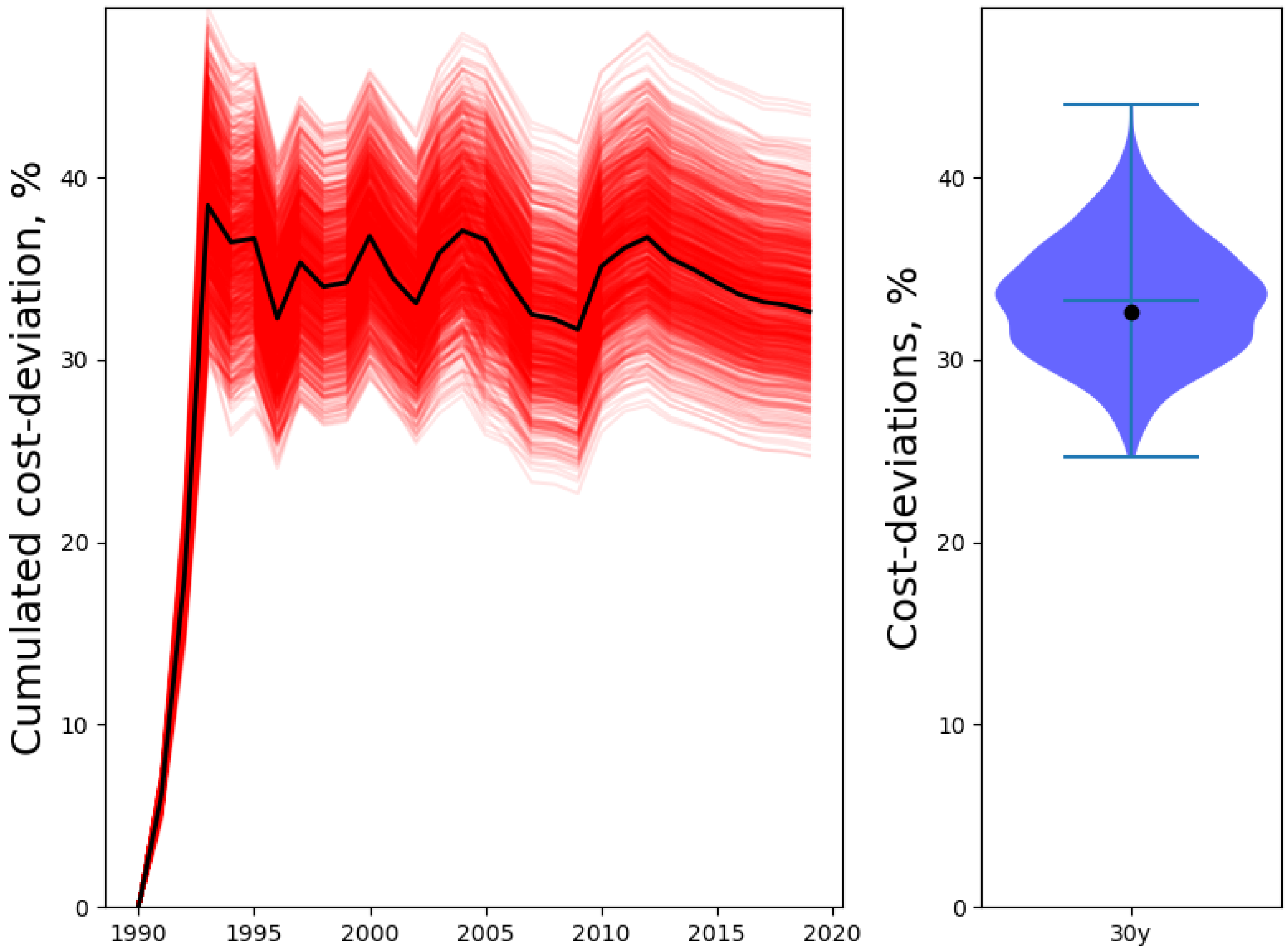

Figure A3-5. Evolution of cost deviations in Bulgaria in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

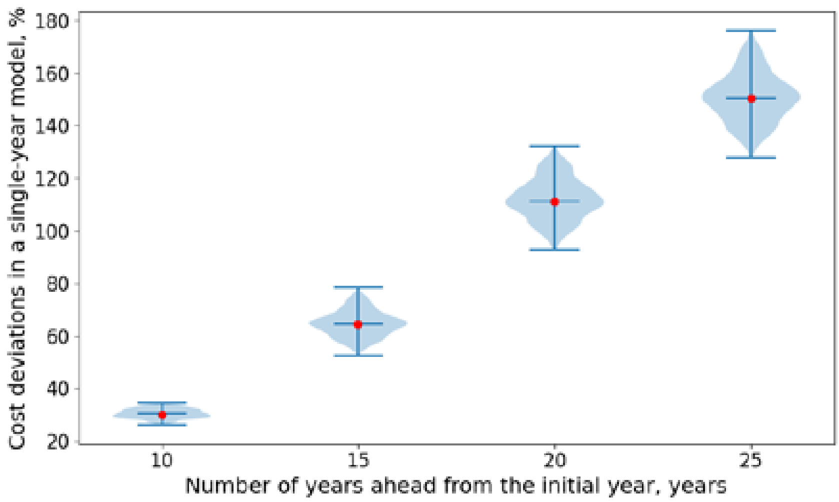

Figure A3-6. Evolution of cost deviations in Bulgaria for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

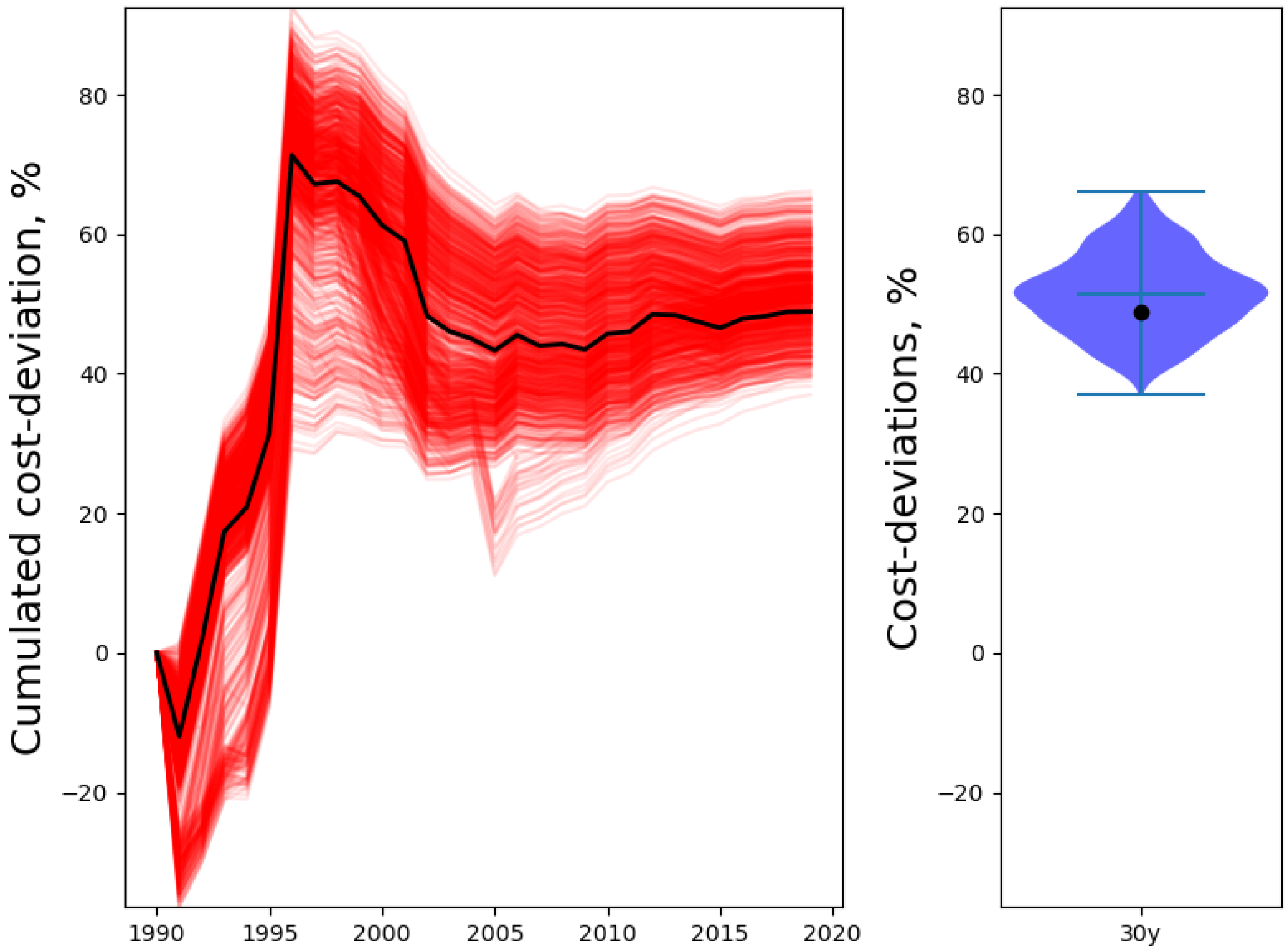

Figure A3-7. Evolution of cost deviations in Switzerland in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

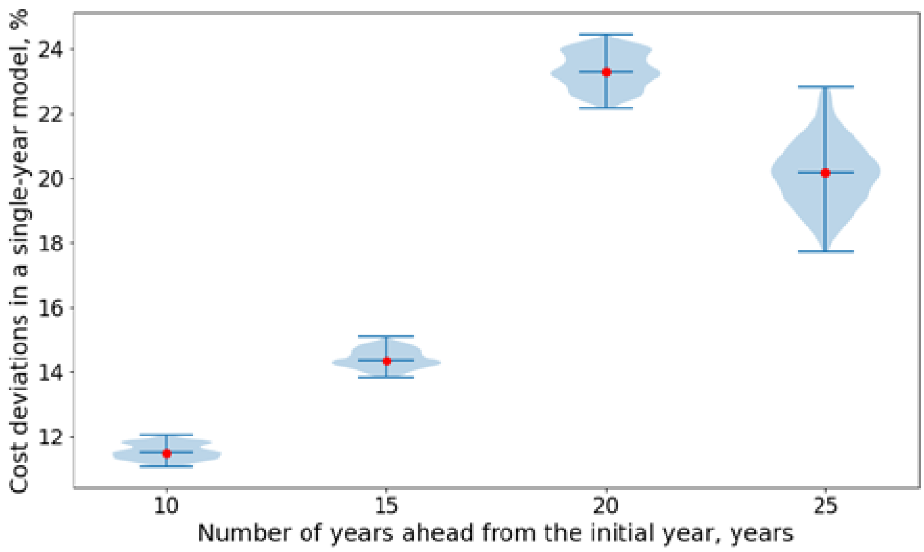

Figure A3-8. Evolution of cost deviations in Switzerland for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

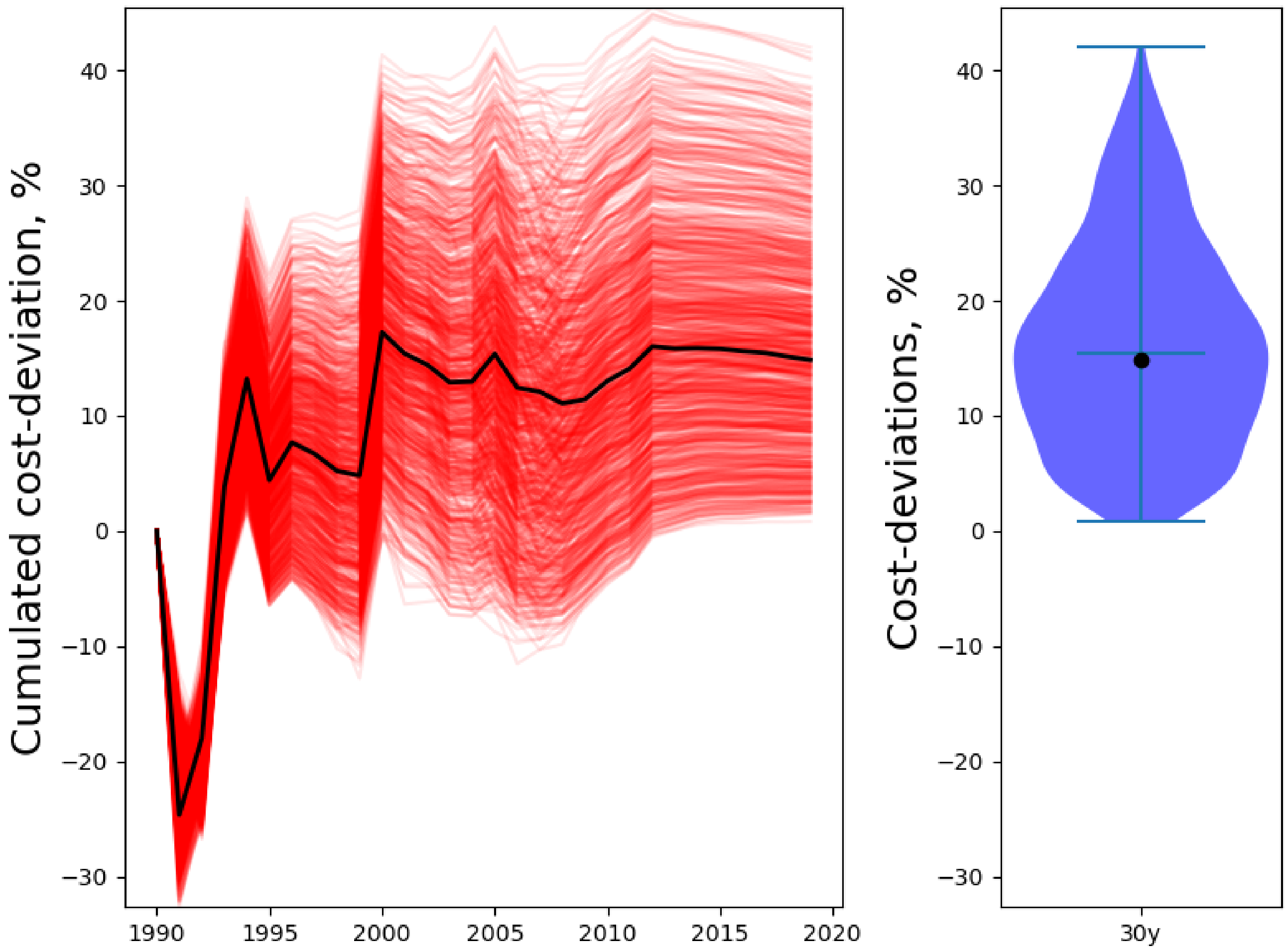

Figure A3-9. Evolution of cost deviations in Cyprus in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

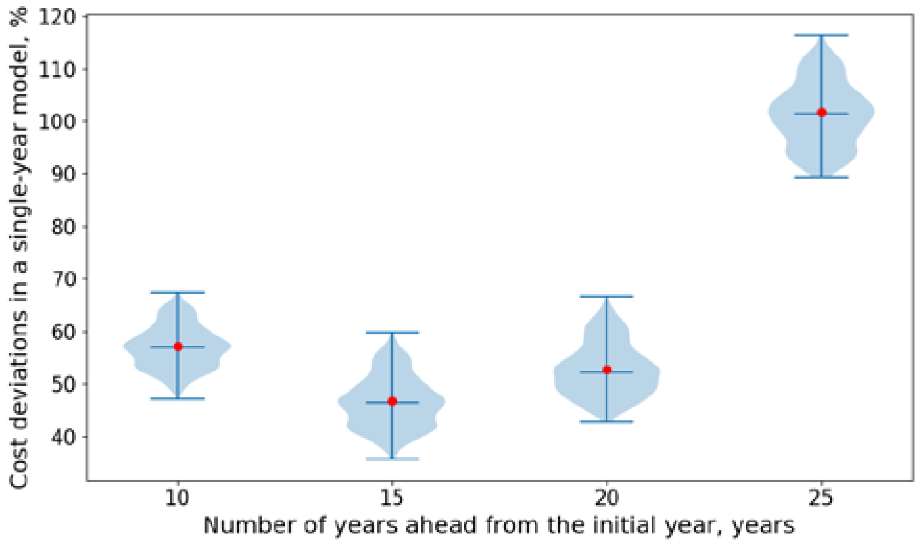

Figure A3-10. Evolution of cost deviations in Cyprus for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

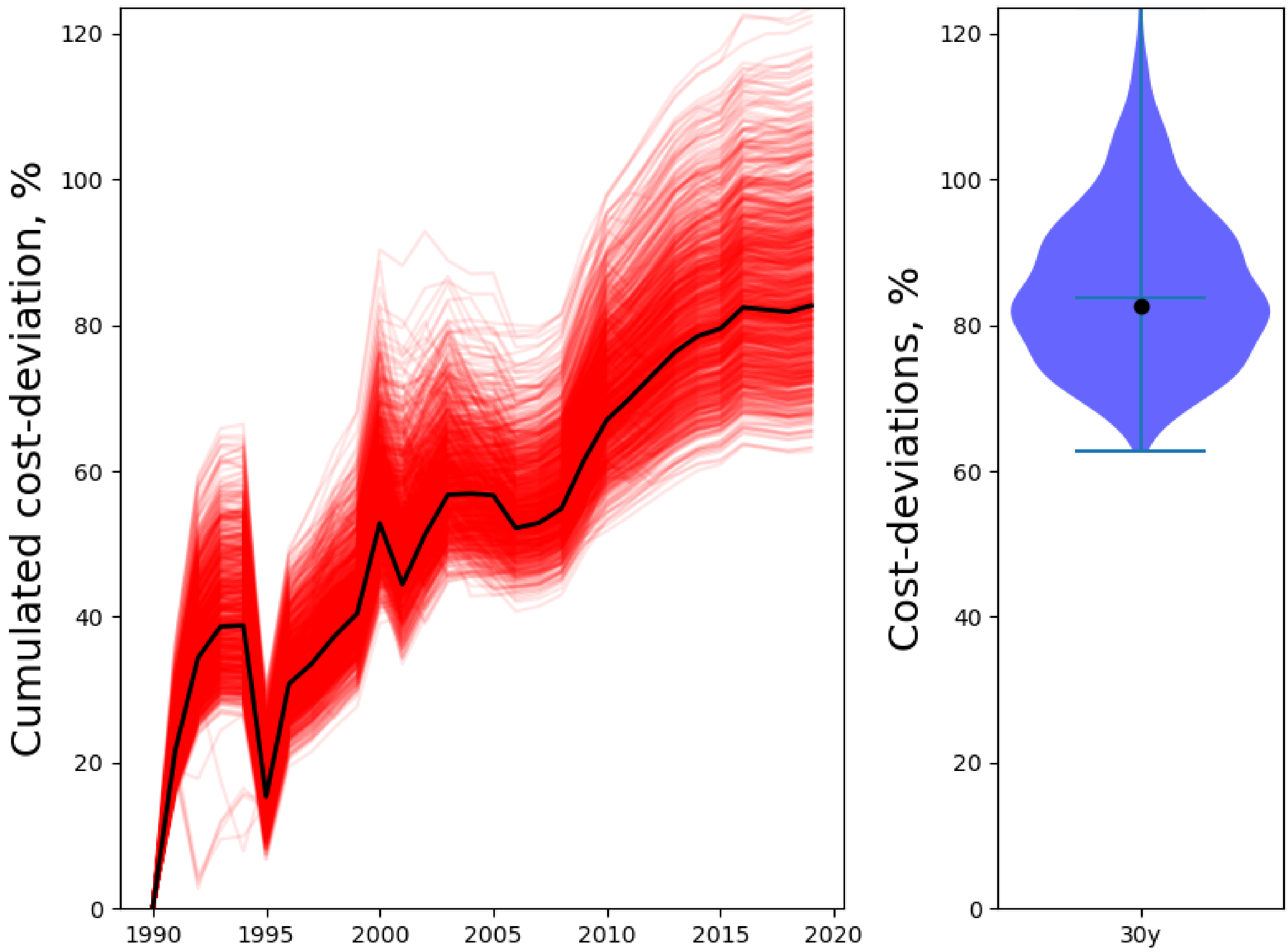

Figure A3-11. Evolution of cost deviations in Czechia in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

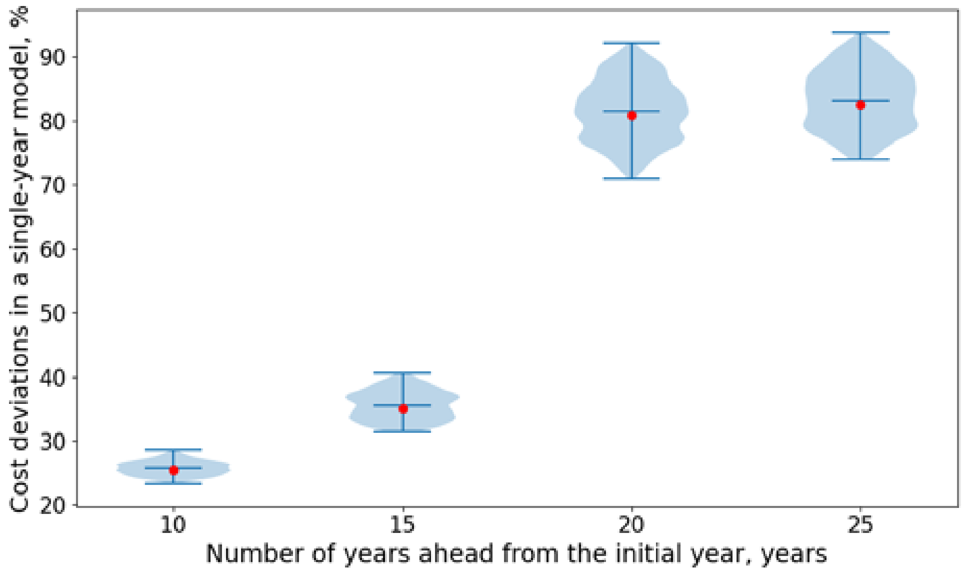

Figure A3-12. Evolution of cost deviations in Czechia for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

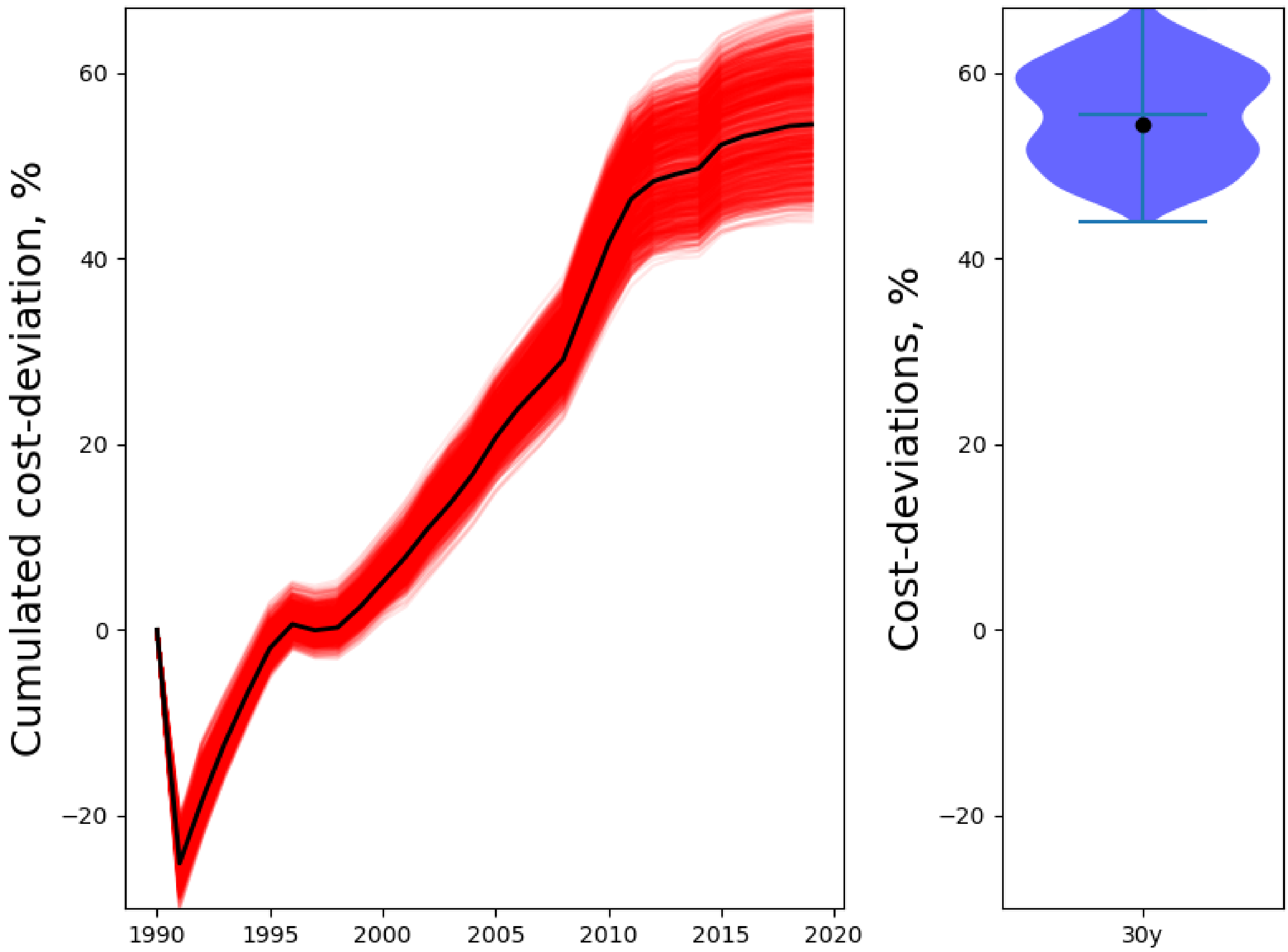

Figure A3-13. Evolution of cost deviations in Germany in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

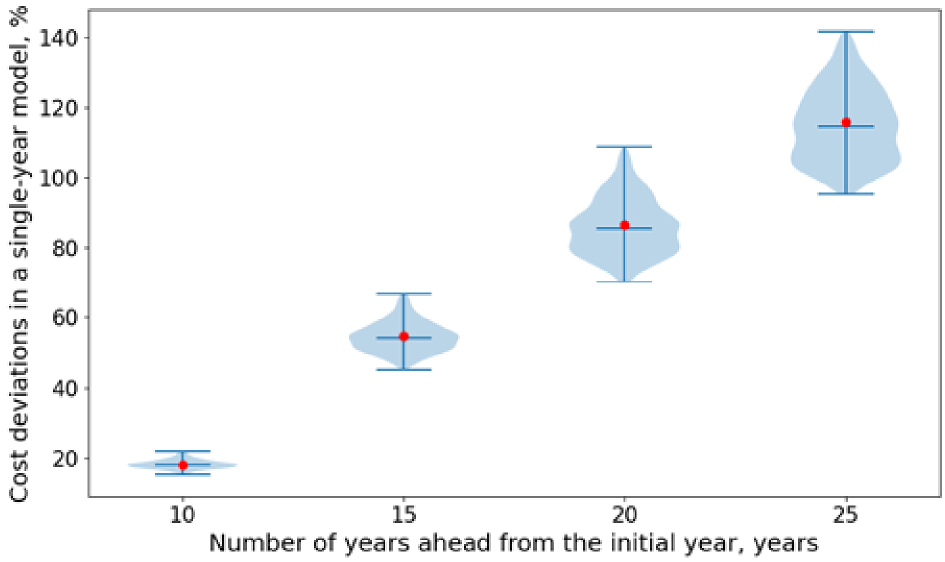

Figure A3-14. Evolution of cost deviations in Germany for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

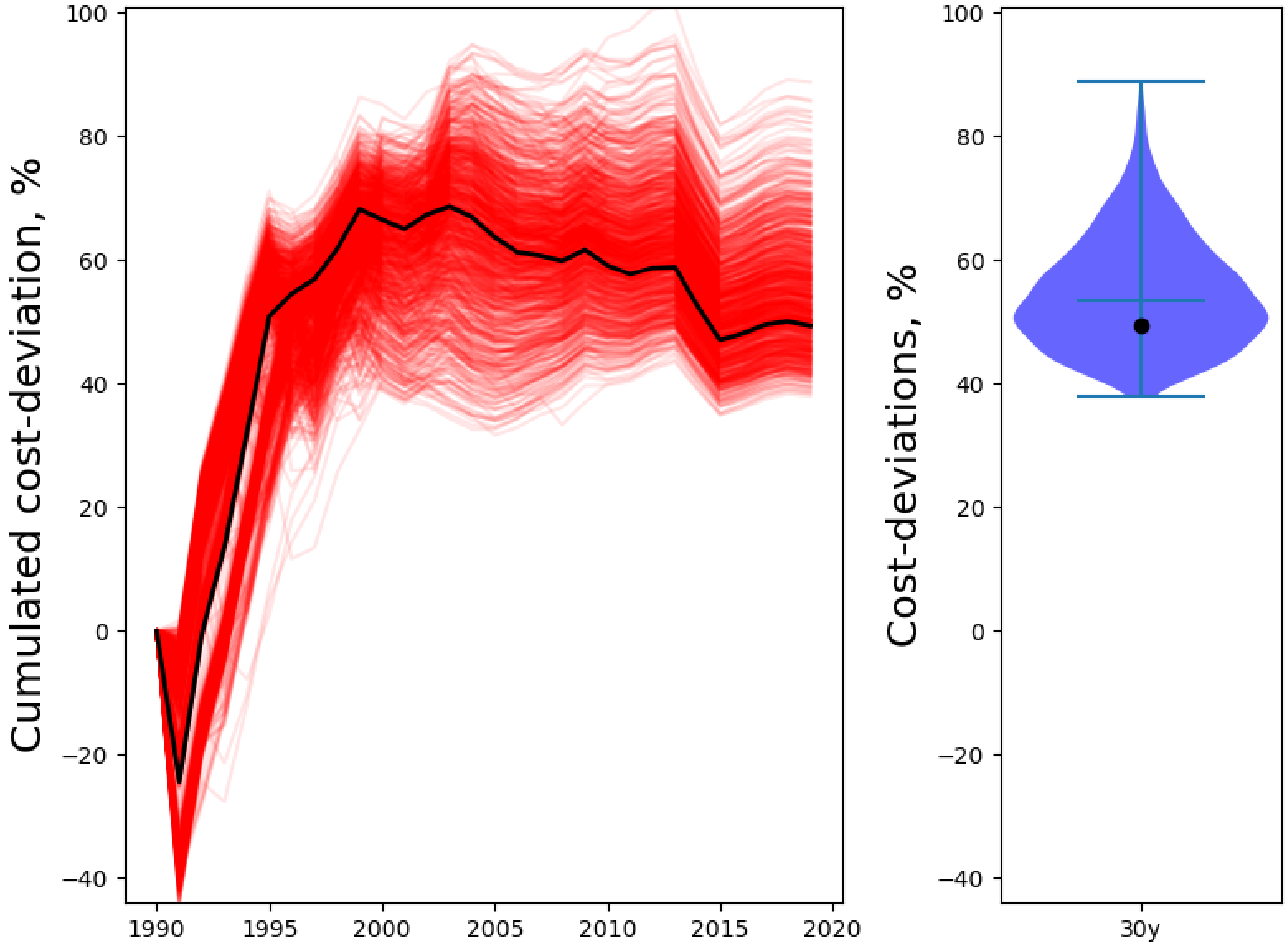

Figure A3-15. Evolution of cost deviations in Denmark in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

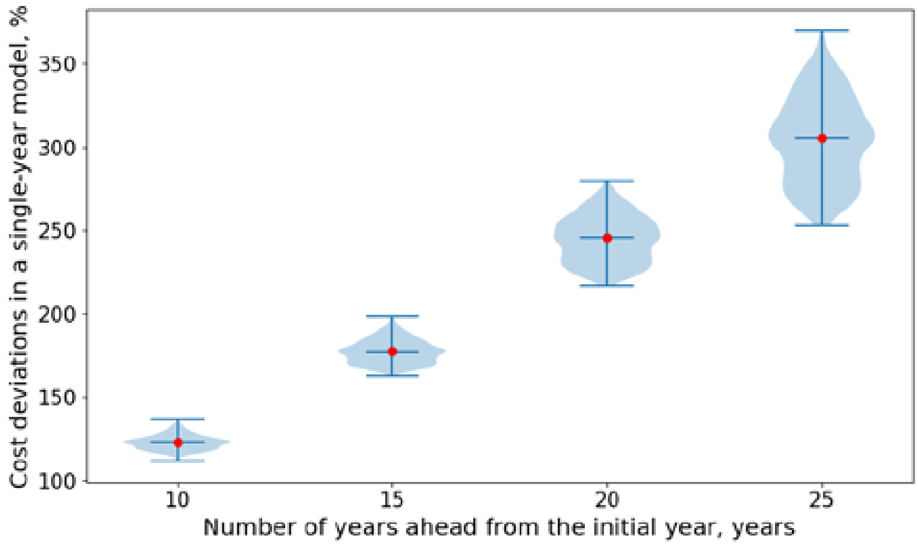

Figure A3-16. Evolution of cost deviations in Denmark for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

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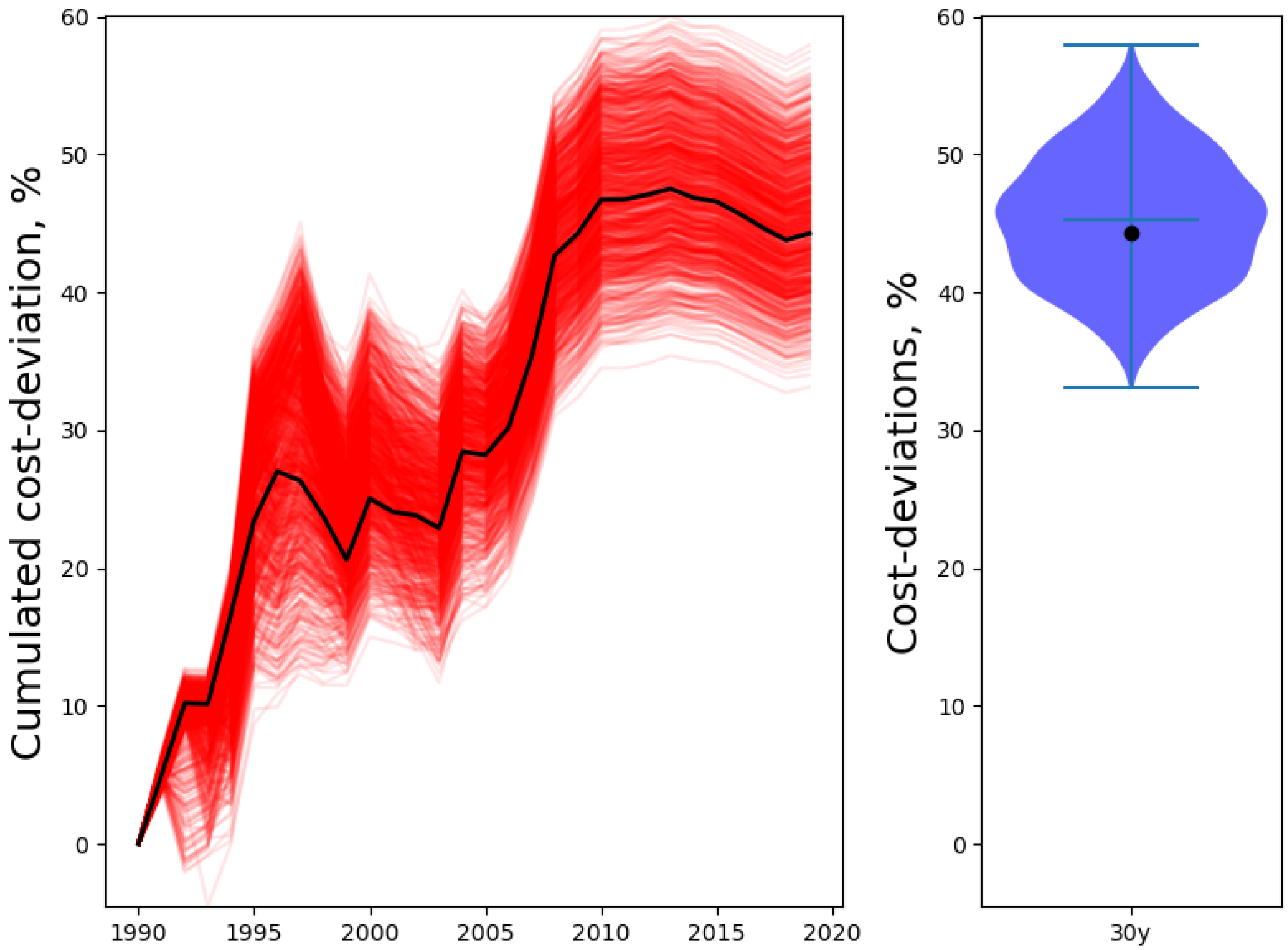

Figure A3-17. Evolution of cost deviations in Spain in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

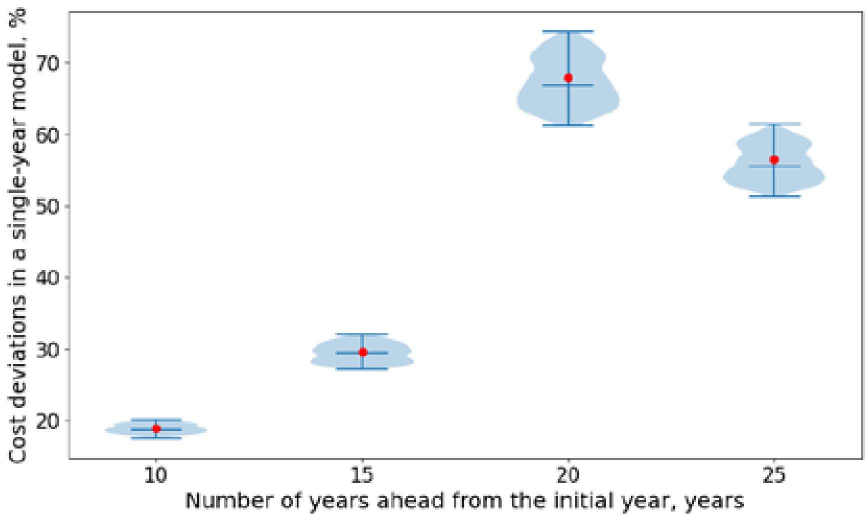

Figure A3-18. Evolution of cost deviations in Spain for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

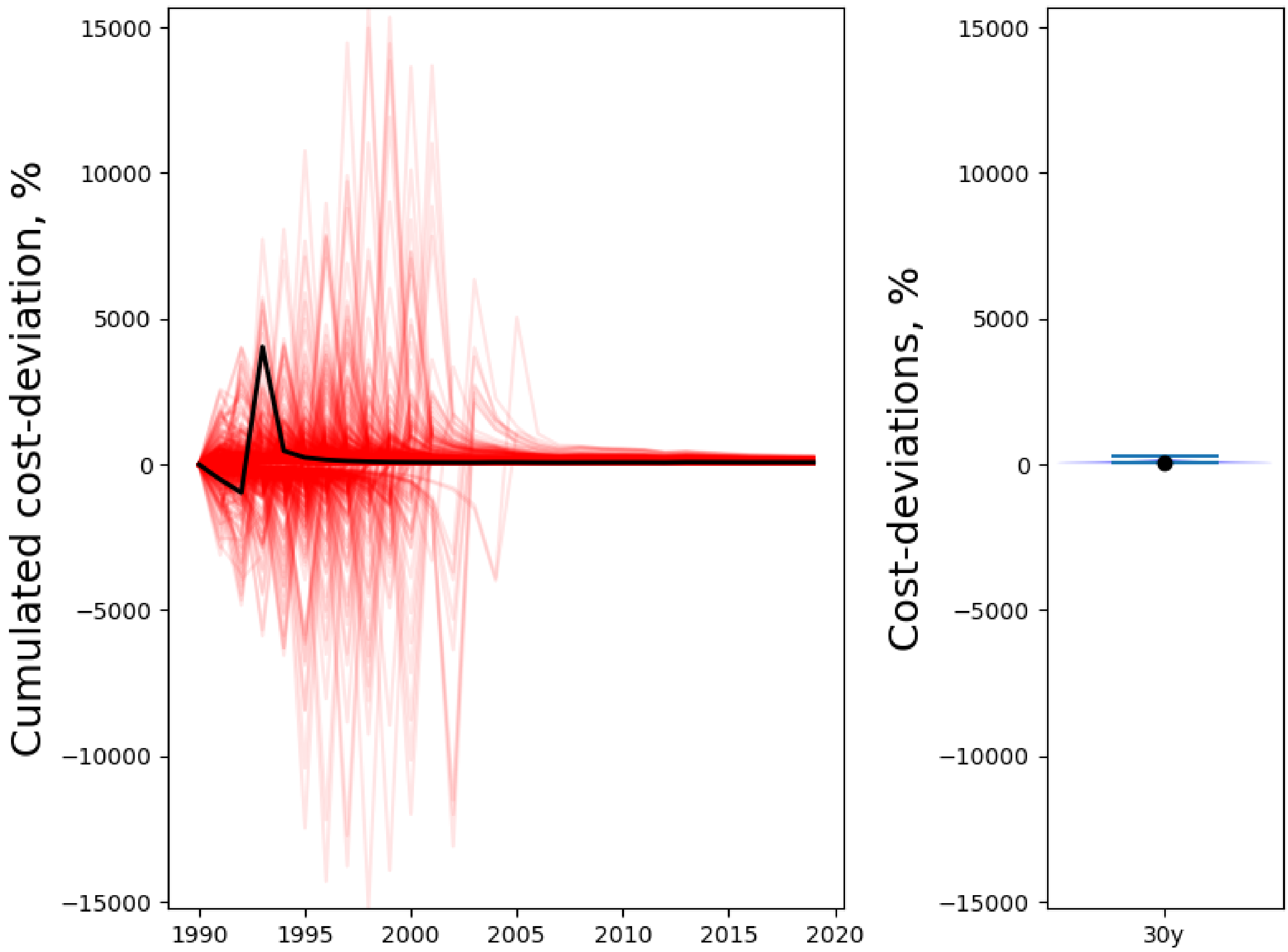

Figure A3-19. Evolution of cost deviations in Estonia in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

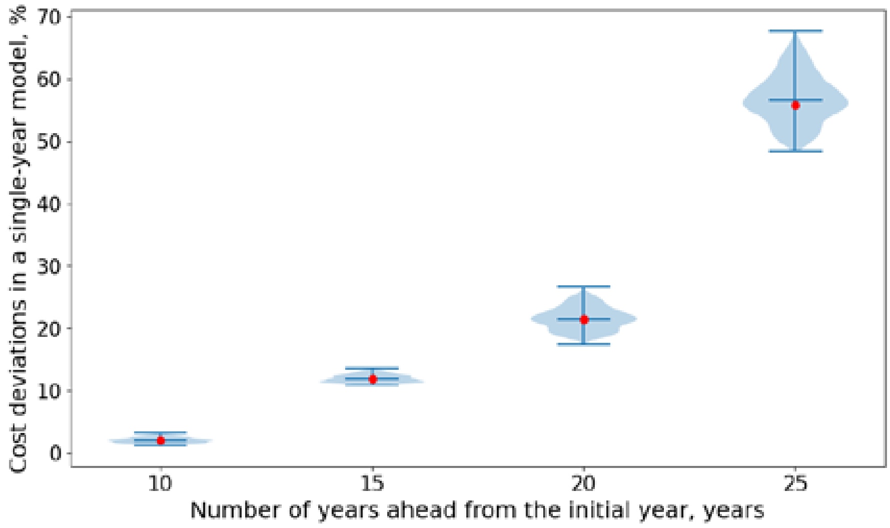

Figure A3-20. Evolution of cost deviations in Estonia for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

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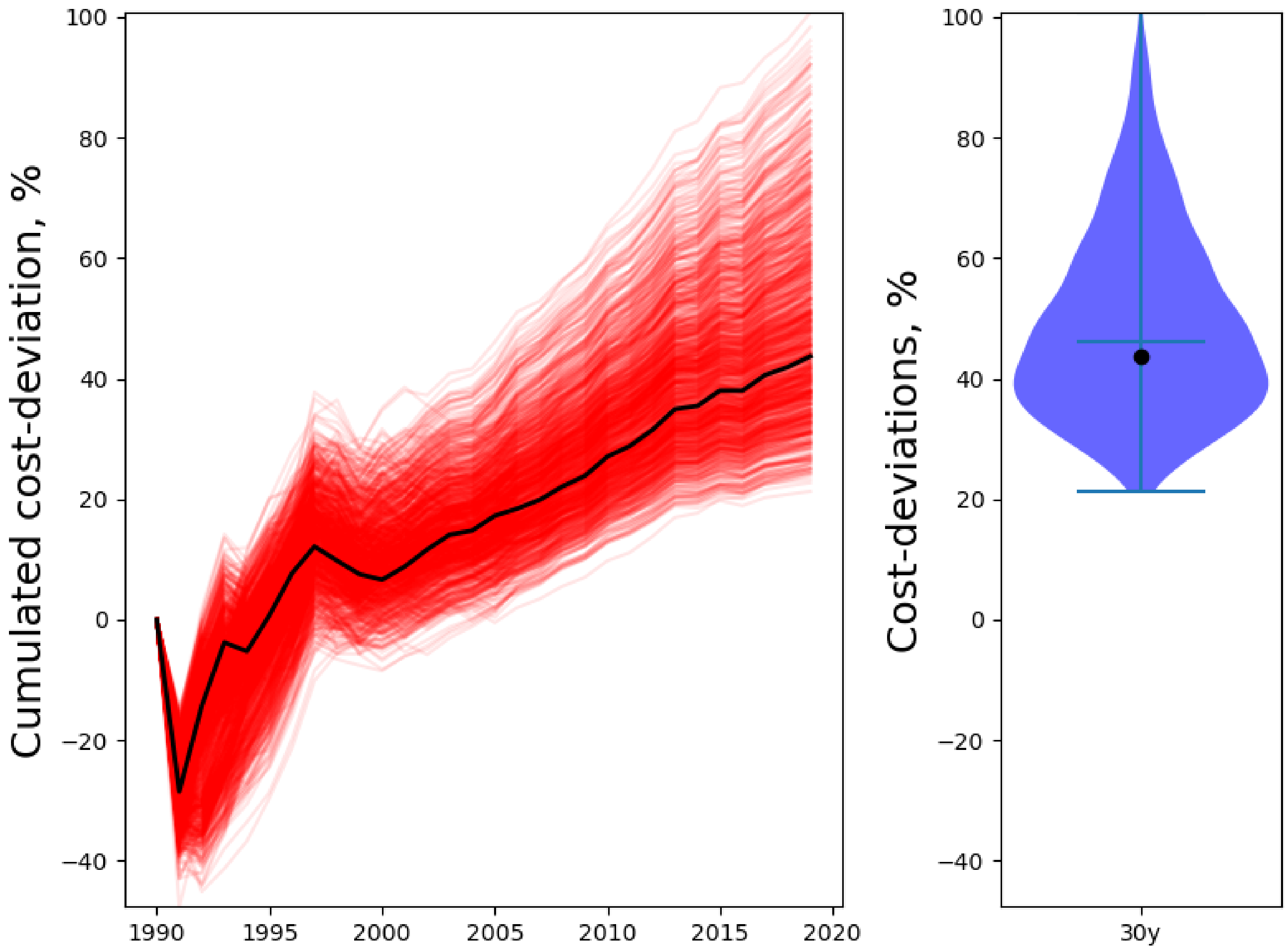

Figure A3-21. Evolution of cost deviations in Finland in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

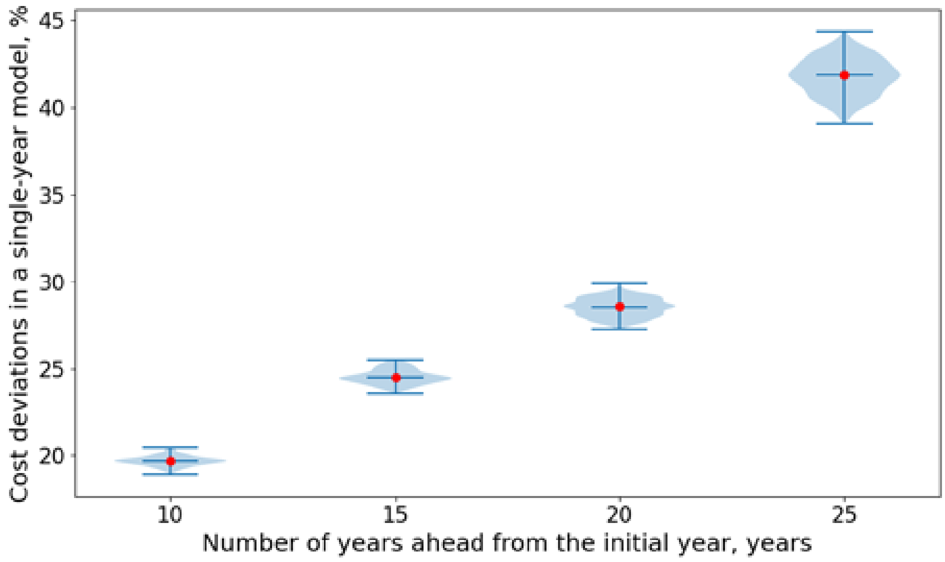

Figure A3-22. Evolution of cost deviations in Finland for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

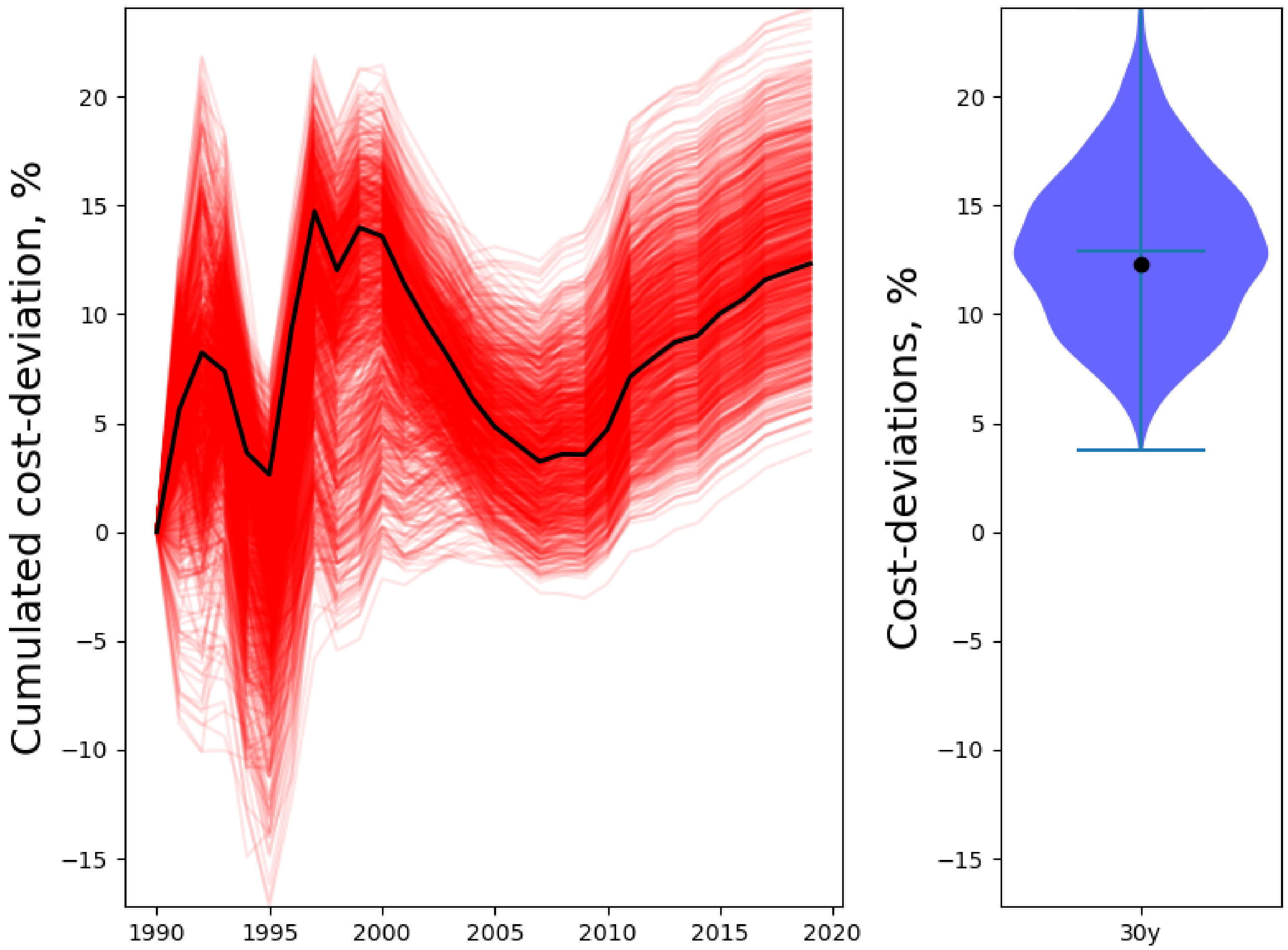

Figure A3-23. Evolution of cost deviations in France in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

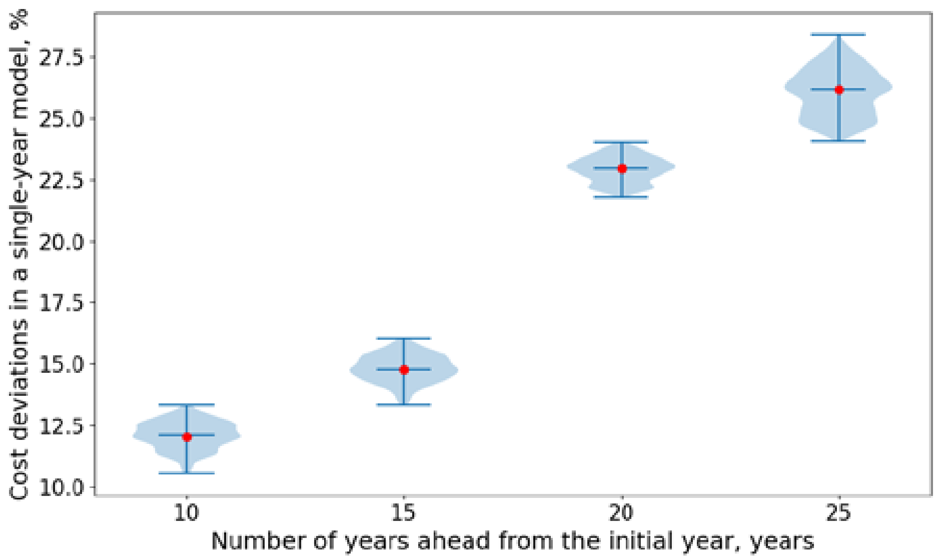

Figure A3-24. Evolution of cost deviations in France for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

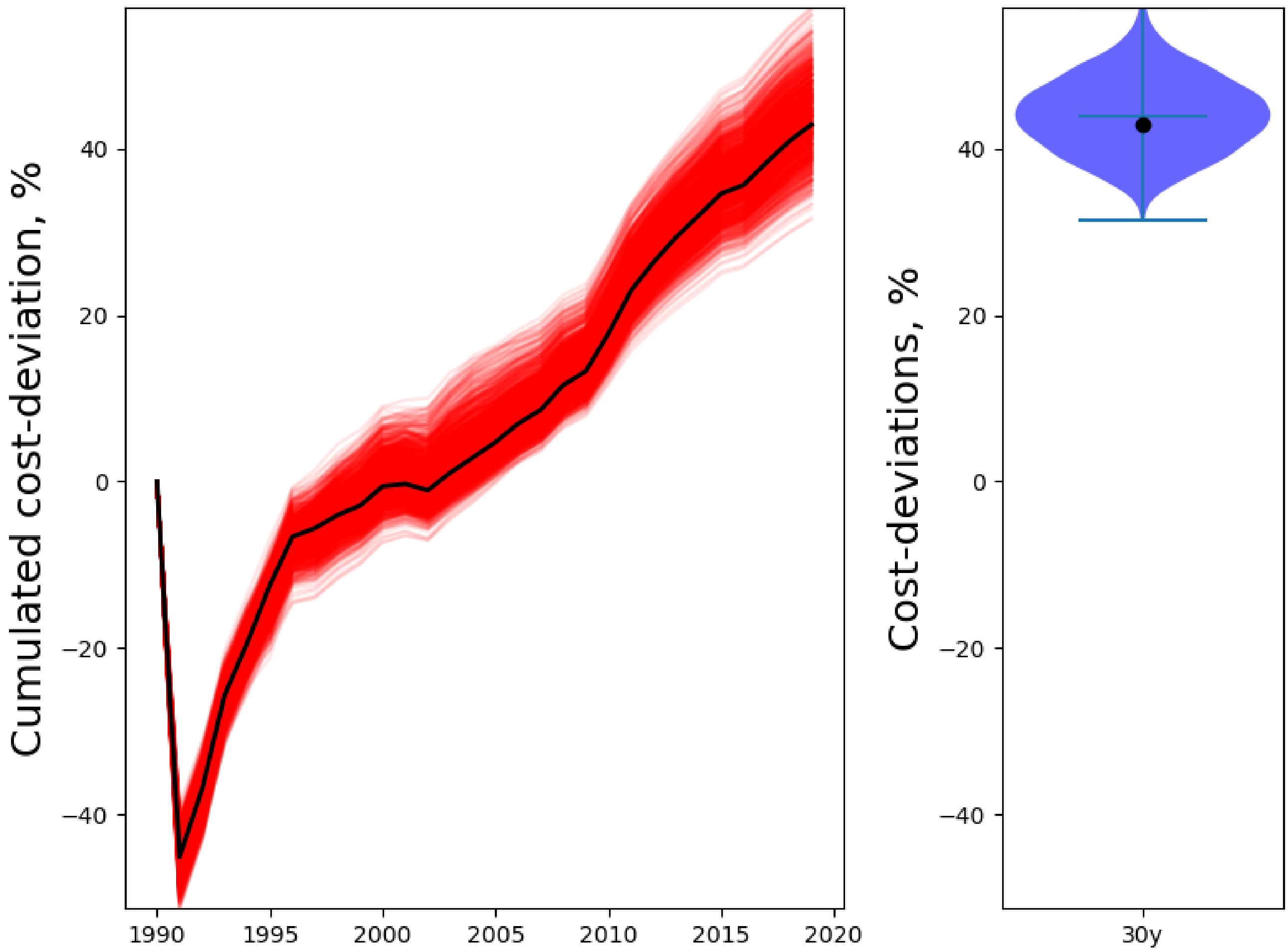

Figure A3-25. Evolution of cost deviations in United Kingdom in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

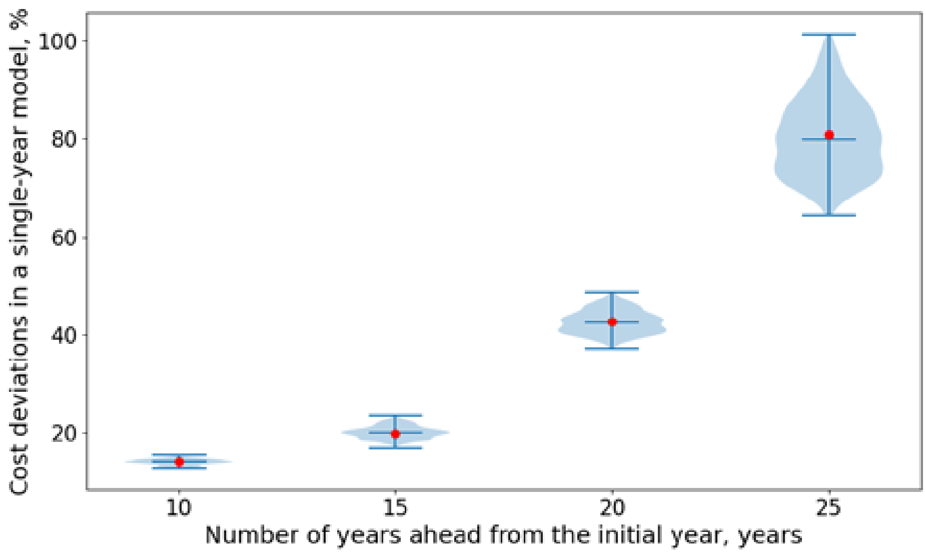

Figure A3-26. Evolution of cost deviations in United Kingdom for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

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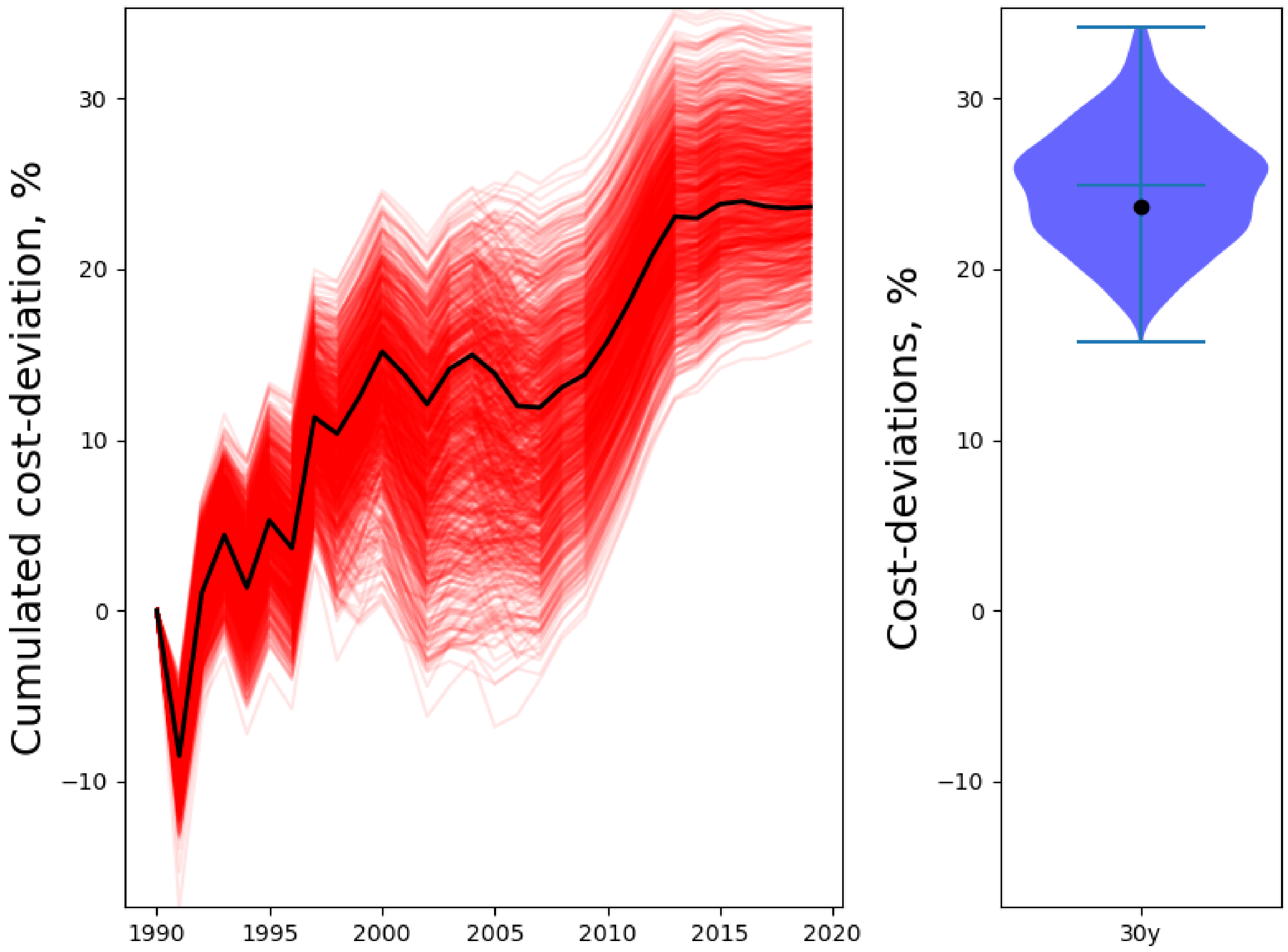

Figure A3-27. Evolution of cost deviations in Greece in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

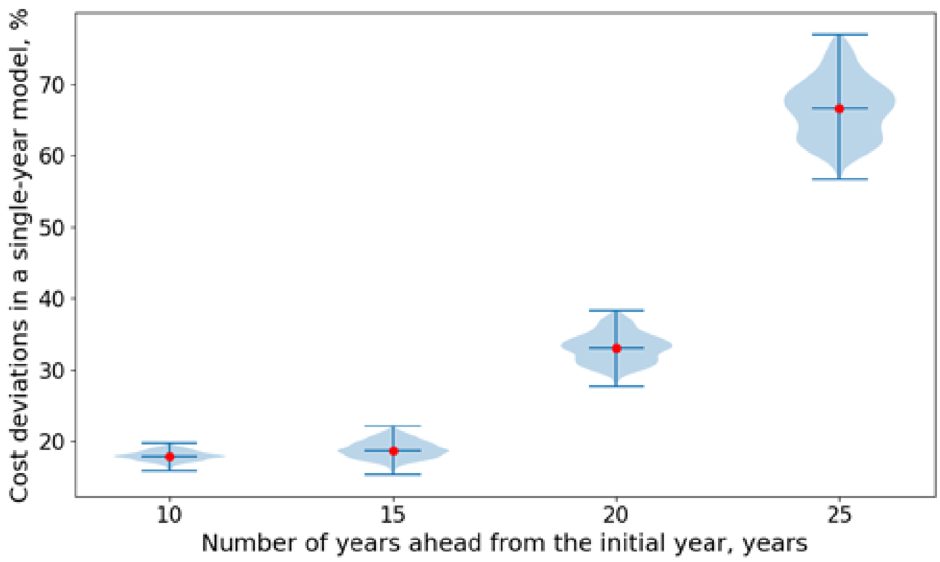

Figure A3-28. Evolution of cost deviations in Greece for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

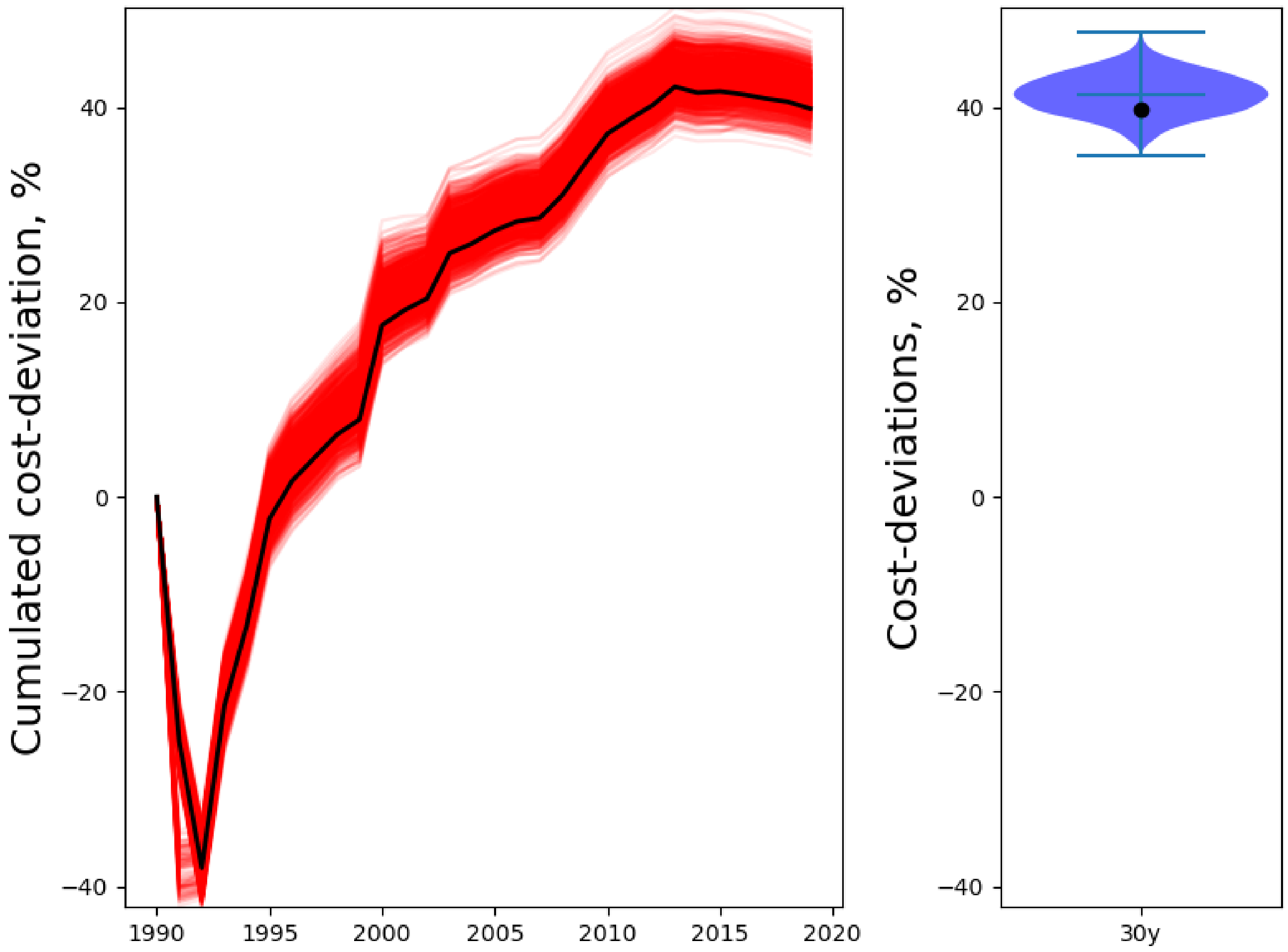

Figure A3-29. Evolution of cost deviations in Croatia in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

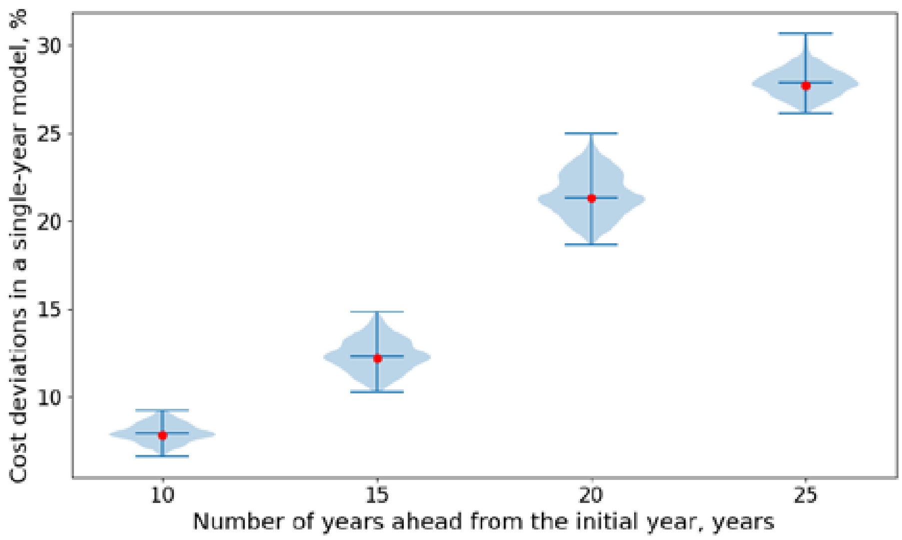

Figure A3-30. Evolution of cost deviations in Croatia for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

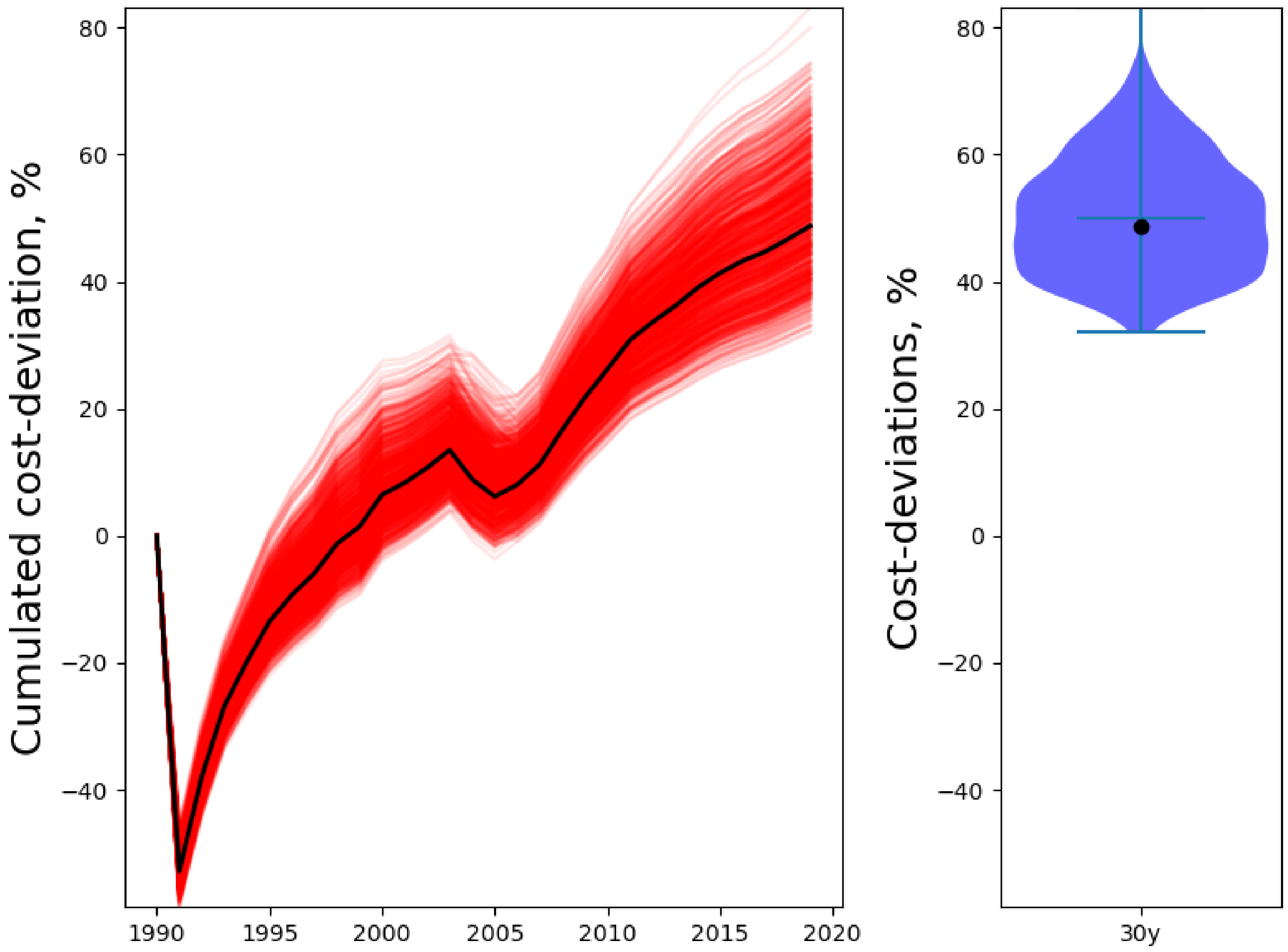

Figure A3-31. Evolution of cost deviations in Hungary in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

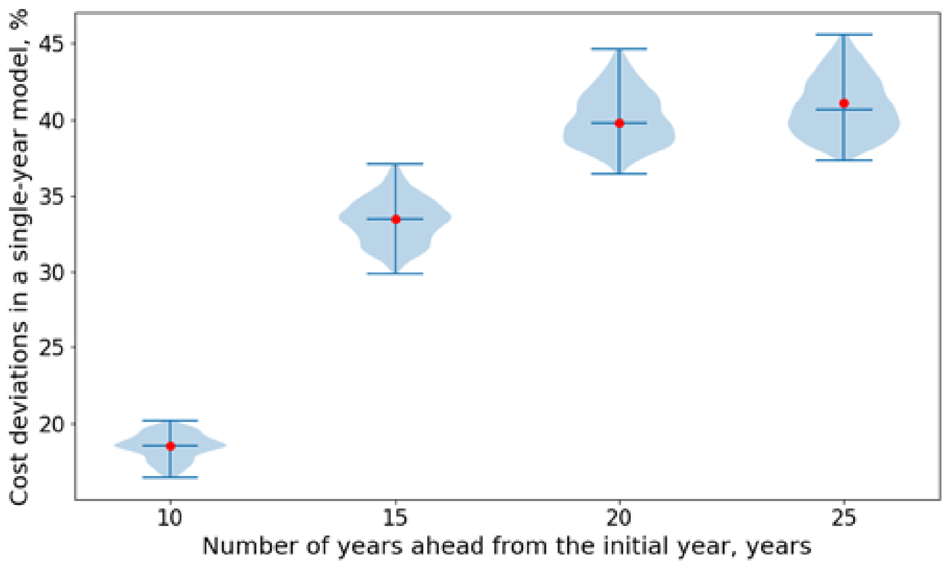

Figure A3-32. Evolution of cost deviations in Hungary for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

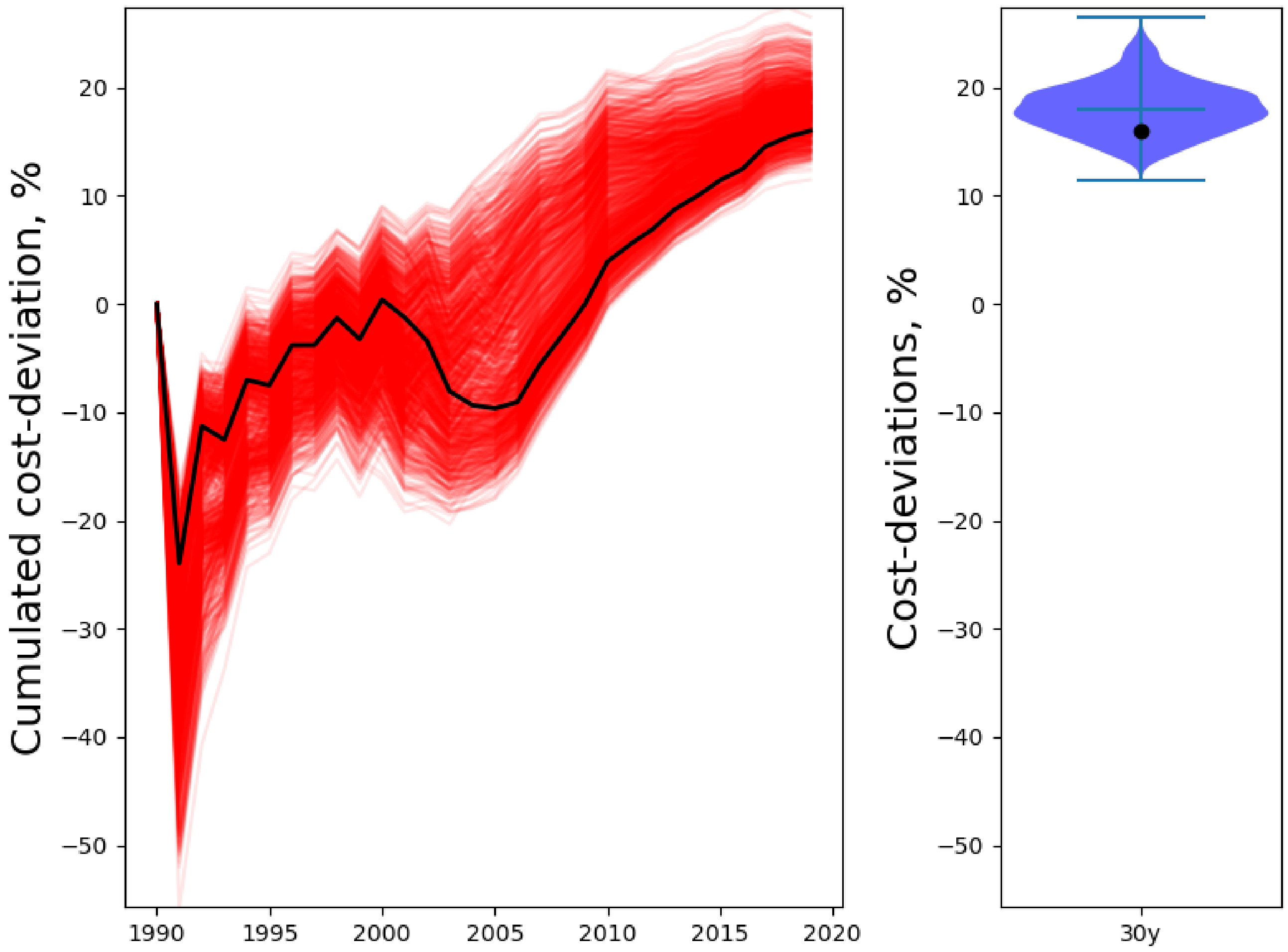

Figure A3-33. Evolution of cost deviations in Ireland in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

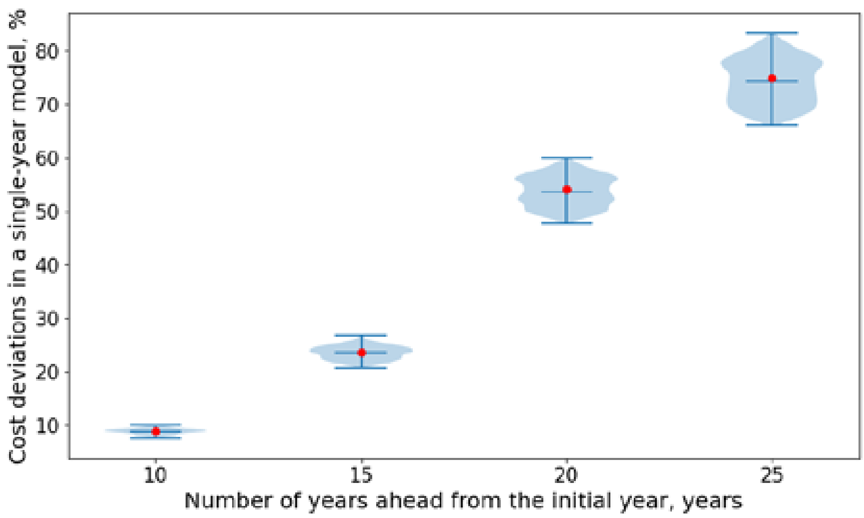

Figure A3-34. Evolution of cost deviations in Ireland for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

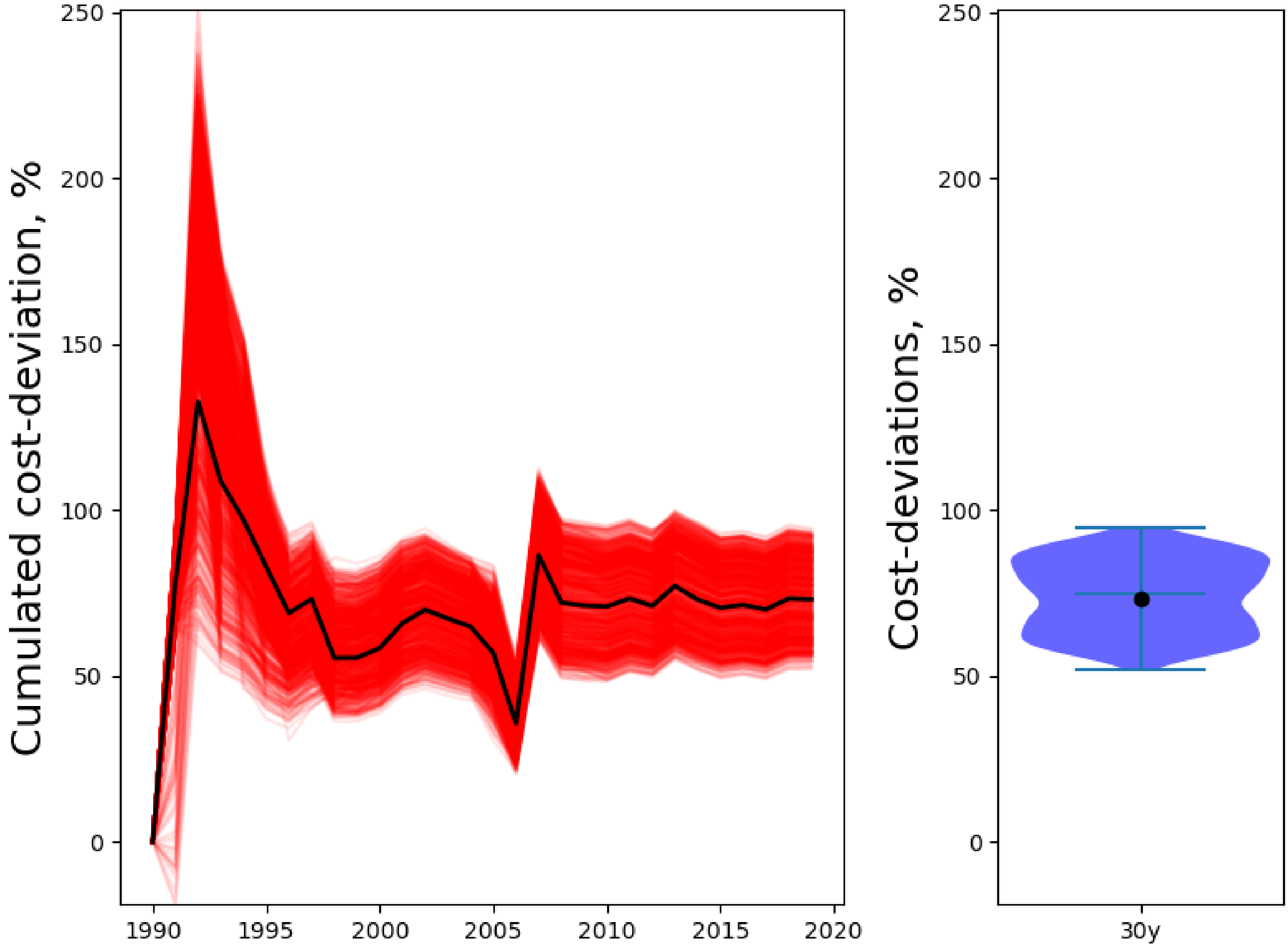

Figure A3-35. Evolution of cost deviations in Iceland in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

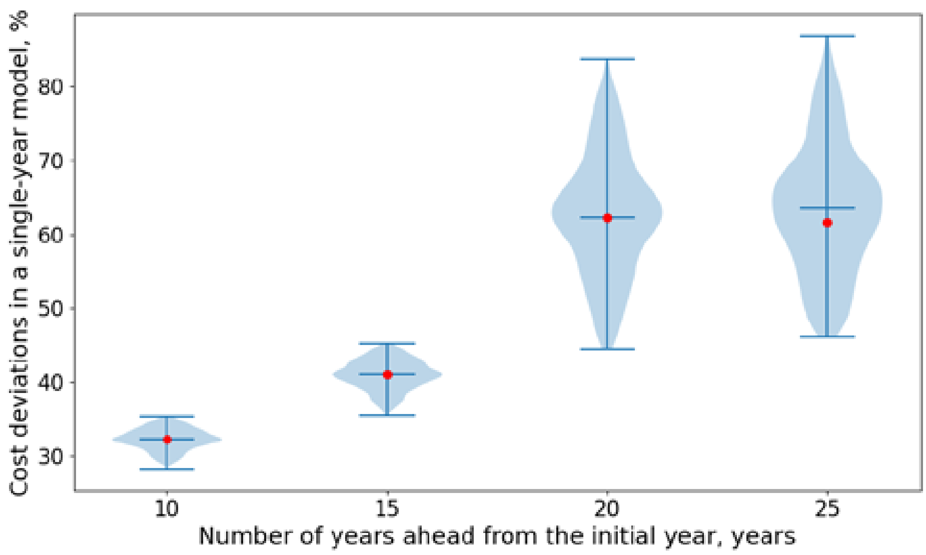

Figure A3-36. Evolution of cost deviations in Iceland for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

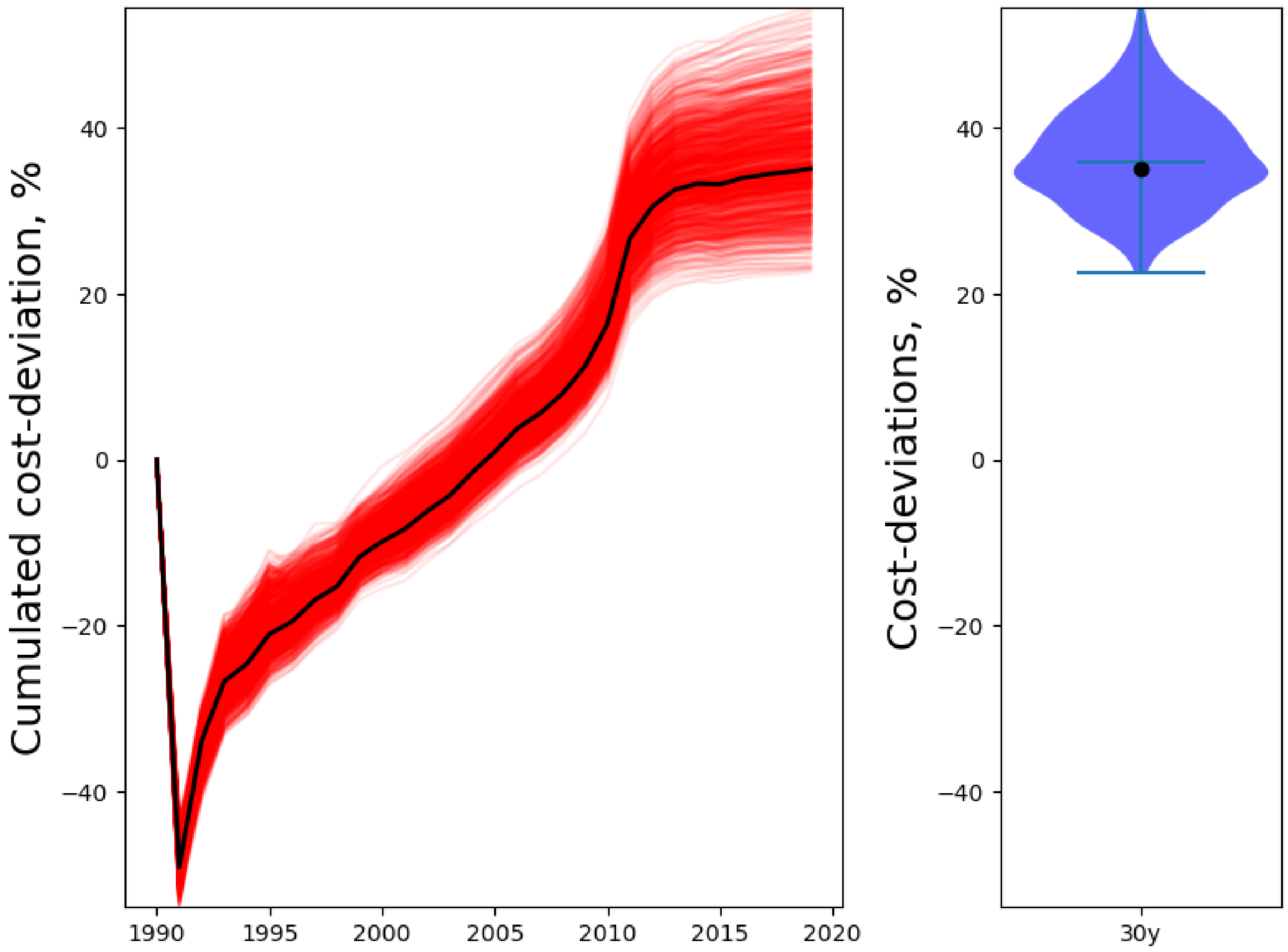

Figure A3-37. Evolution of cost deviations in Italy in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

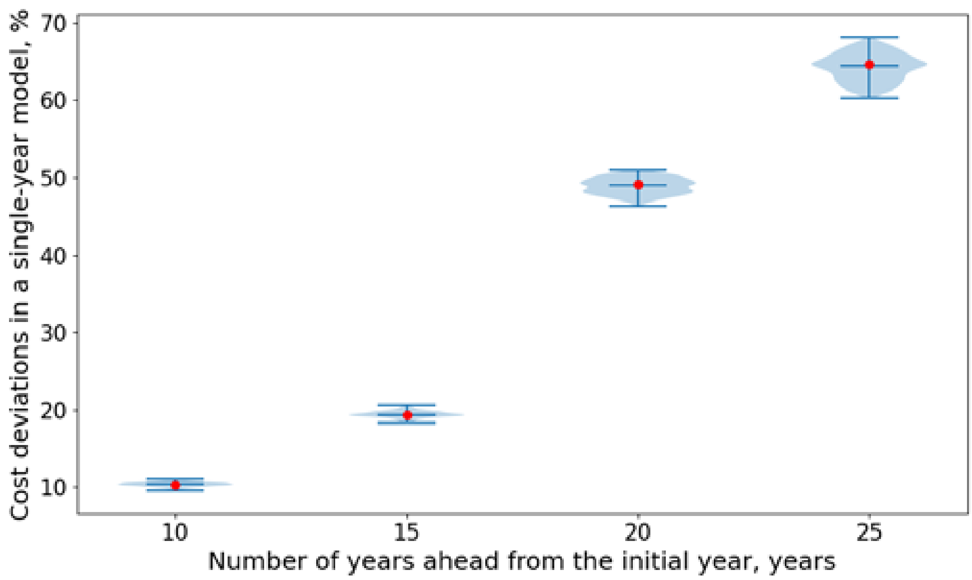

Figure A3-38. Evolution of cost deviations in Italy for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

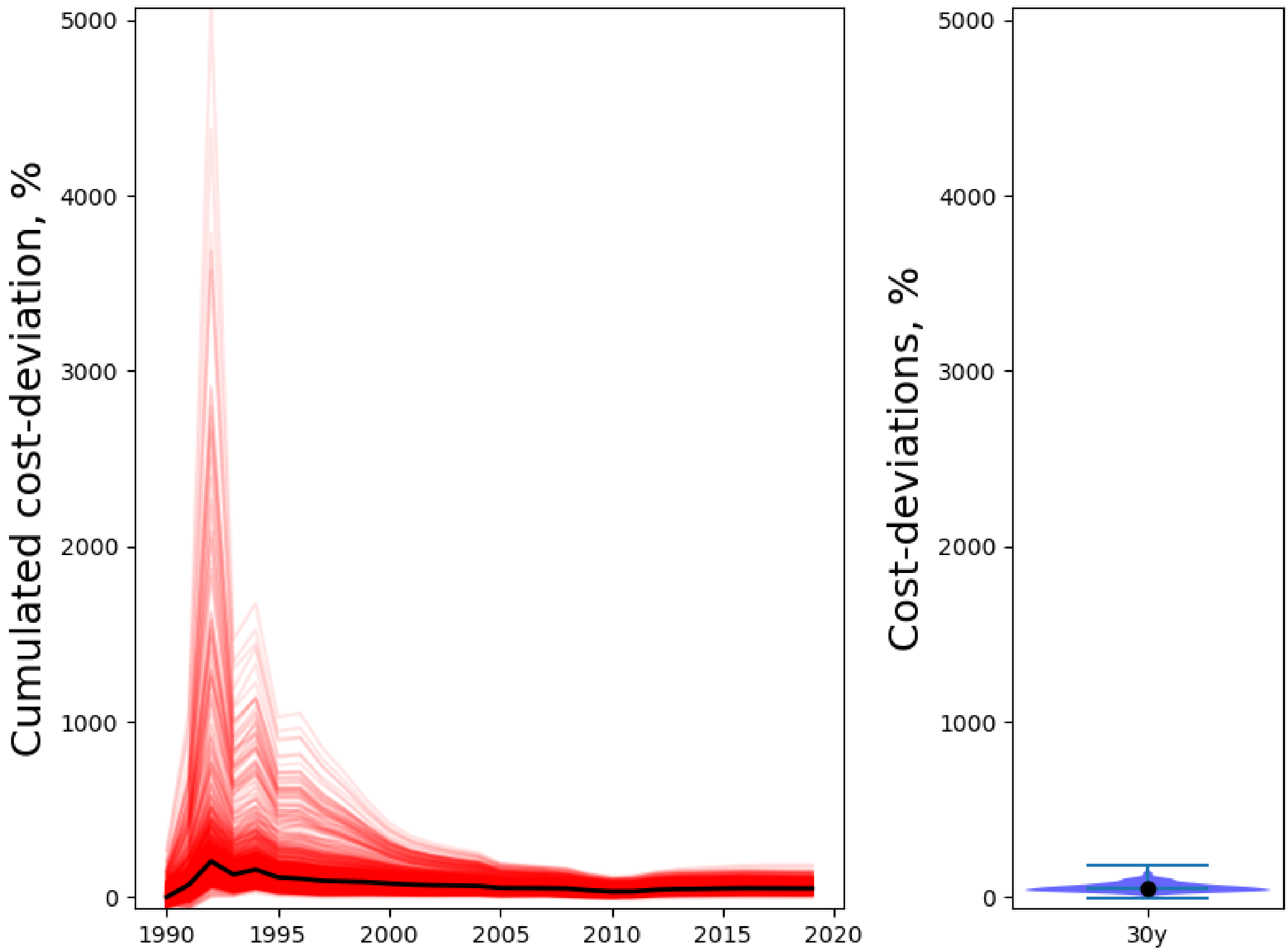

Figure A3-39. Evolution of cost deviations in Lithuania in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

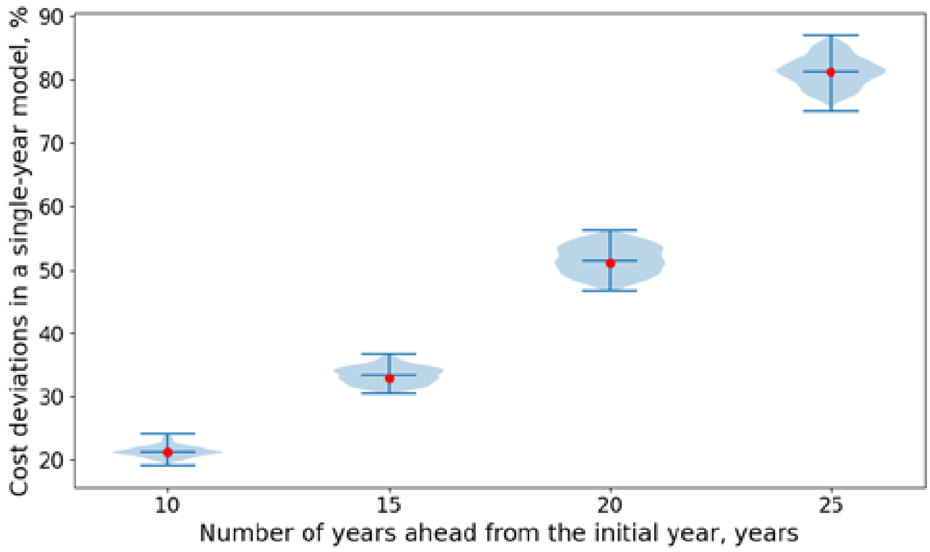

Figure A3-40. Evolution of cost deviations in Lithuania for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

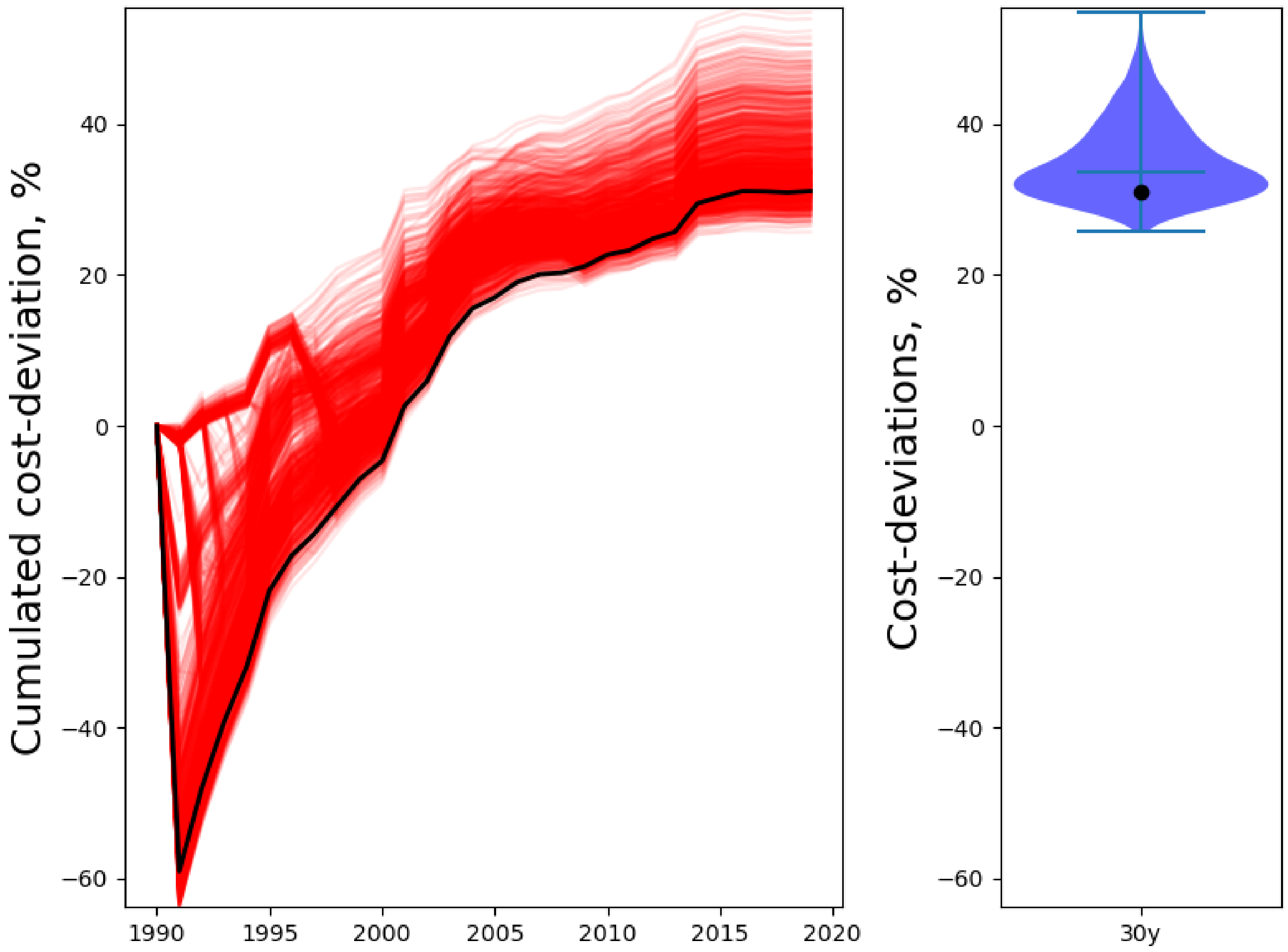

Figure A3-41. Evolution of cost deviations in Luxembourg in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

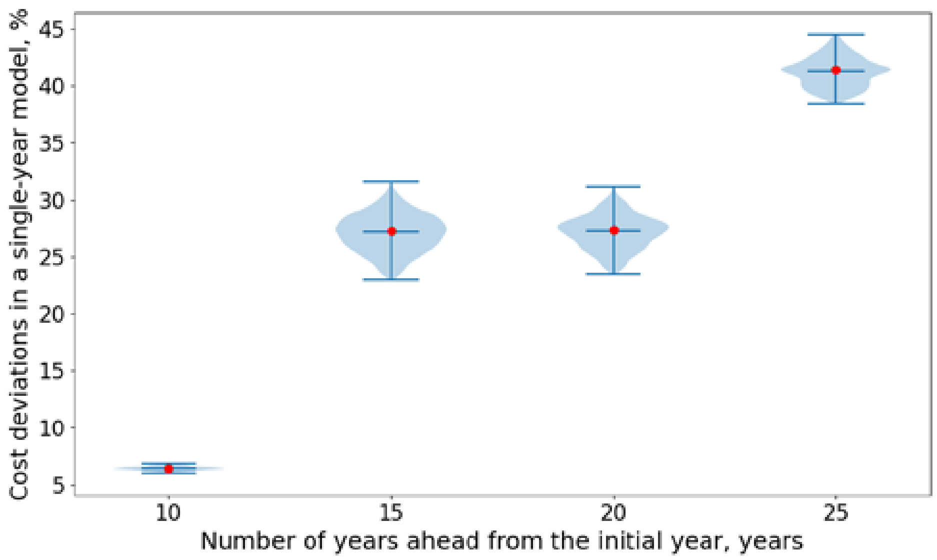

Figure A3-42. Evolution of cost deviations in Luxembourg for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

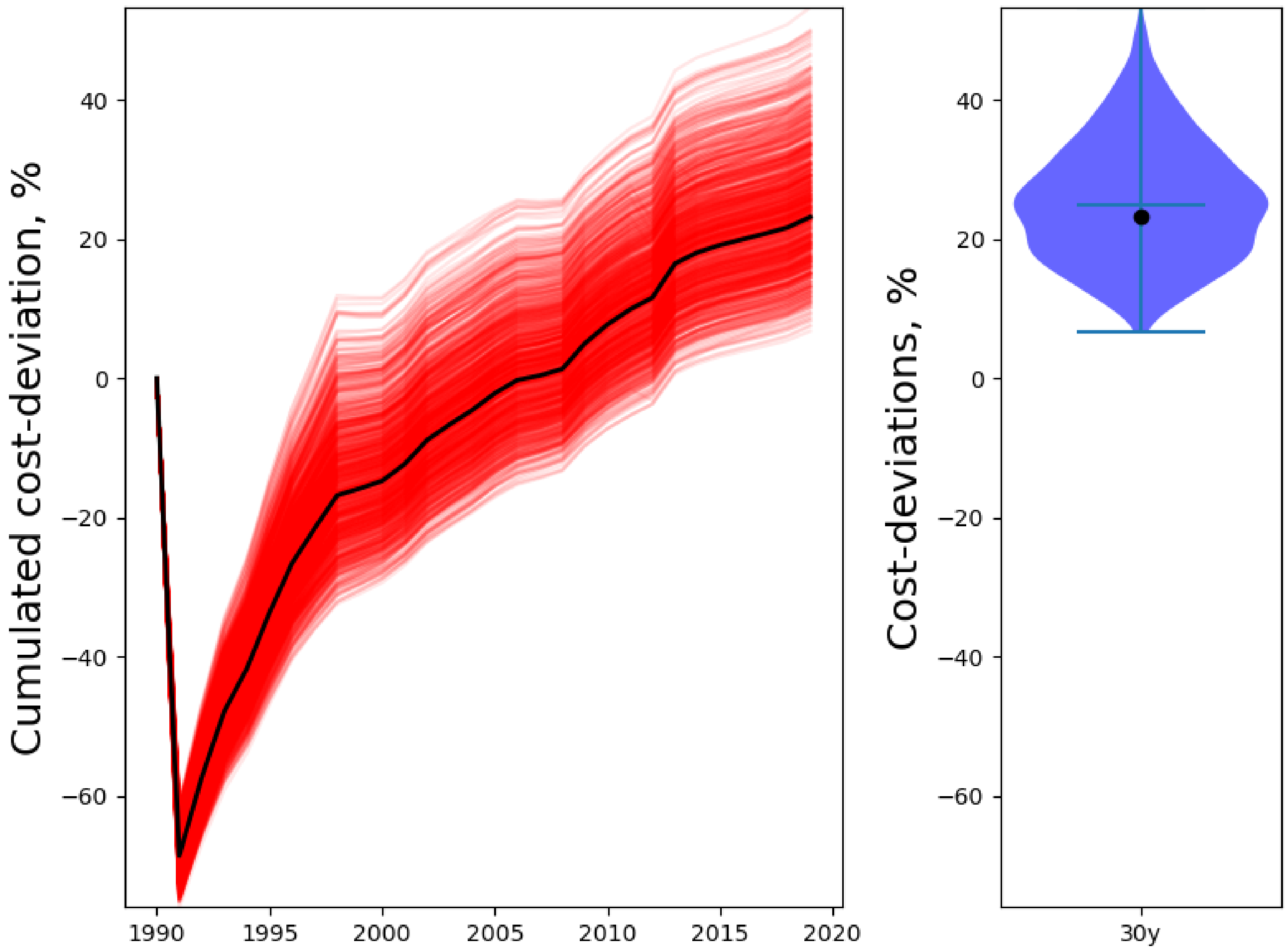

Figure A3-43. Evolution of cost deviations in Latvia in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

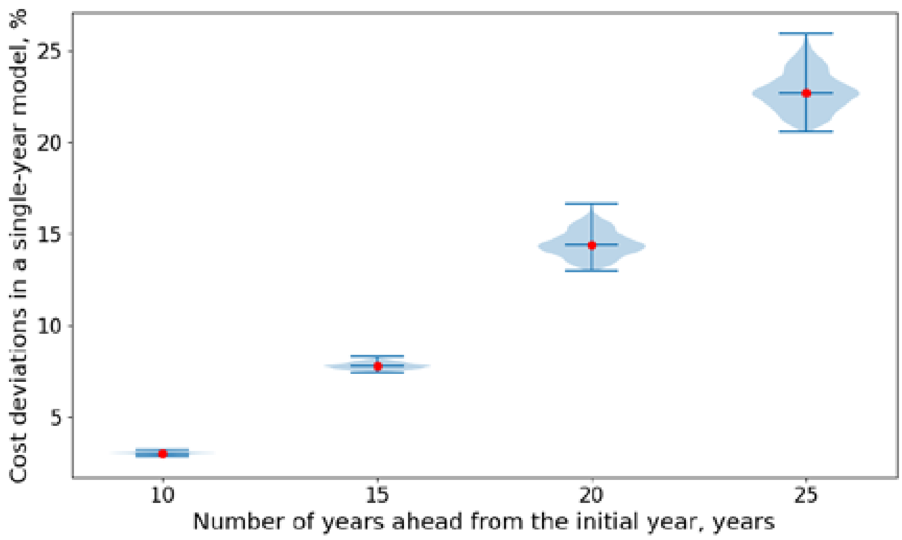

Figure A3-44. Evolution of cost deviations in Latvia for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

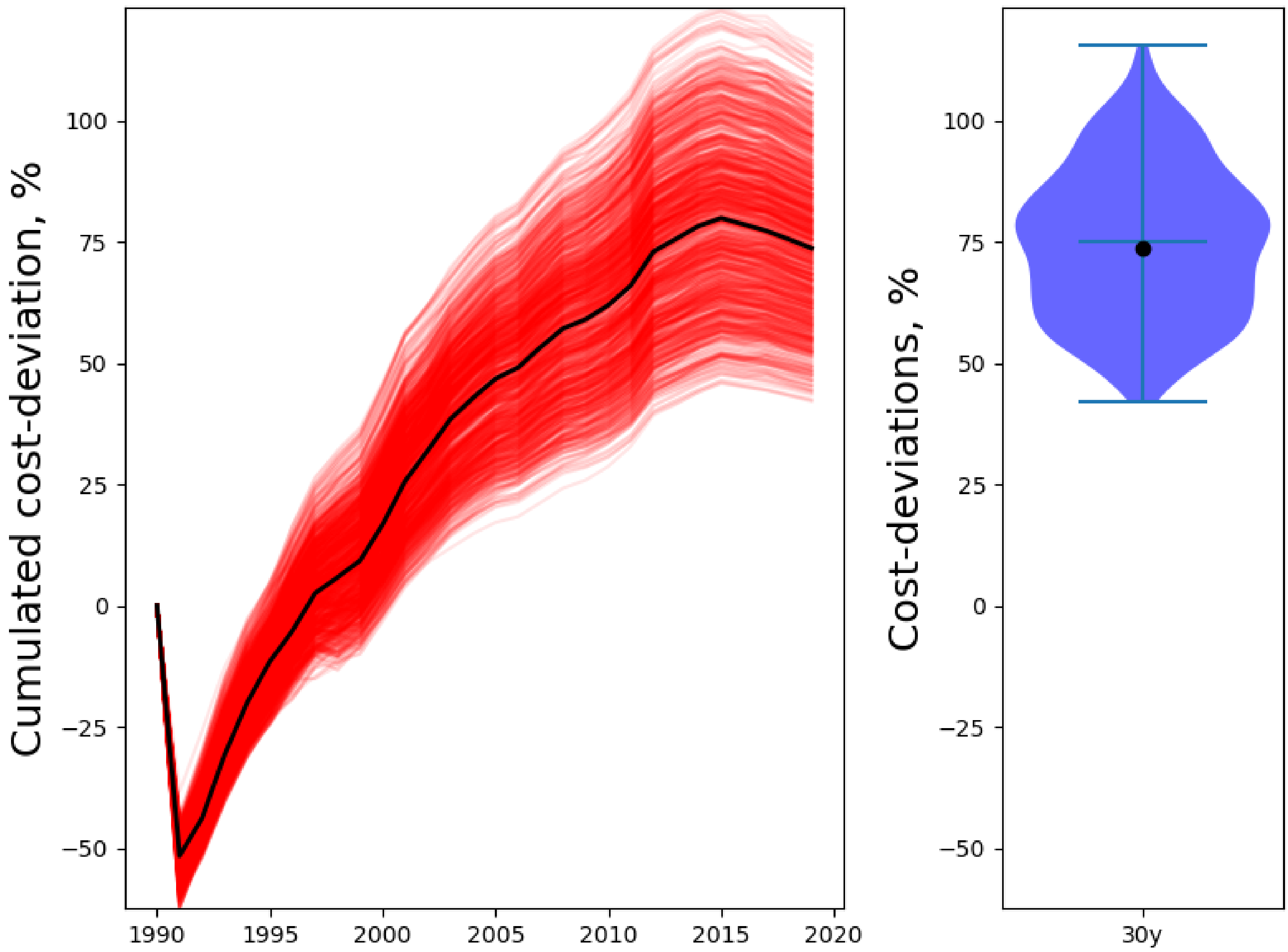

Figure A3-45. Evolution of cost deviations in Malta in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

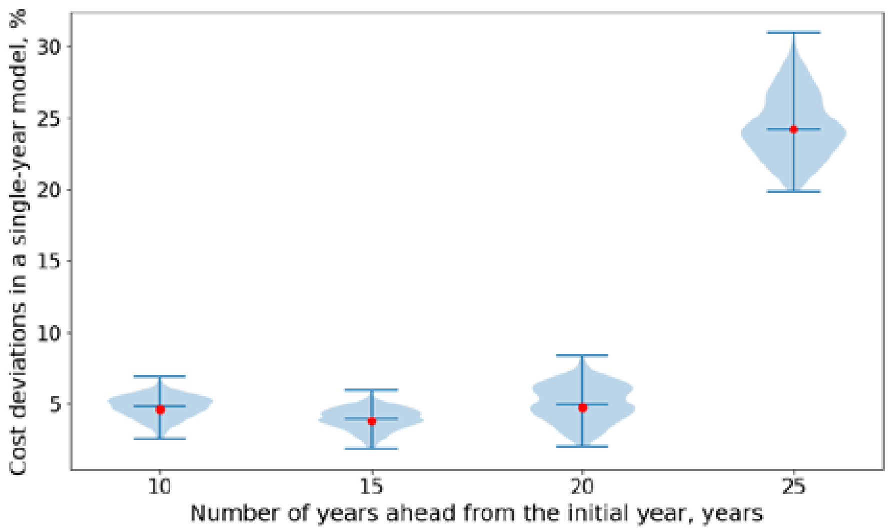

Figure A3-46. Evolution of cost deviations in Malta for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

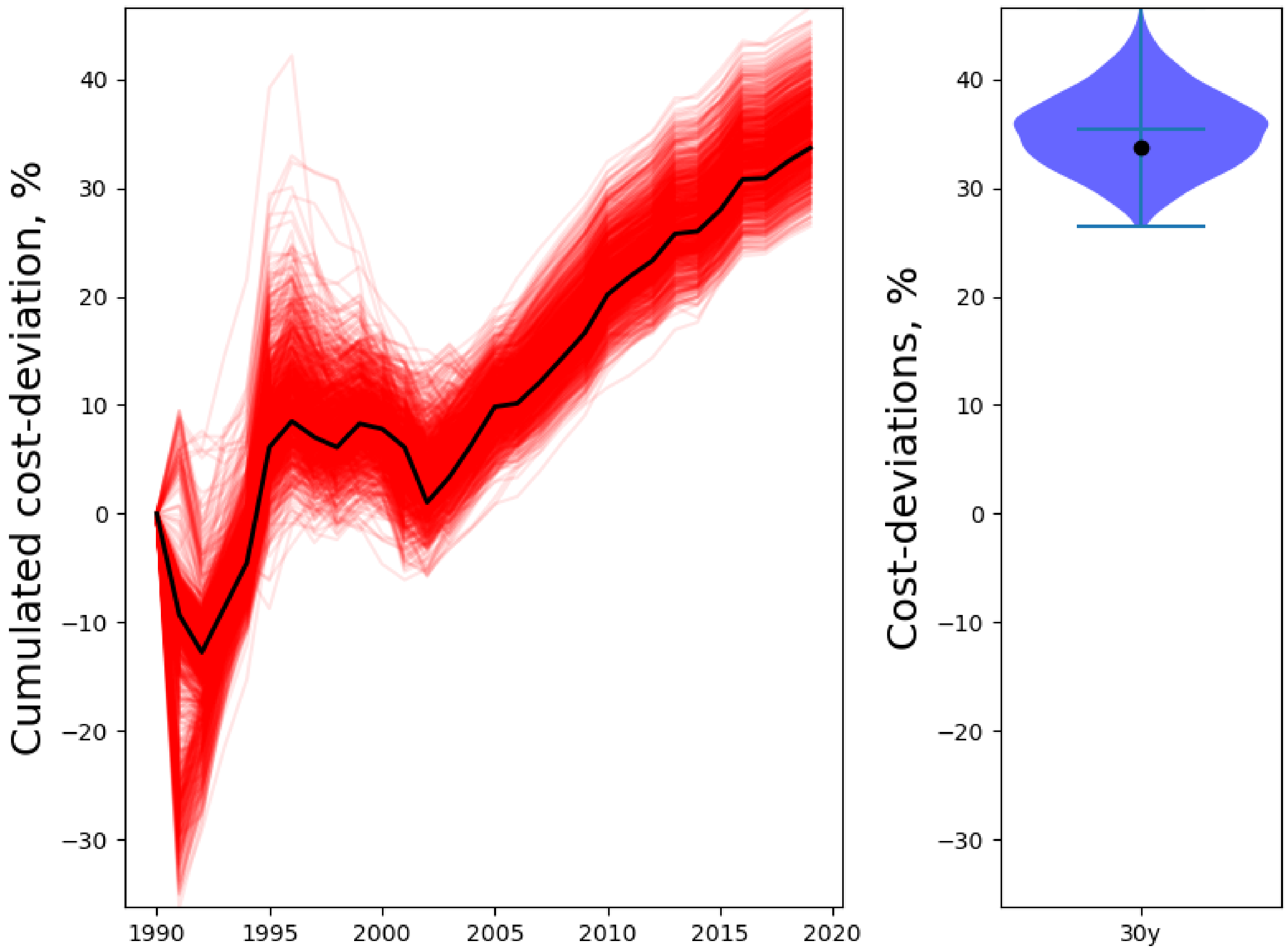

Figure A3-47. Evolution of cost deviations in the Netherlands in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

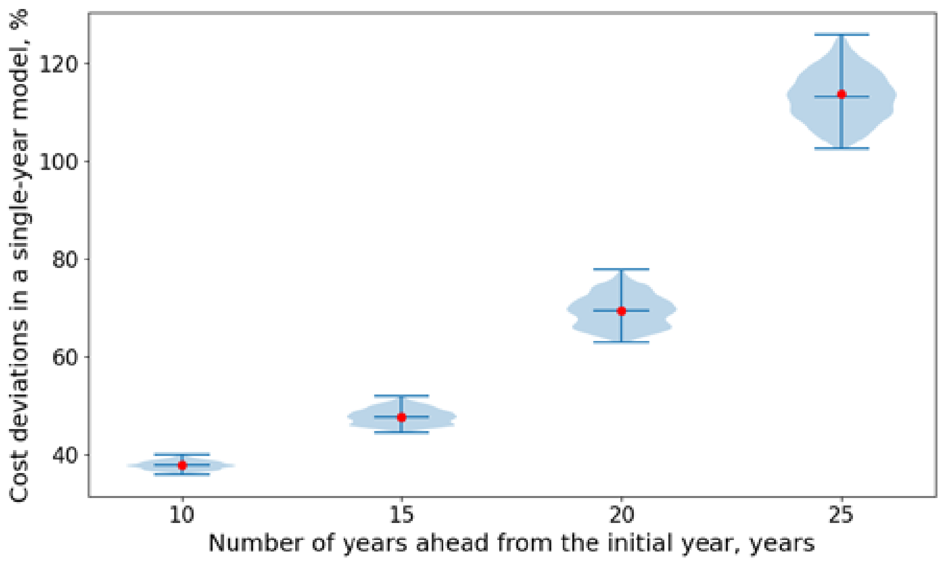

Figure A3-48. Evolution of cost deviations in the Netherlands for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

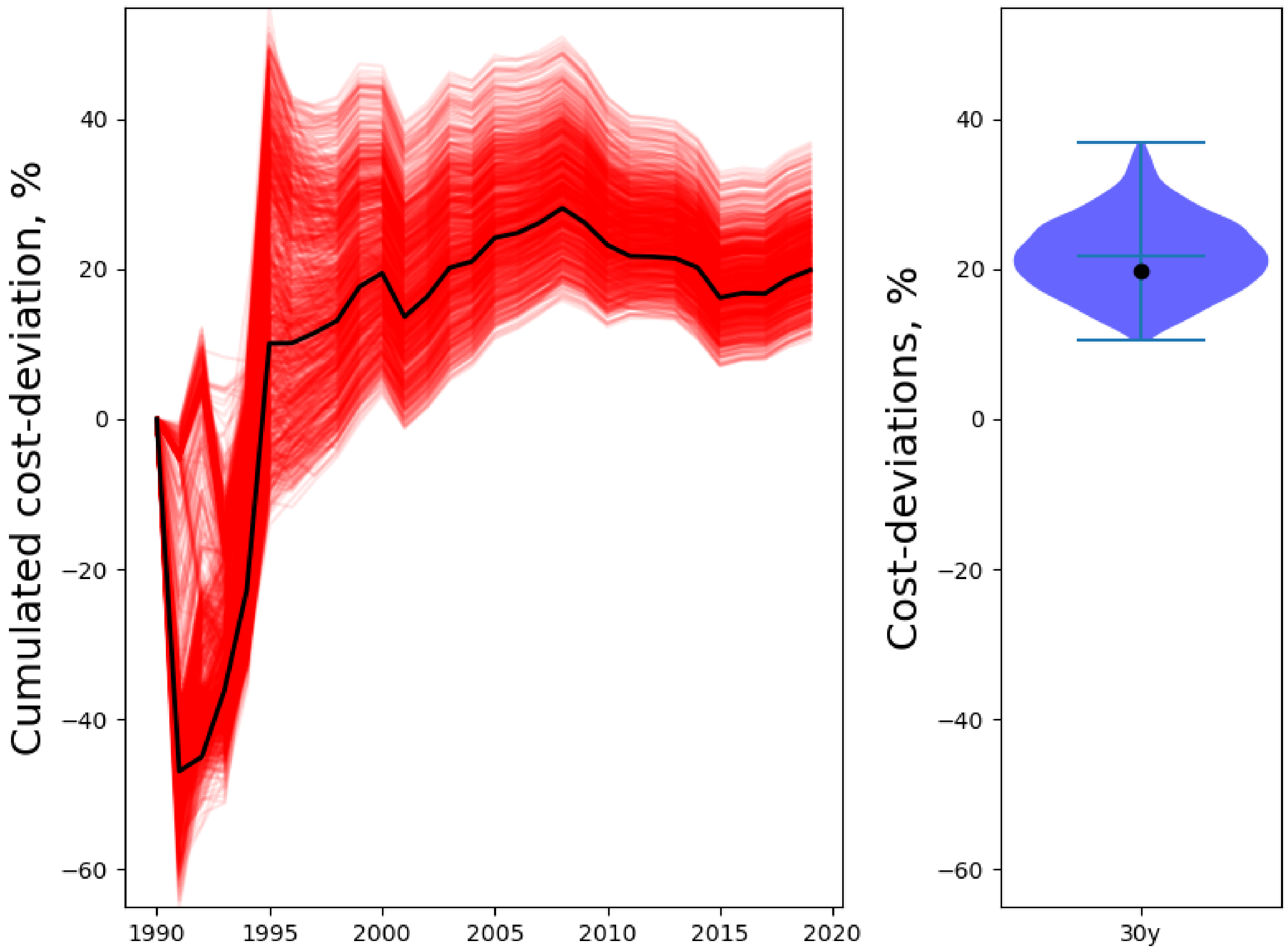

Figure A3-49. Evolution of cost deviations in Norway in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

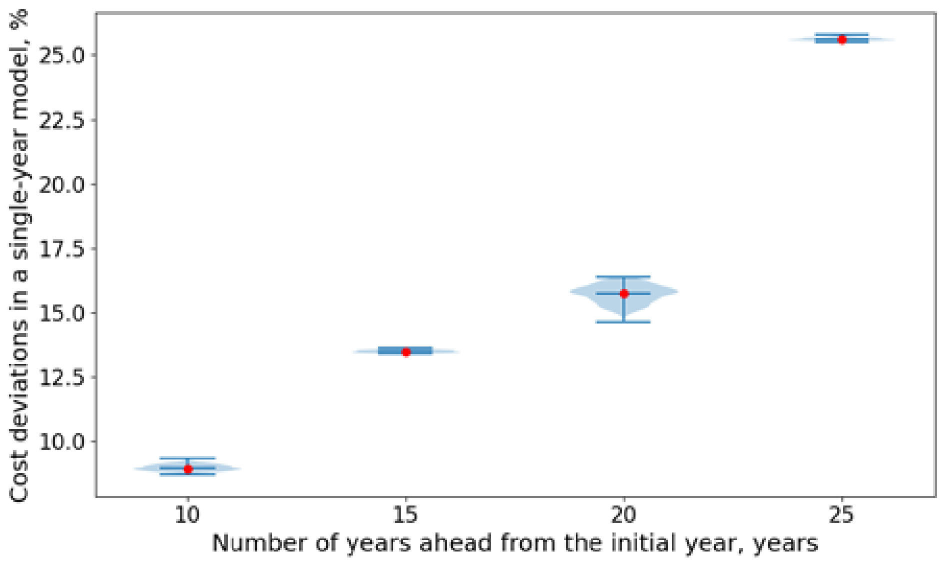

Figure A3-50. Evolution of cost deviations in Norway for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

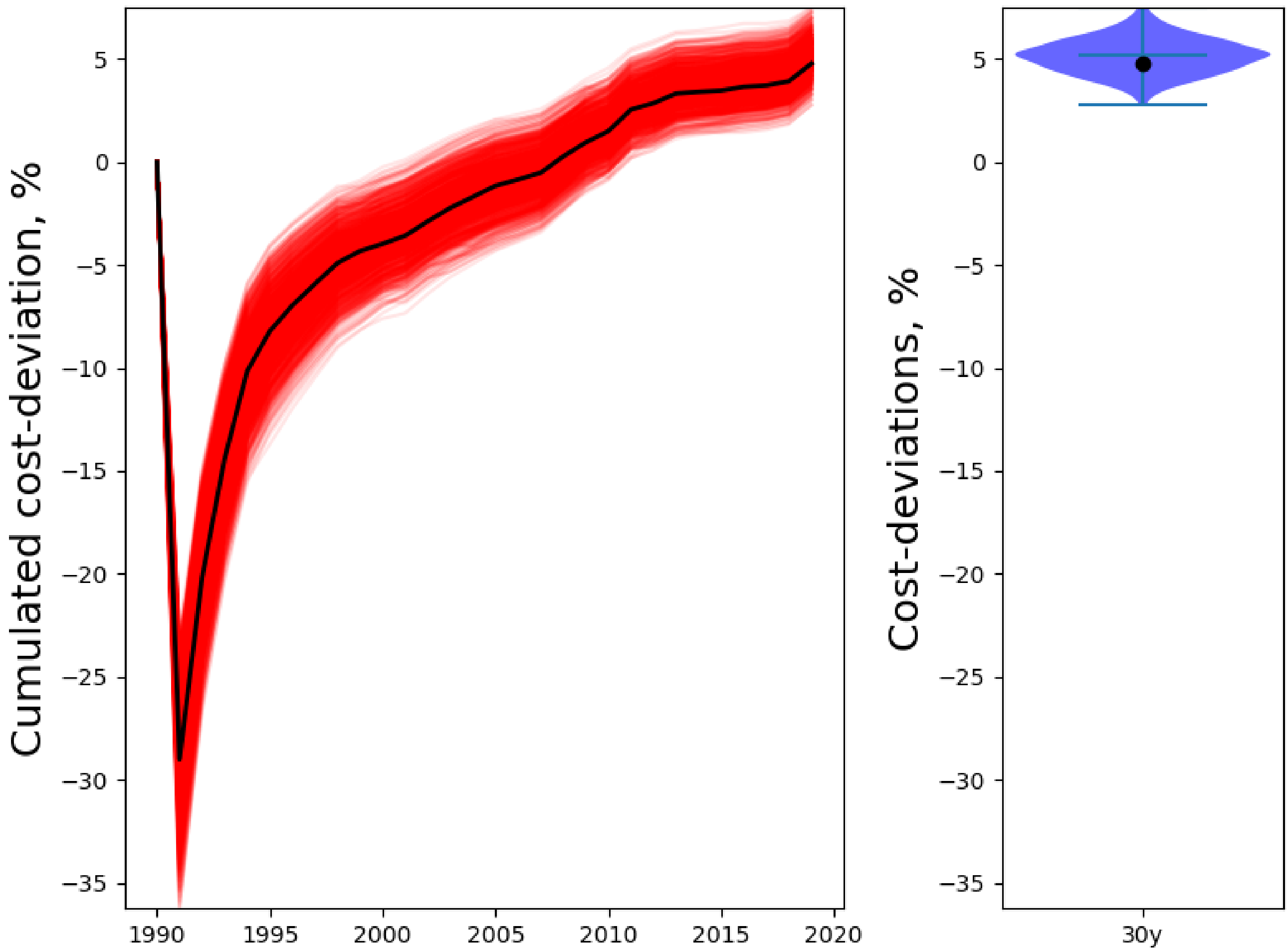

Figure A3-51. Evolution of cost deviations in Poland in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

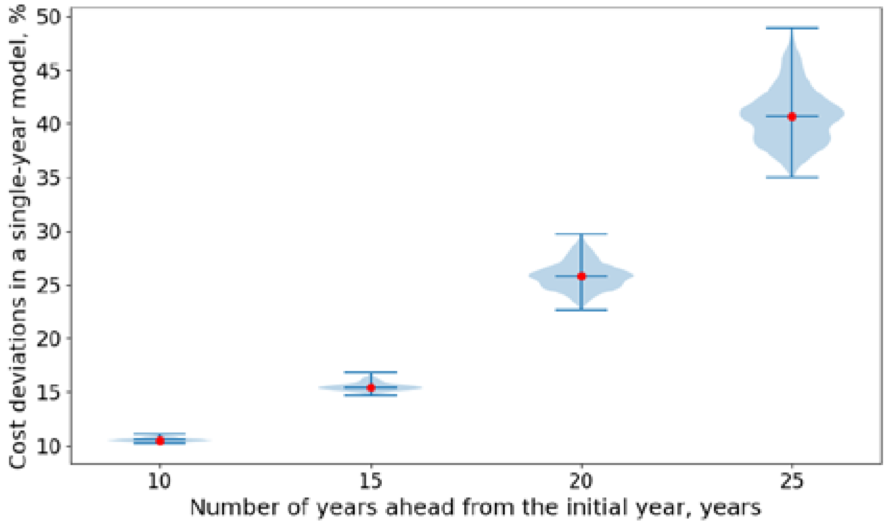

Figure A3-52. Evolution of cost deviations in Poland for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

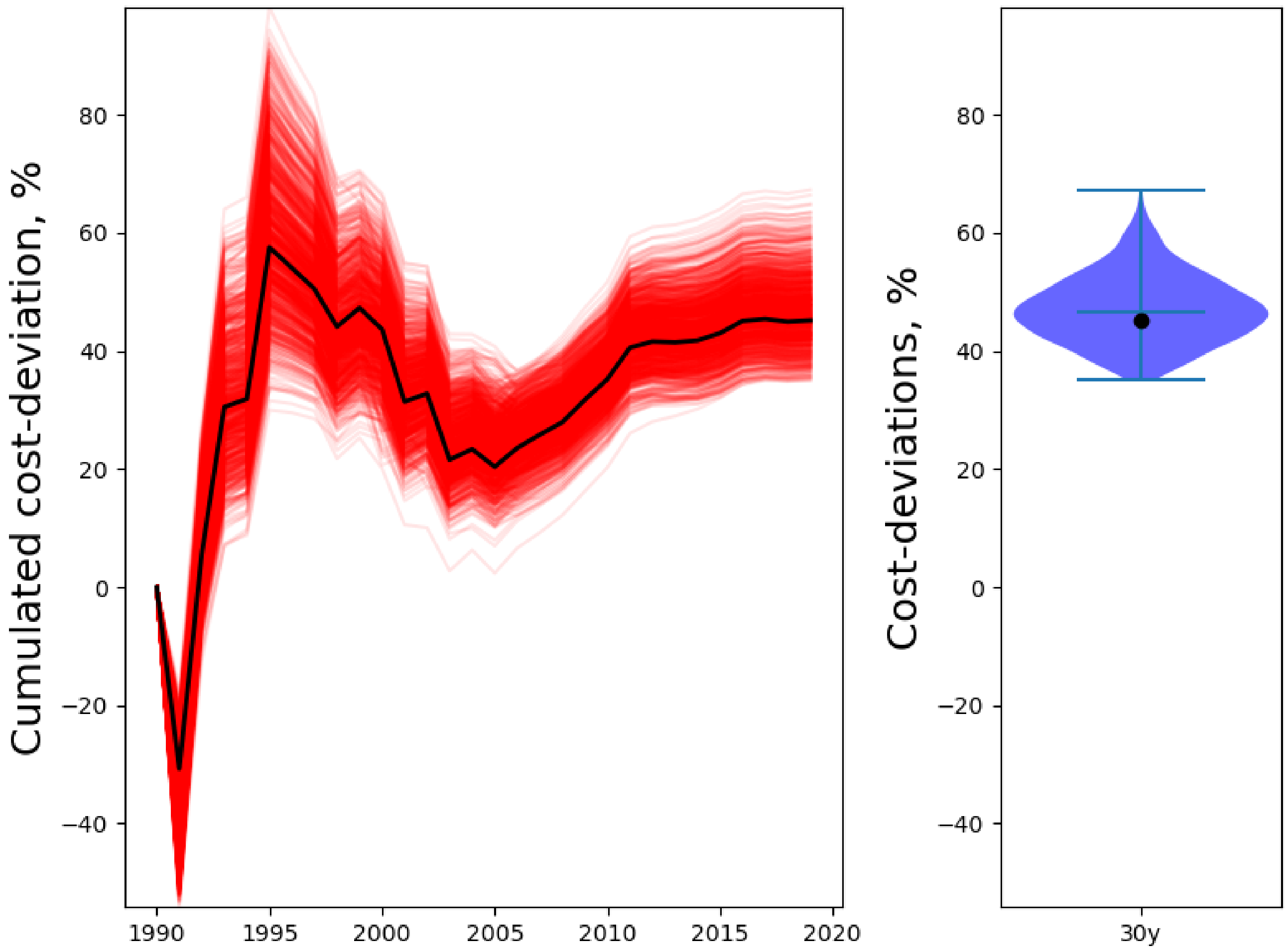

Figure A3-53. Evolution of cost deviations in Portugal in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

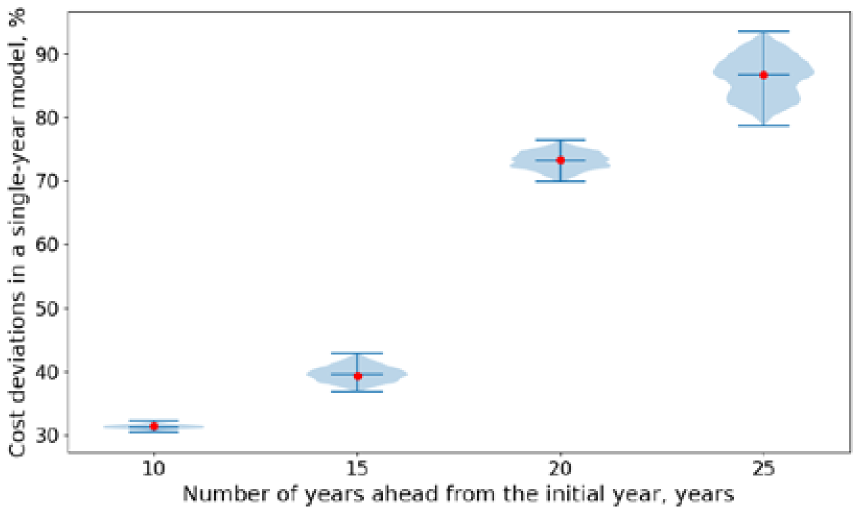

Figure A3-54. Evolution of cost deviations in Portugal for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

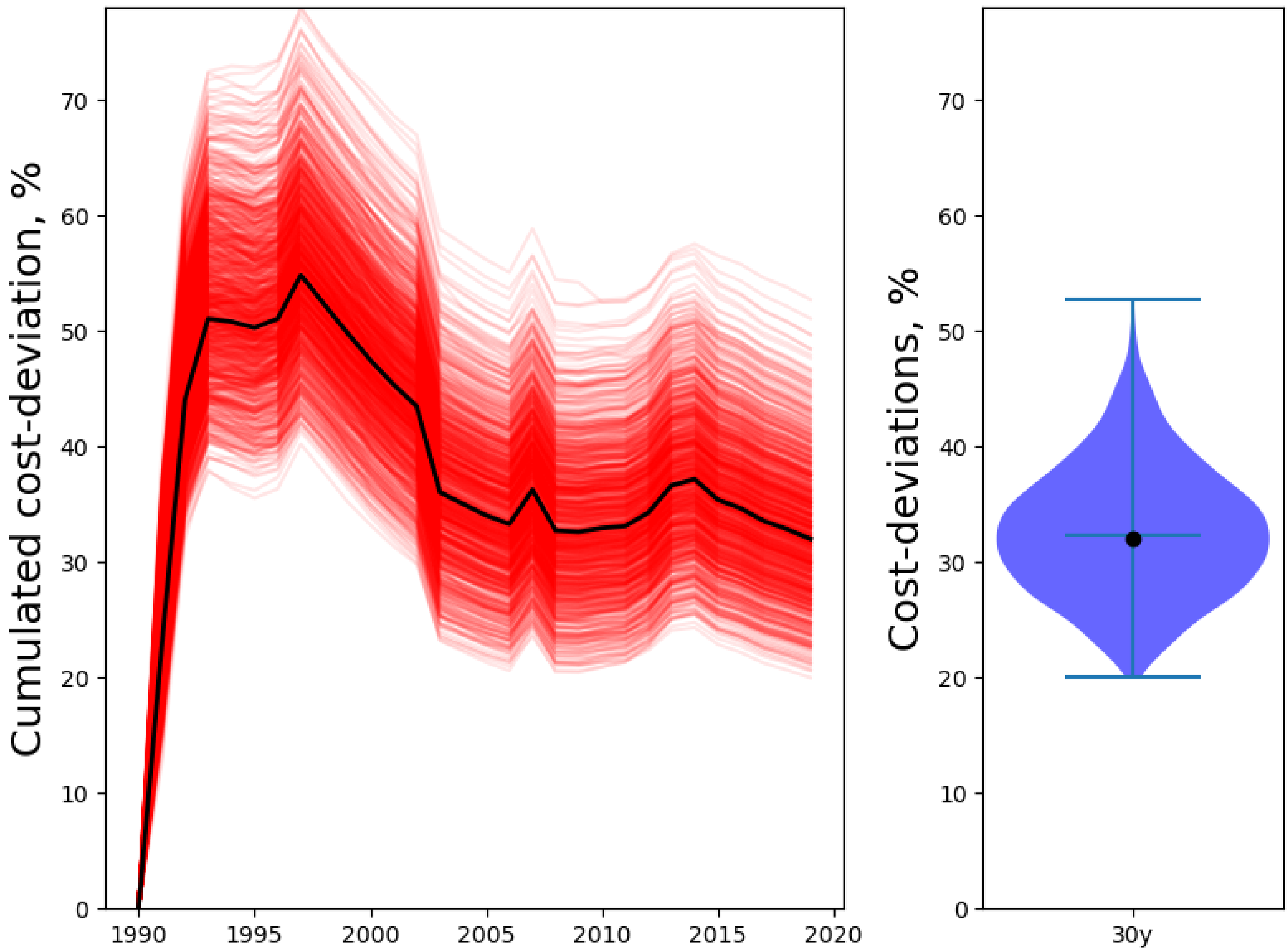

Figure A3-55. Evolution of cost deviations in Romania in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

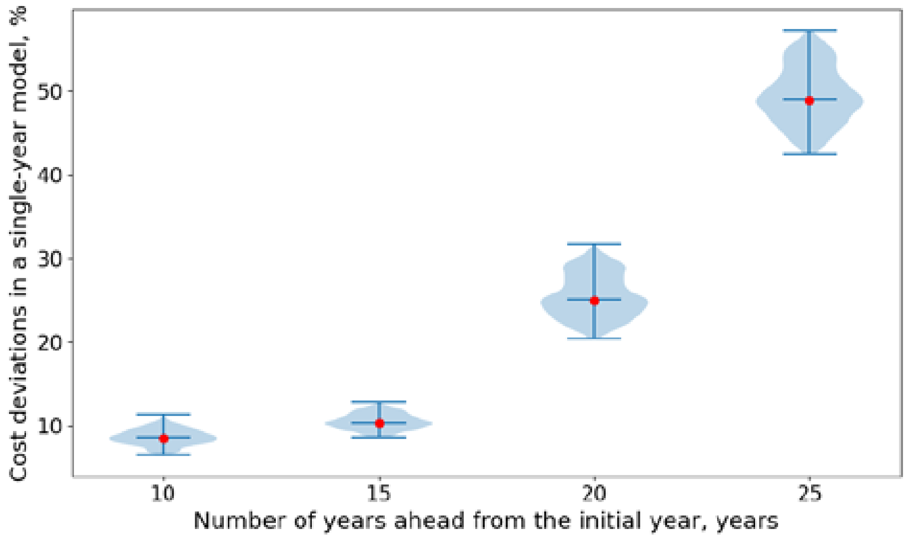

Figure A3-56. Evolution of cost deviations in Romania for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

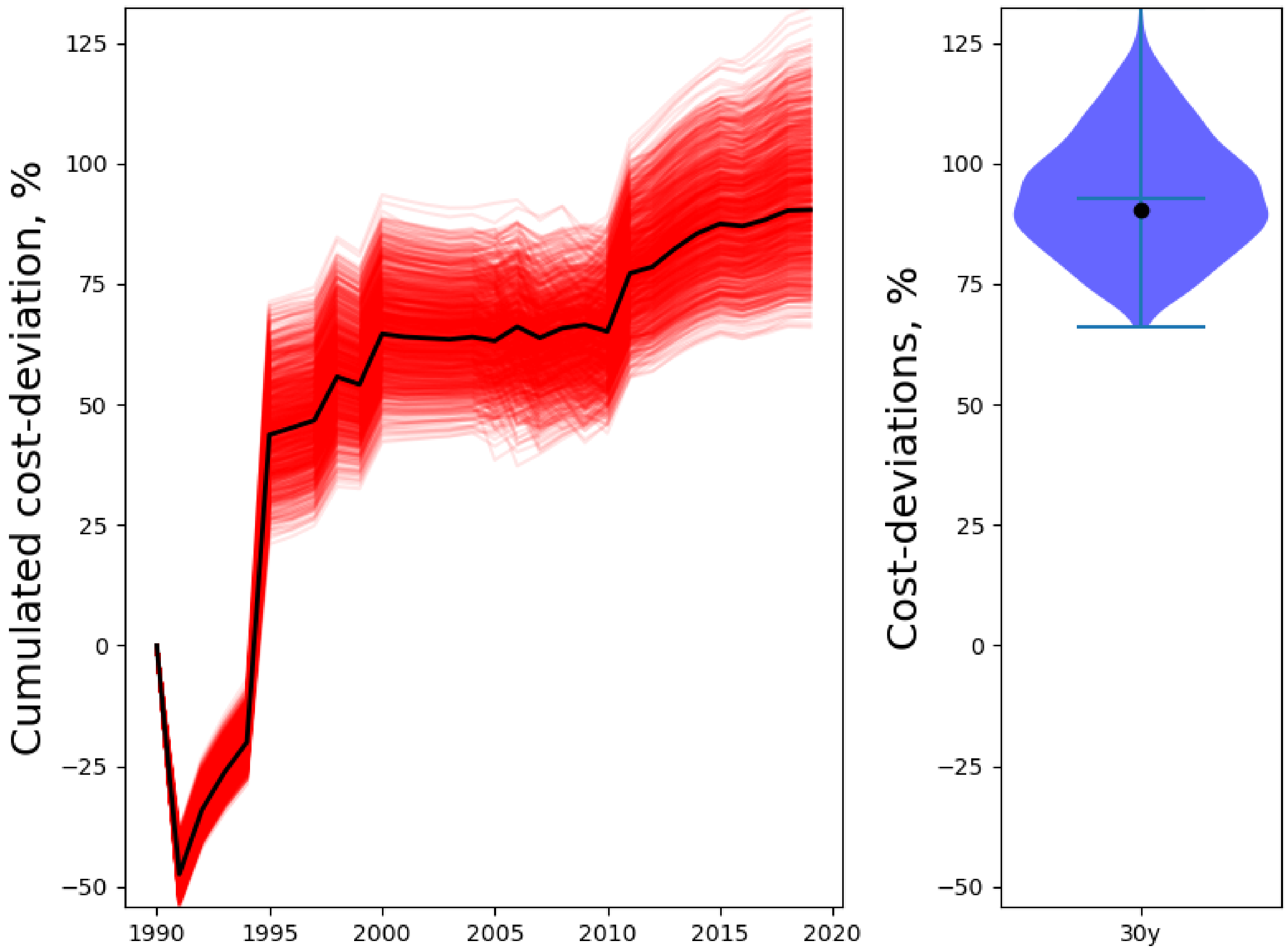

Figure A3-57. Evolution of cost deviations in Slovakia in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

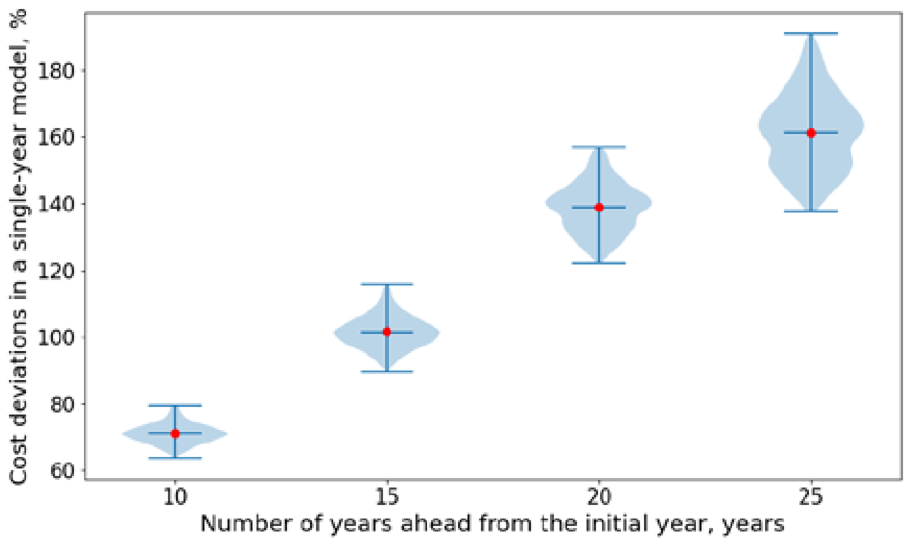

Figure A3-58. Evolution of cost deviations in Slovakia for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

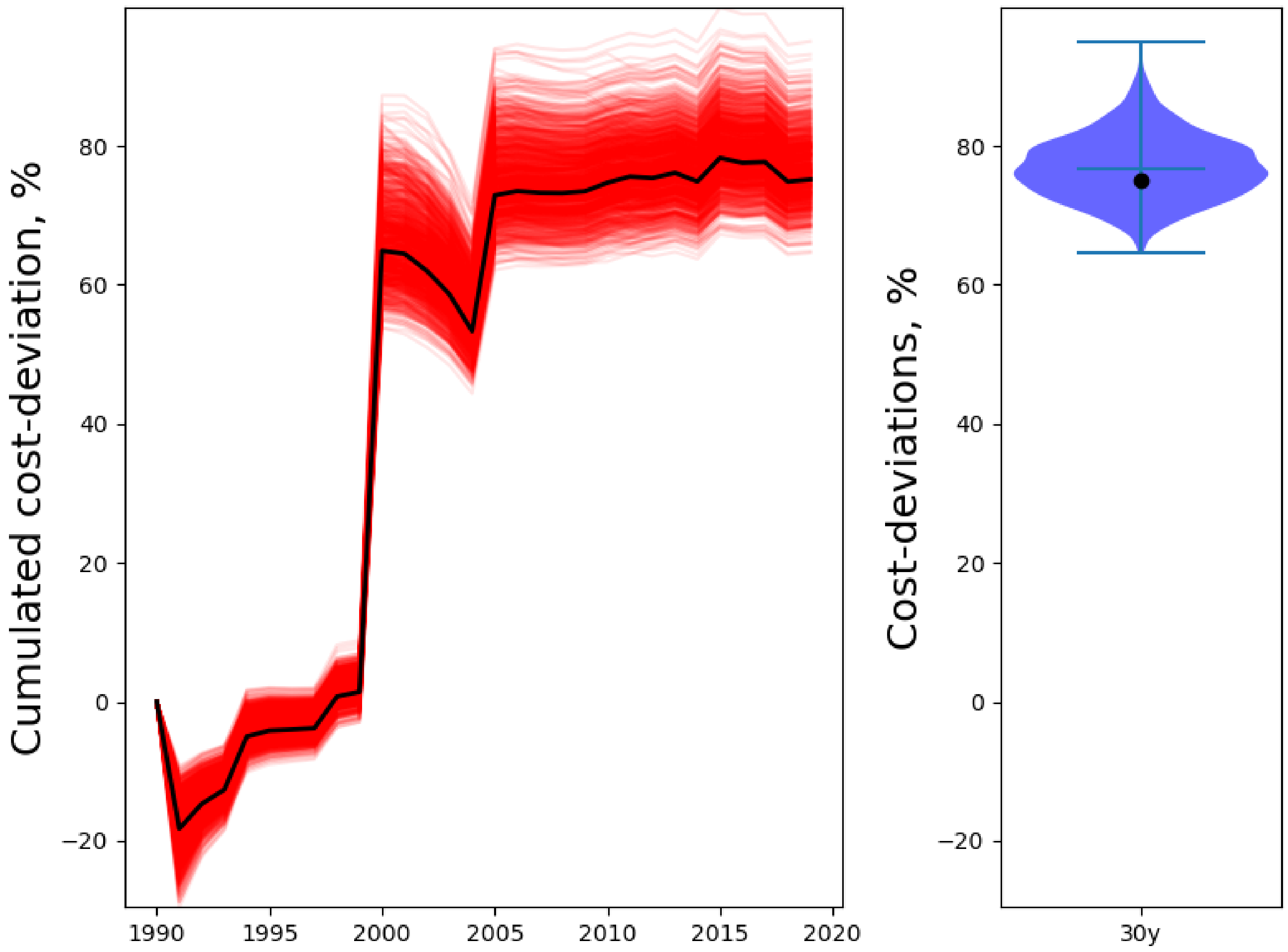

Figure A3-59. Evolution of cost deviations in Slovenia in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

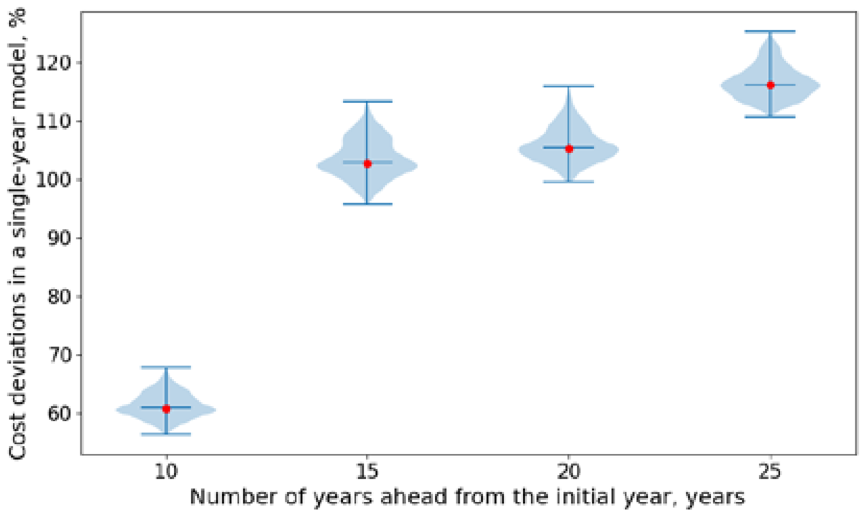

Figure A3-60. Evolution of cost deviations in Slovenia for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

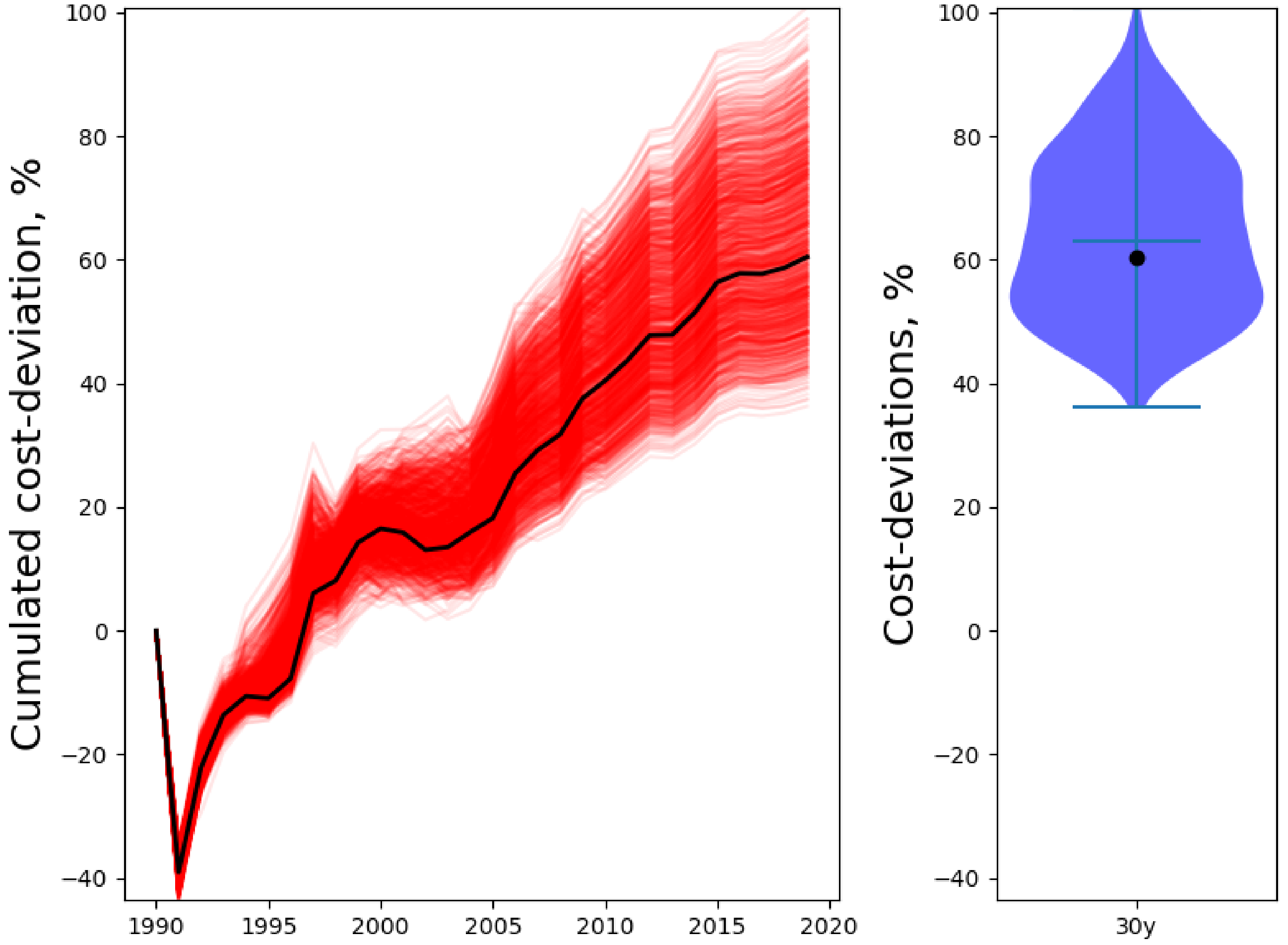

Figure A3-61. Evolution of cost deviations in Sweden in 1.000 Monte Carlo simulations and the deterministic version (black line) of a multi-year model (left) and the corresponding distribution for the model 30 years ahead (right). The black line and dot represent the deterministic cost deviation.

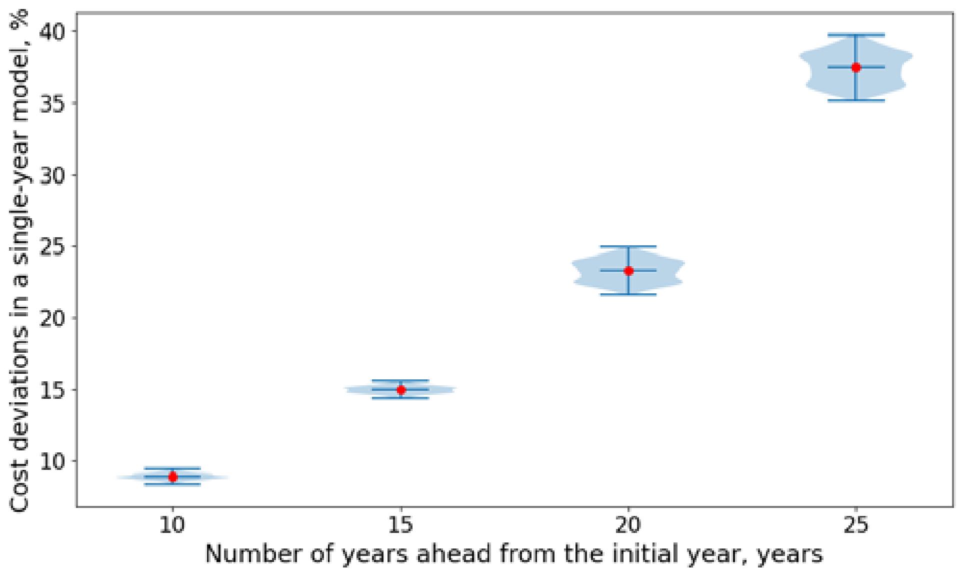

Figure A3-62. Evolution of cost deviations in Sweden for the 1.000 Monte Carlo simulations in a single-year model for 10 (2000), 15, 20 and 25 years ahead (2015). Red dots represent the results corresponding to the deterministic scenarios.

ANNEX B

Contents of ANNEX B

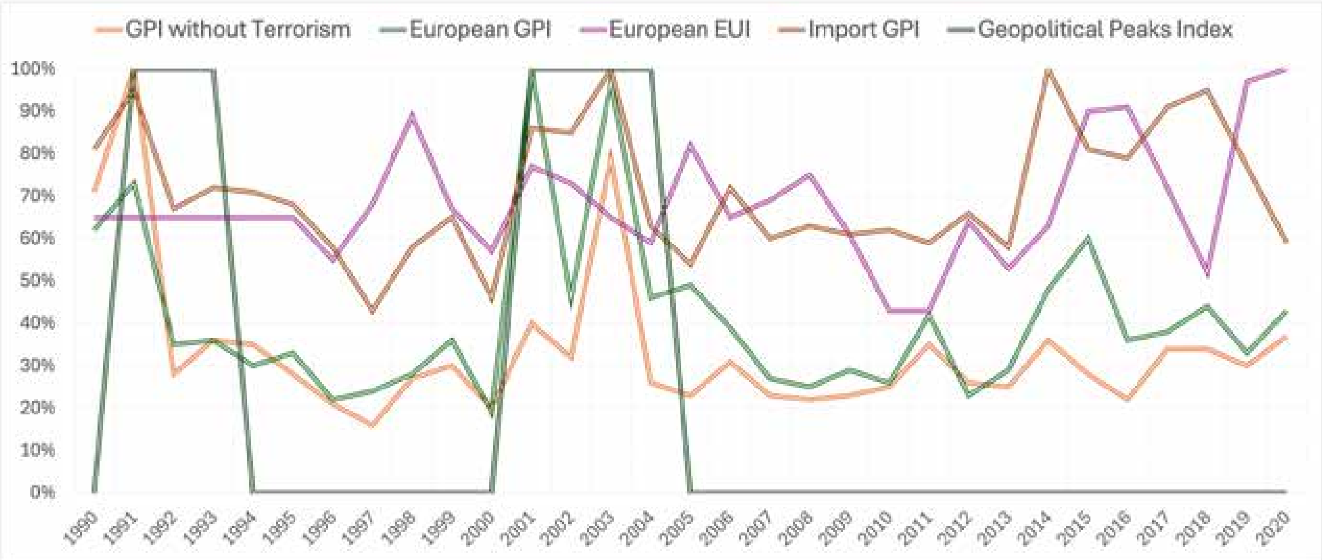

Figure B1. Profiles of constructed geopolitical indices (GPIs) over the period 1990-2019

Section B2. Domestic fossil fuel resources of European countries.

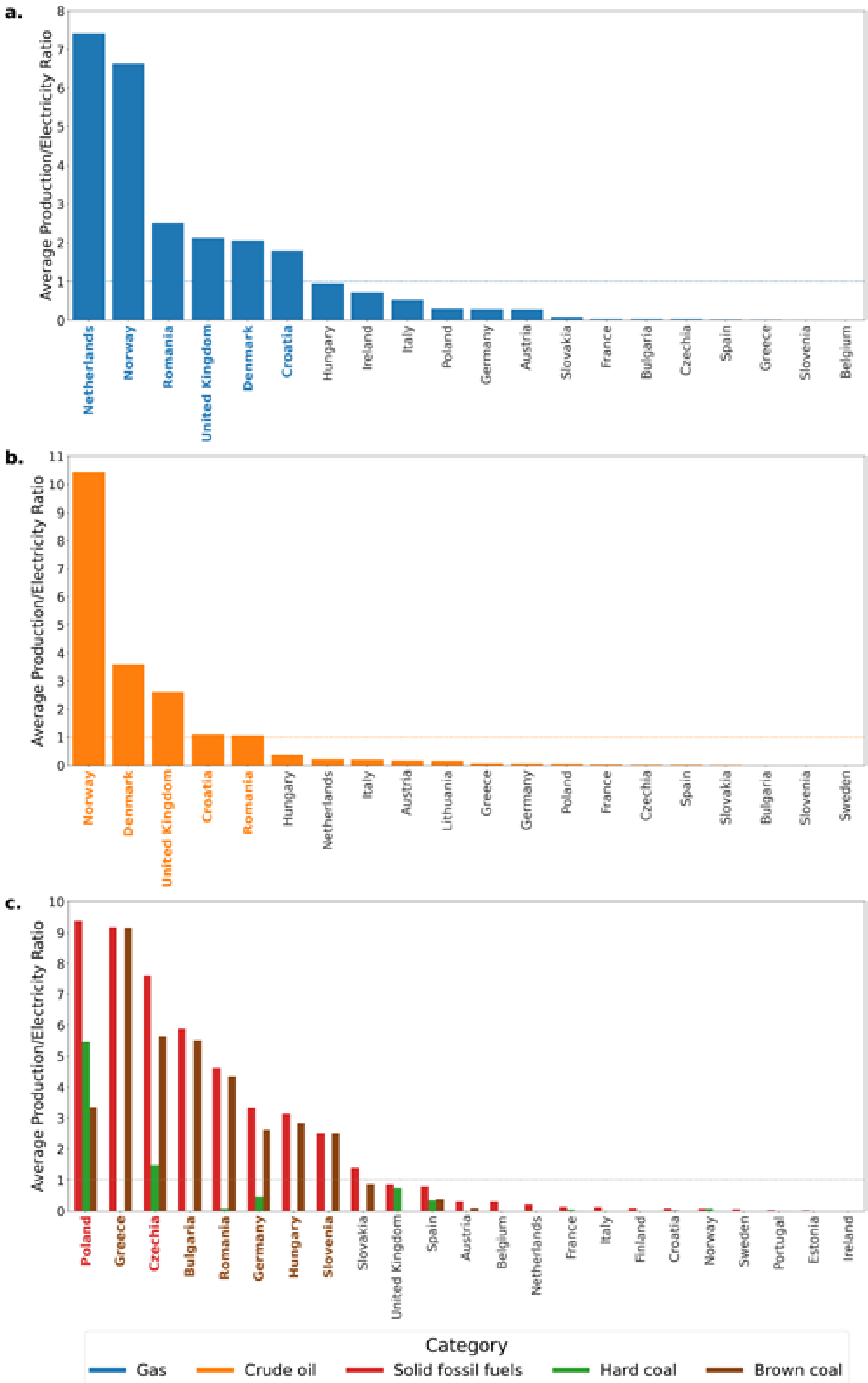

Figure B2. Information for the selection of countries to apply the two model versions focused on domestic resources. The figure shows the ratio of average yearly indigenous production of (a) gas, (b) oil, (c) coal production (in TJ) to yearly electricity generation (in TJ) by country over the period 1990-2019 (source: Eurostat). Countries with values higher than one are highlighted in colour.

As shown, for each type of fossil fuel, only a few countries produce them in significant amounts. Hence, we assume that they can potentially rely on increased electricity production from these sources during periods with elevated geopolitical risks. For the cases when the ratio of average energy production from the source to overall electricity production is greater than one, we consider this type of fossil fuel to be domestic for this country, in addition to all renewable sources mentioned in the main text. The table with countries and their domestic fossil fuels is Table B2.

Table B2 European countries and their domestic fossil fuels.

Fossil fuel	**Countries with significant resources**
Gas	Denmark, United Kingdom, Croatia, Netherlands, Norway, Romania
Oil	Denmark, United Kingdom, Croatia, Norway, Romania
Brown coal	Bulgaria, Czech Republic, Germany, Greece, Hungary, Poland, Romania, Slovenia
Hard coal	Czech Republic, Poland

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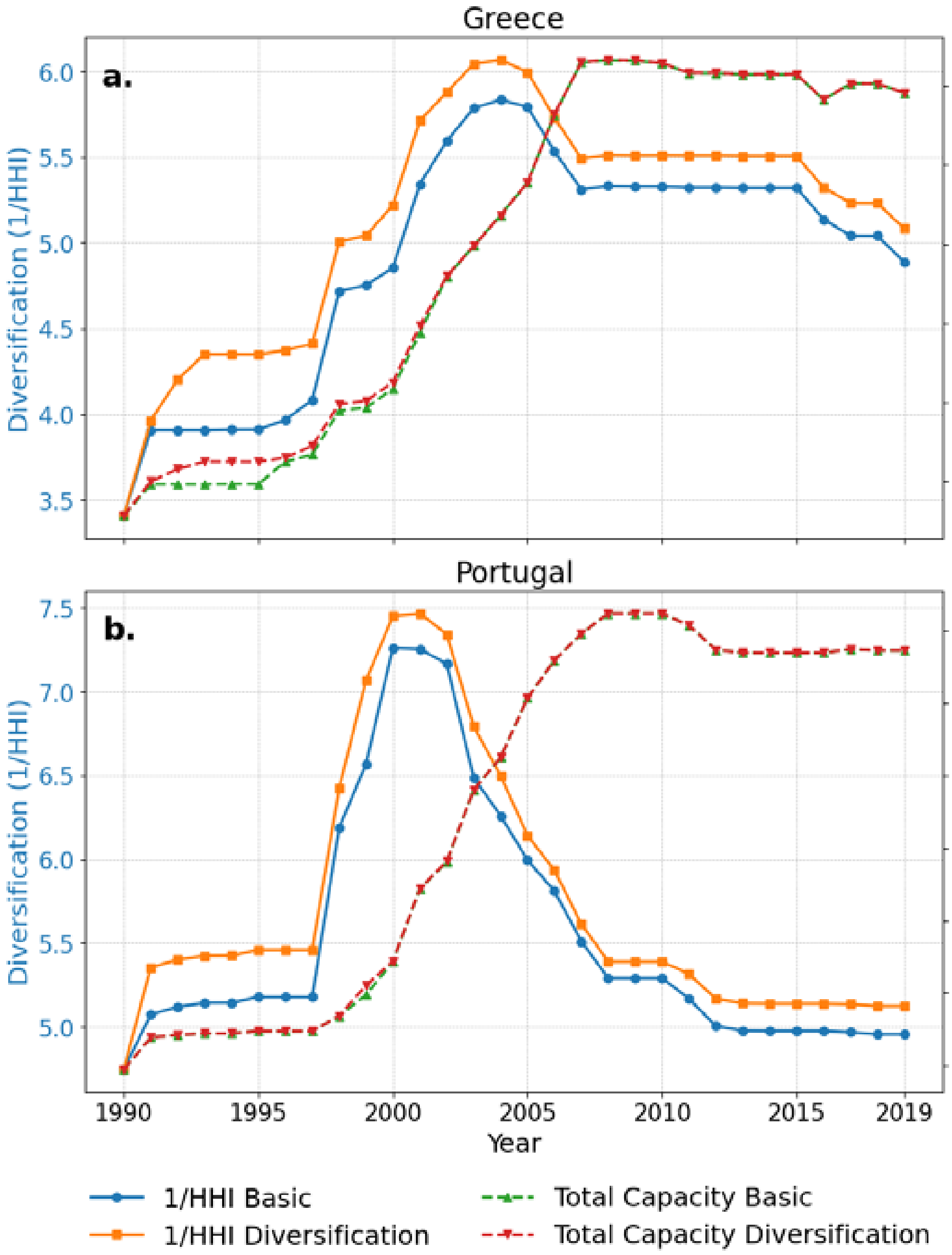

Figure B3. Evolution of the total installed capacity and the diversification parameter (1/HHI) in the Basic and Diversification versions for two countries: (a) Greece and (b) Portugal

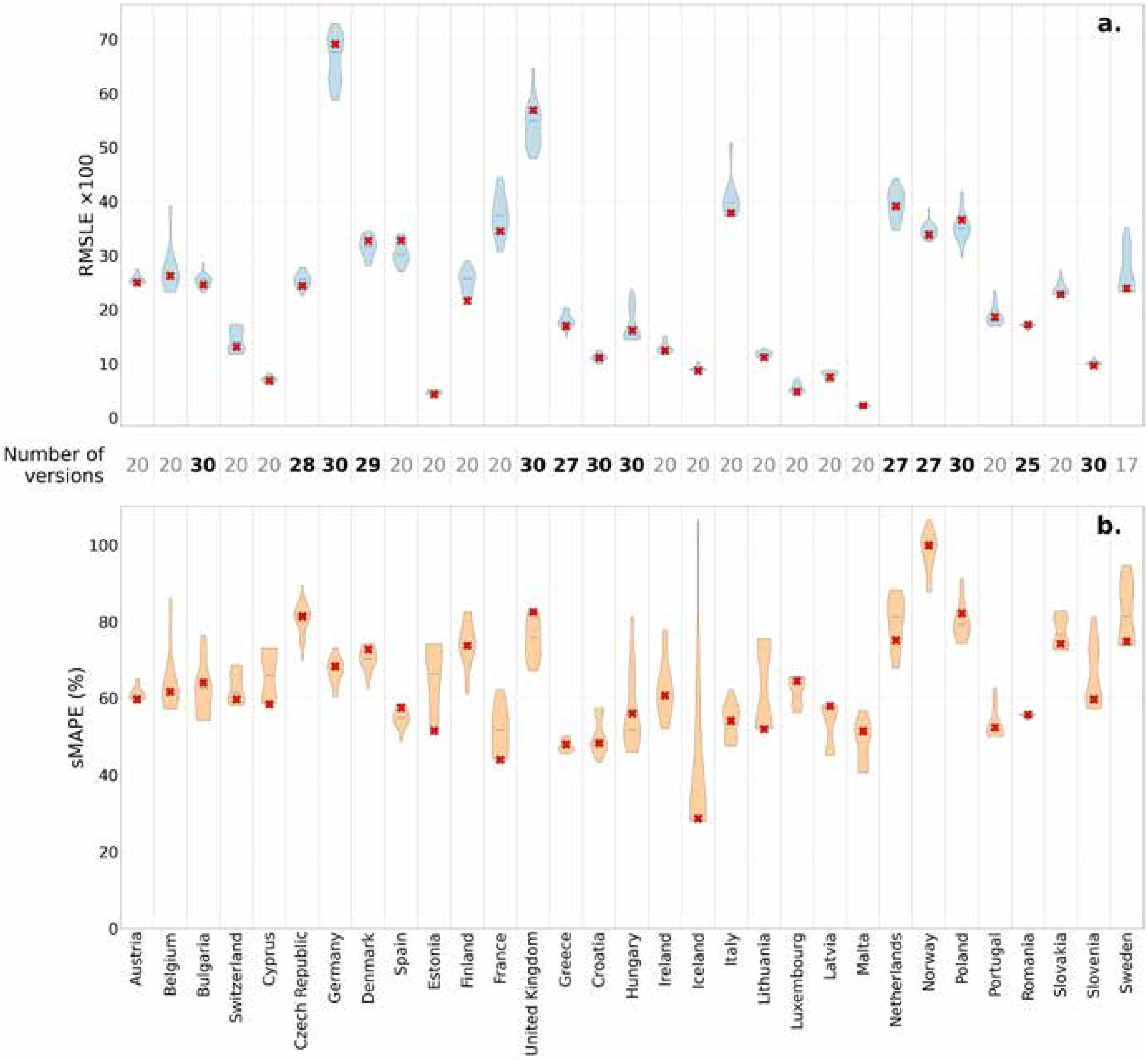

Figure B4. Accuracy of the modeled pathways quantified by absolute values of (a) RSMLE and (b) sMAPE for all different model versions for each of the five GPIs (in total 30 versions per country at maximum). Basic versions are shown with red crosses. Higher values mean lower accuracy. The total number of model versions that compute feasible solutions is shown between the plots; numbers for countries with domestic fossil fuels are written in bold.

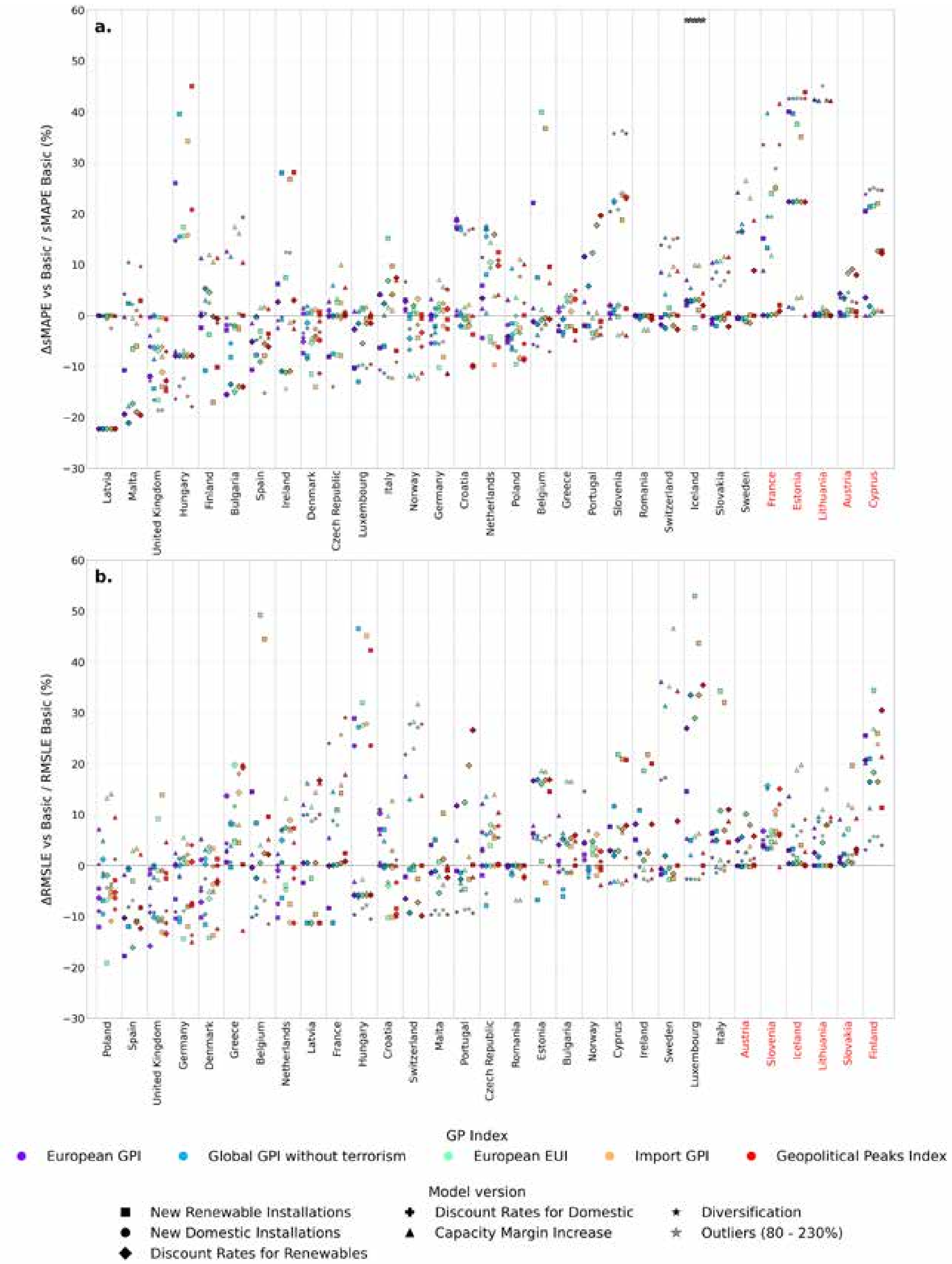

Figure B5. Scatter plots with calculated relative differences in (a) sMAPE and (b) RSMLE between the Basic and calculated model versions for each of the GPI across all countries. Countries are listed in order from highest to lowest RSMLE improvement of the best-performed version. Countries with no improvement of at least 1% in any version are coloured red.

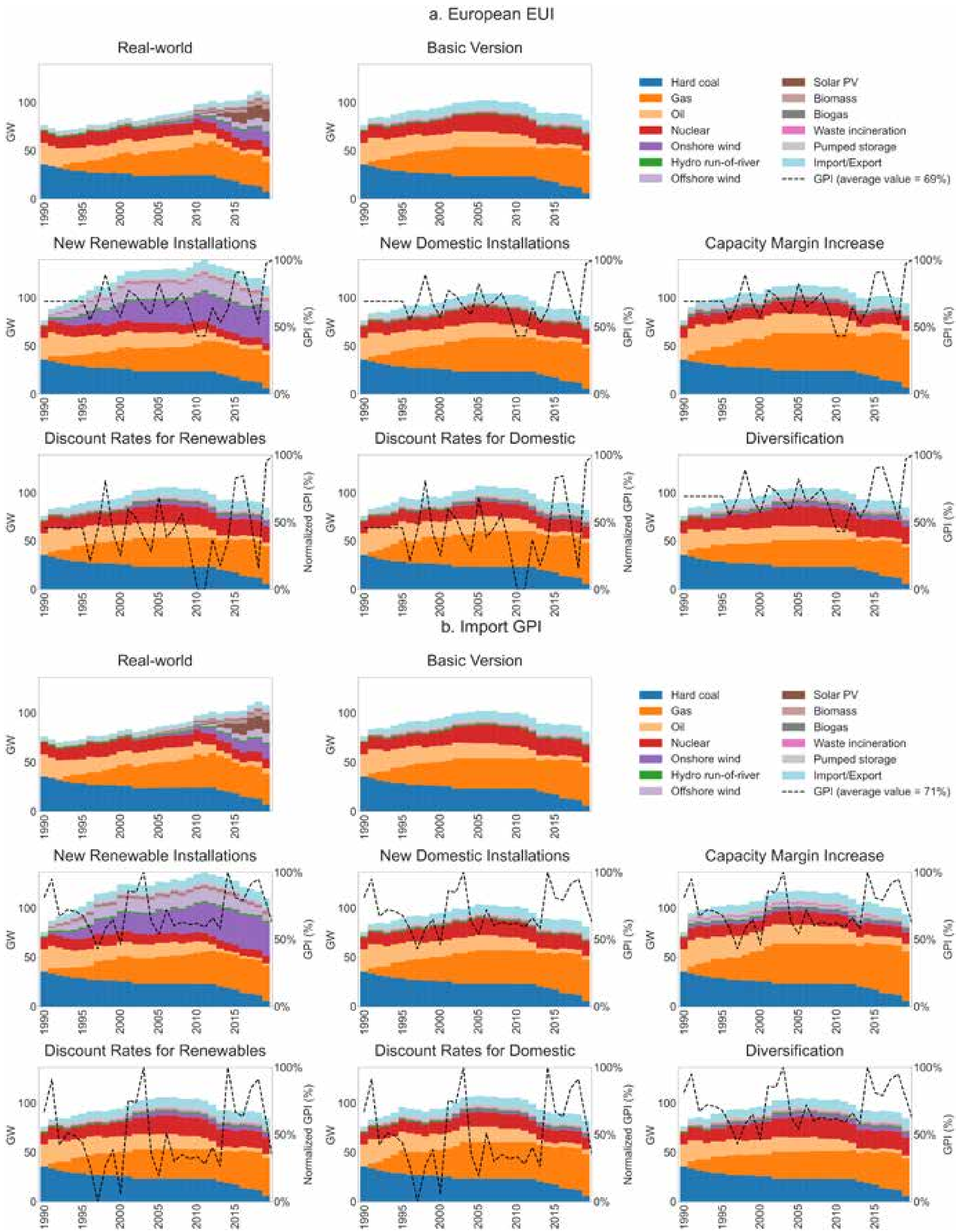

Figure B6-1. Installed capacities for the United Kingdom in all individual model versions for (a) European EUI, (b) Import GPI, (c) Geopolitical Peaks Index, (d) European GPI. The GPR without terrorism GPI is presented in the main text (Figure 2).

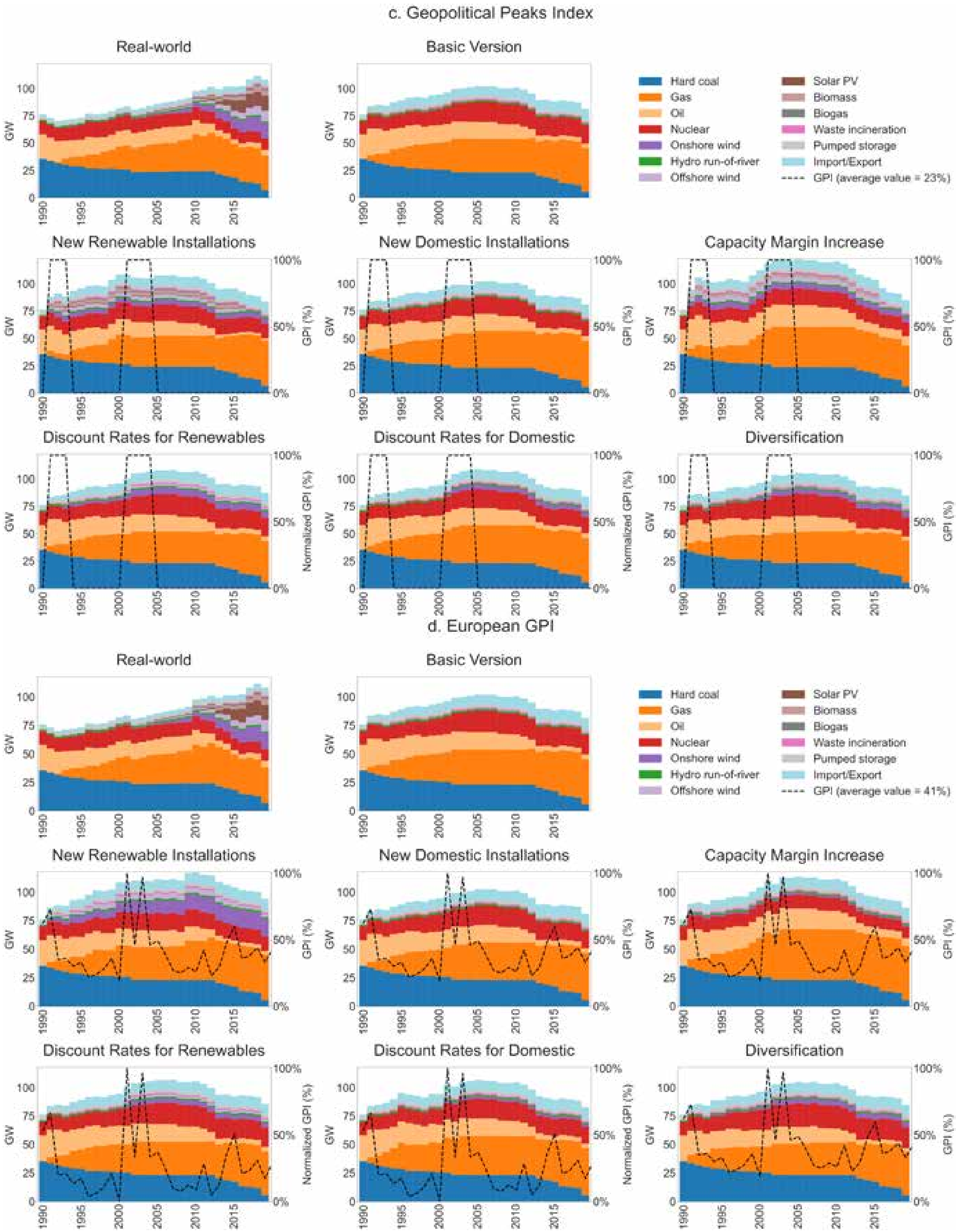

Figure B6-2. Installed capacities for the United Kingdom in all individual model versions for (c) Geopolitical Peaks Index, (d) European GPI. The GPR without terrorism GPI is presented in the main text (Figure 2).

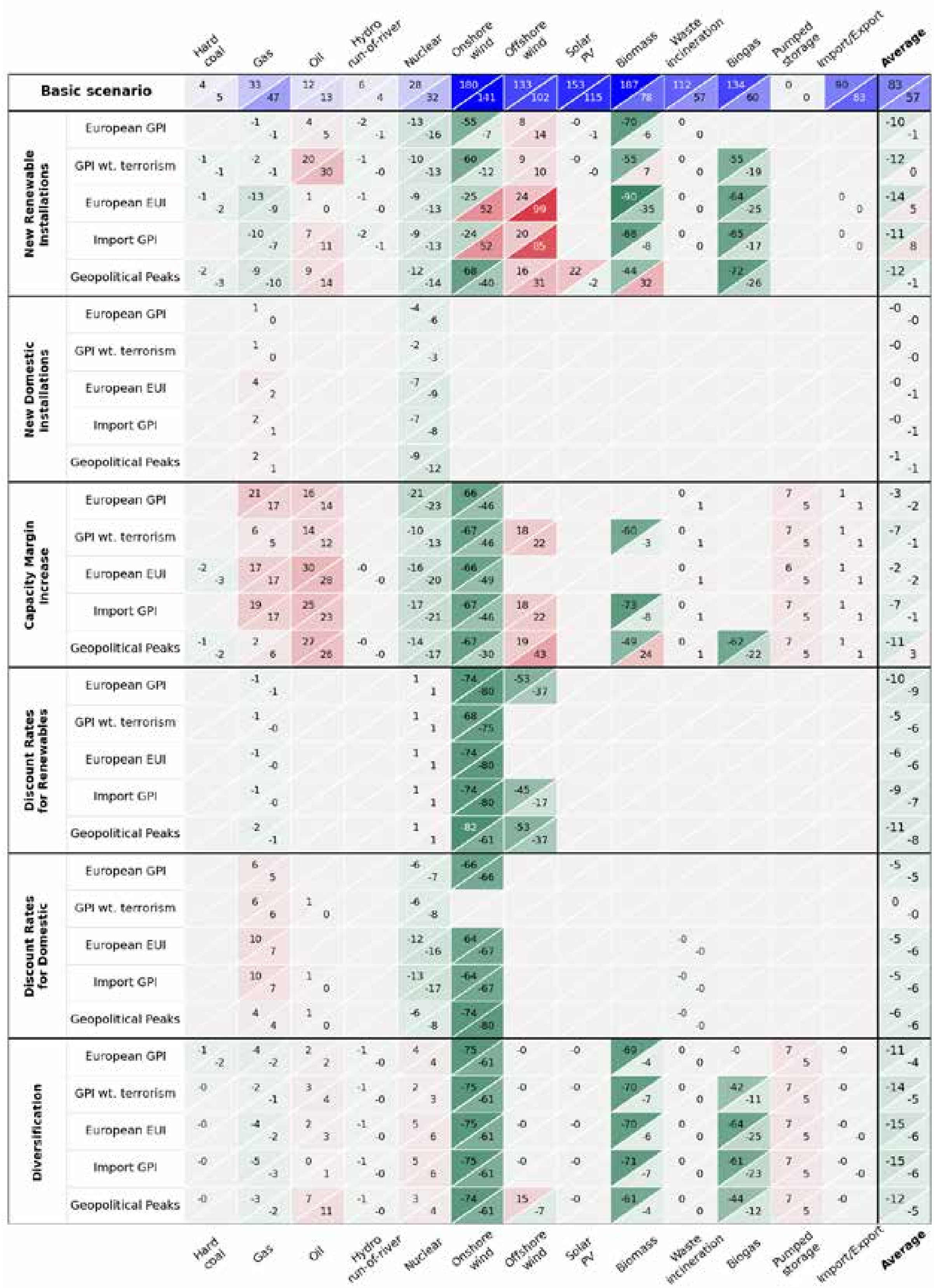

Figure B7. Heatmap with computed sMAPE (top-left) and RMSLE (bottom-right) indicators of the Basic version and deviations in all calculated individual model versions for all GPIs for the United Kingdom. All values ×100.

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Figures S8. For 30 countries (except the UK): (a) installed capacities in real-world transition in 1990-2019, Basic model version, and six different model versions, using Global GPI without terrorism as index, and (b) heatmap with computed sMAPE and RSMLE indicators of the Basic model version and error differences in all other model versions with all GPIs. For the Basic version, absolute values of indicators are shown; for all other versions, the differences with the Basic version as a ratio are shown. Higher values signify less accurate model outputs; hence more accurate outputs are colored green and less accurate colored red.

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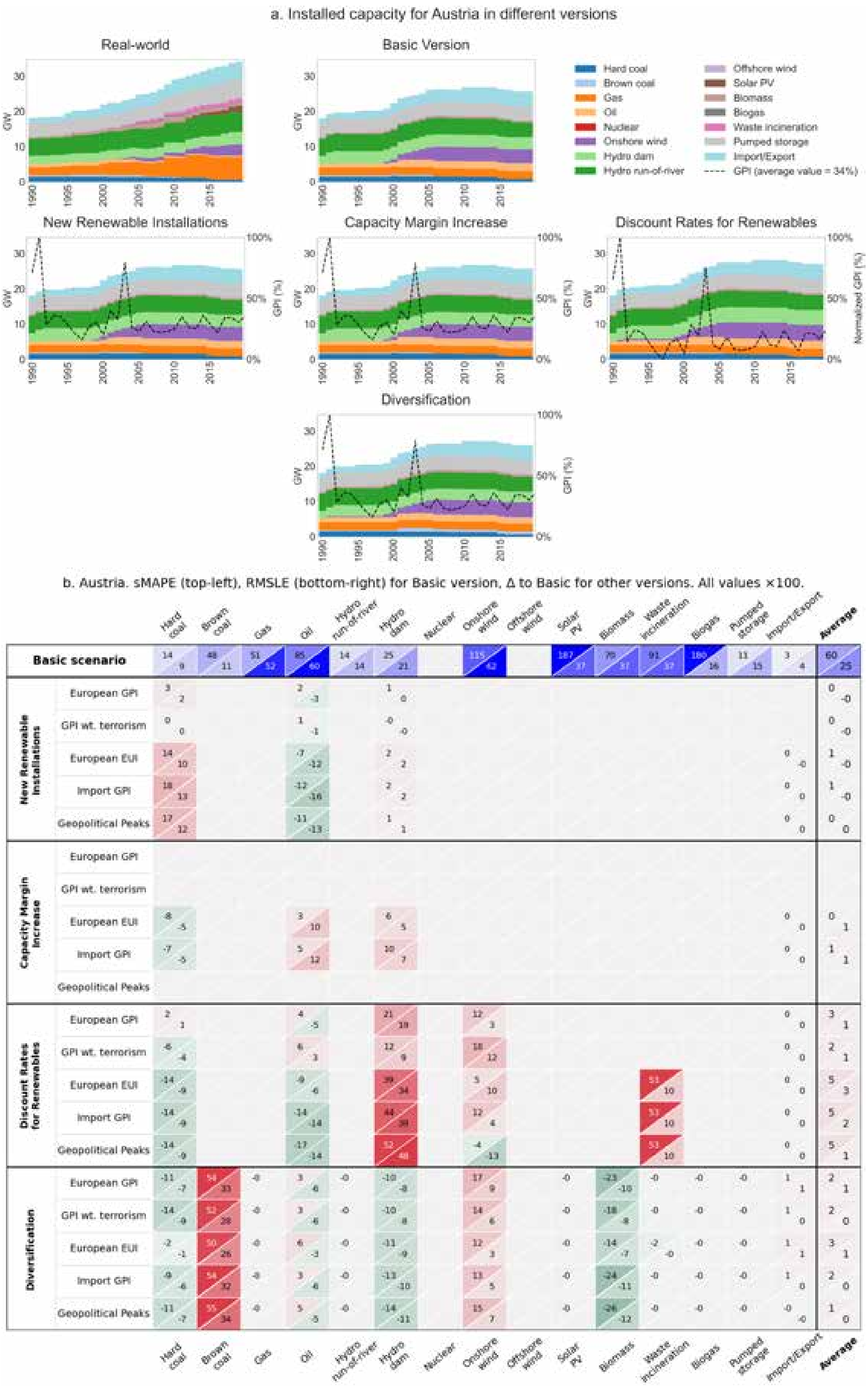

Figure. B8-1. Austria

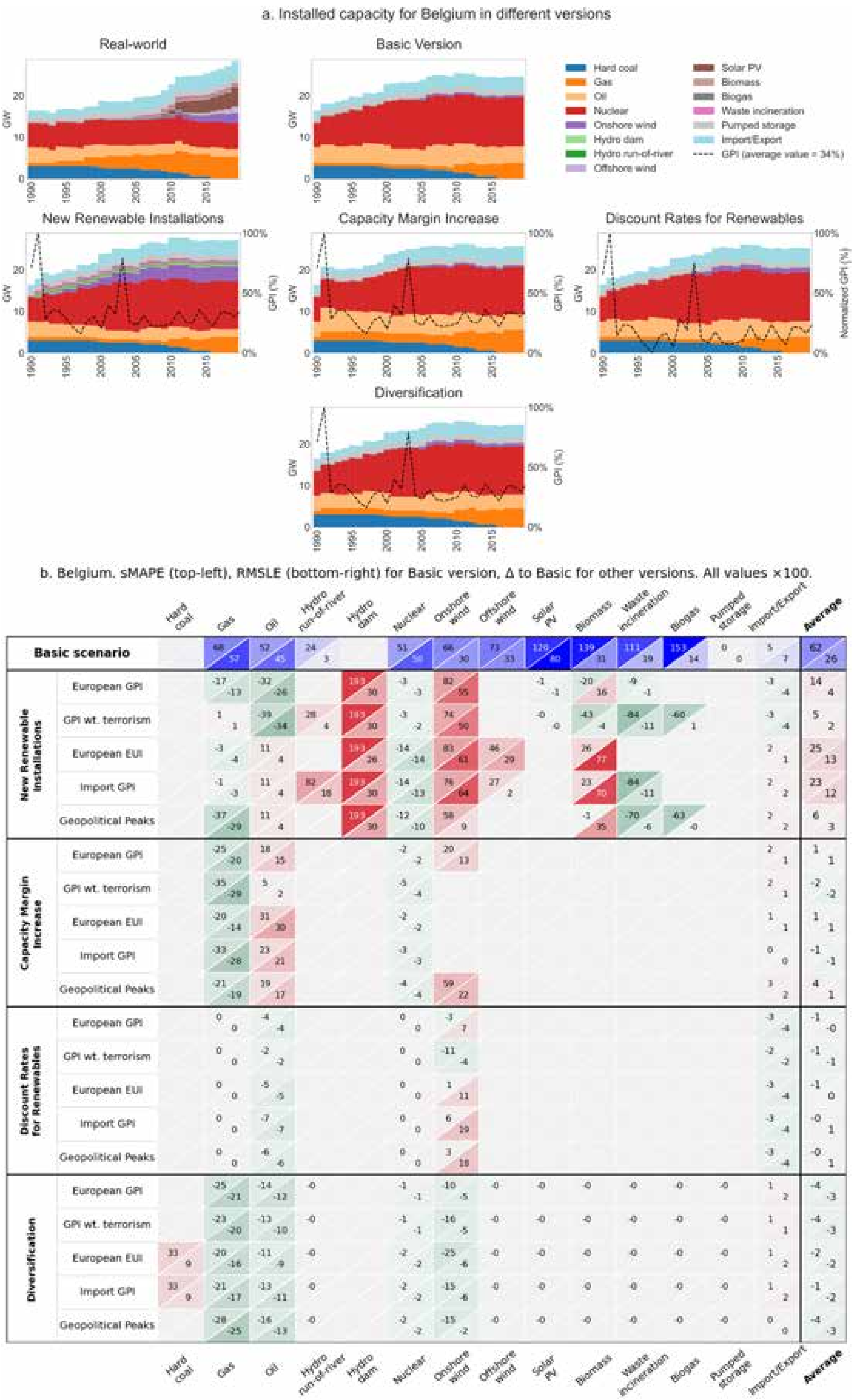

Figure. B8-2. Belgium

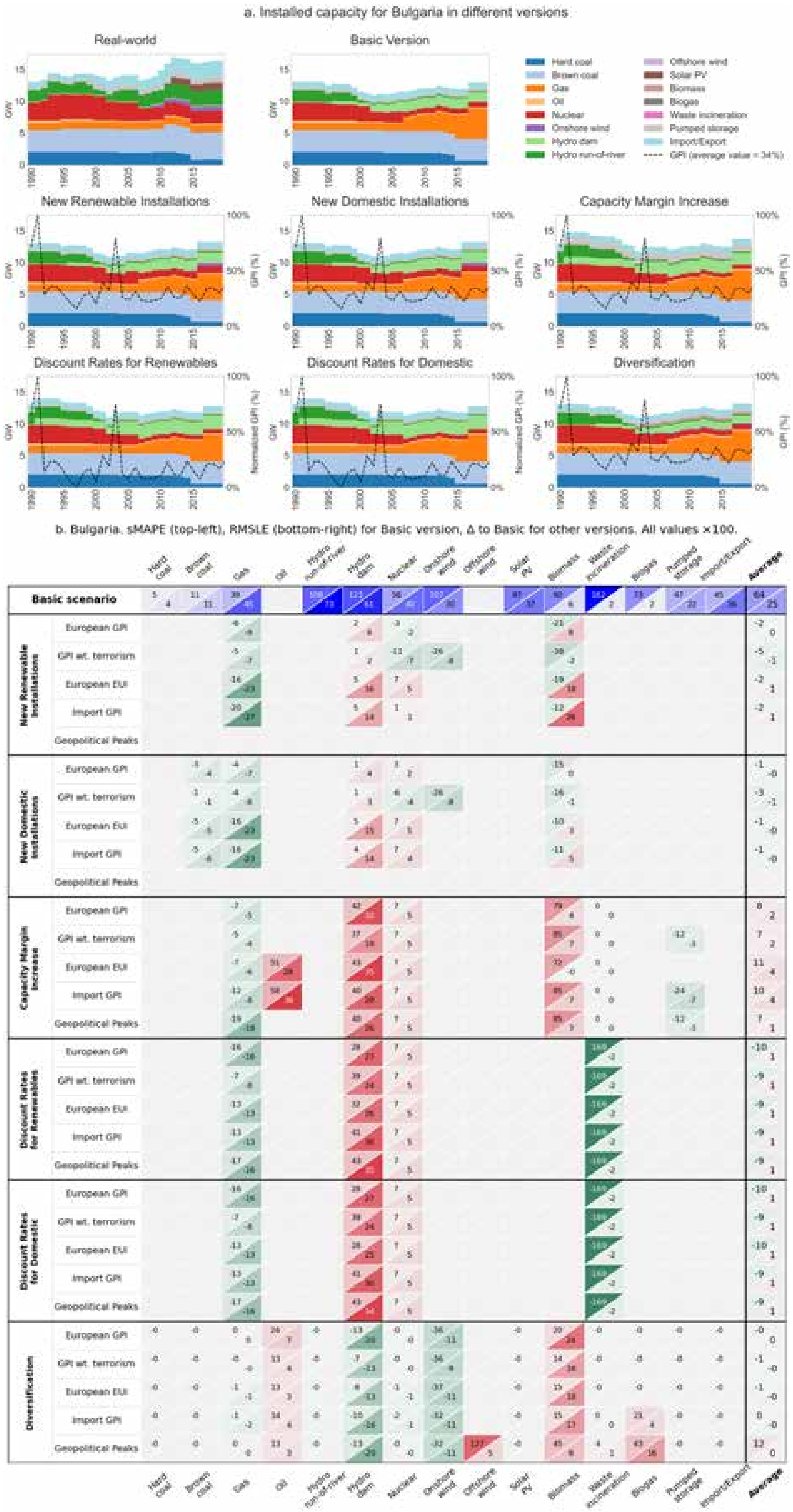

Figure. B8-3. Bulgaria

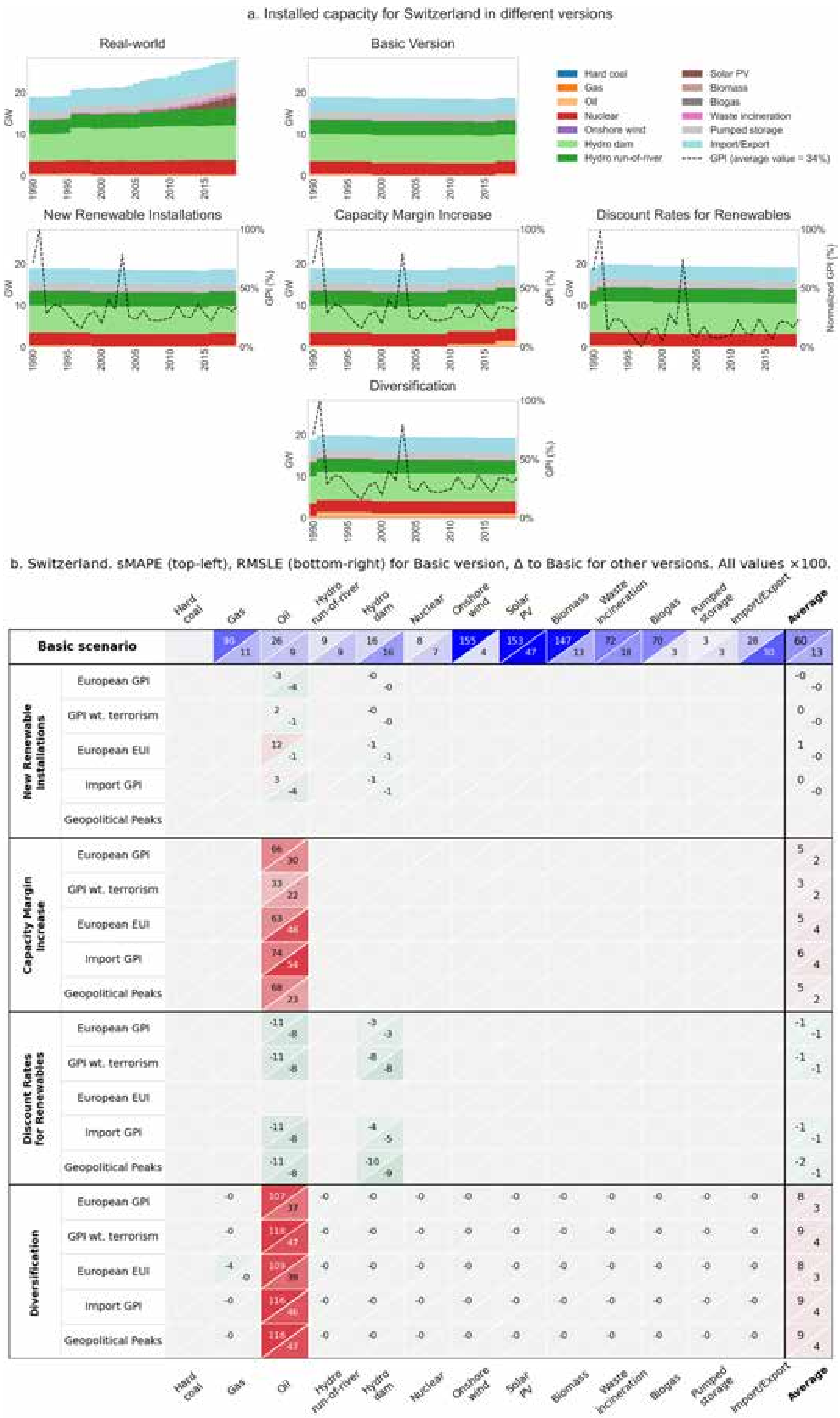

Figure. B8-4. Switzerland

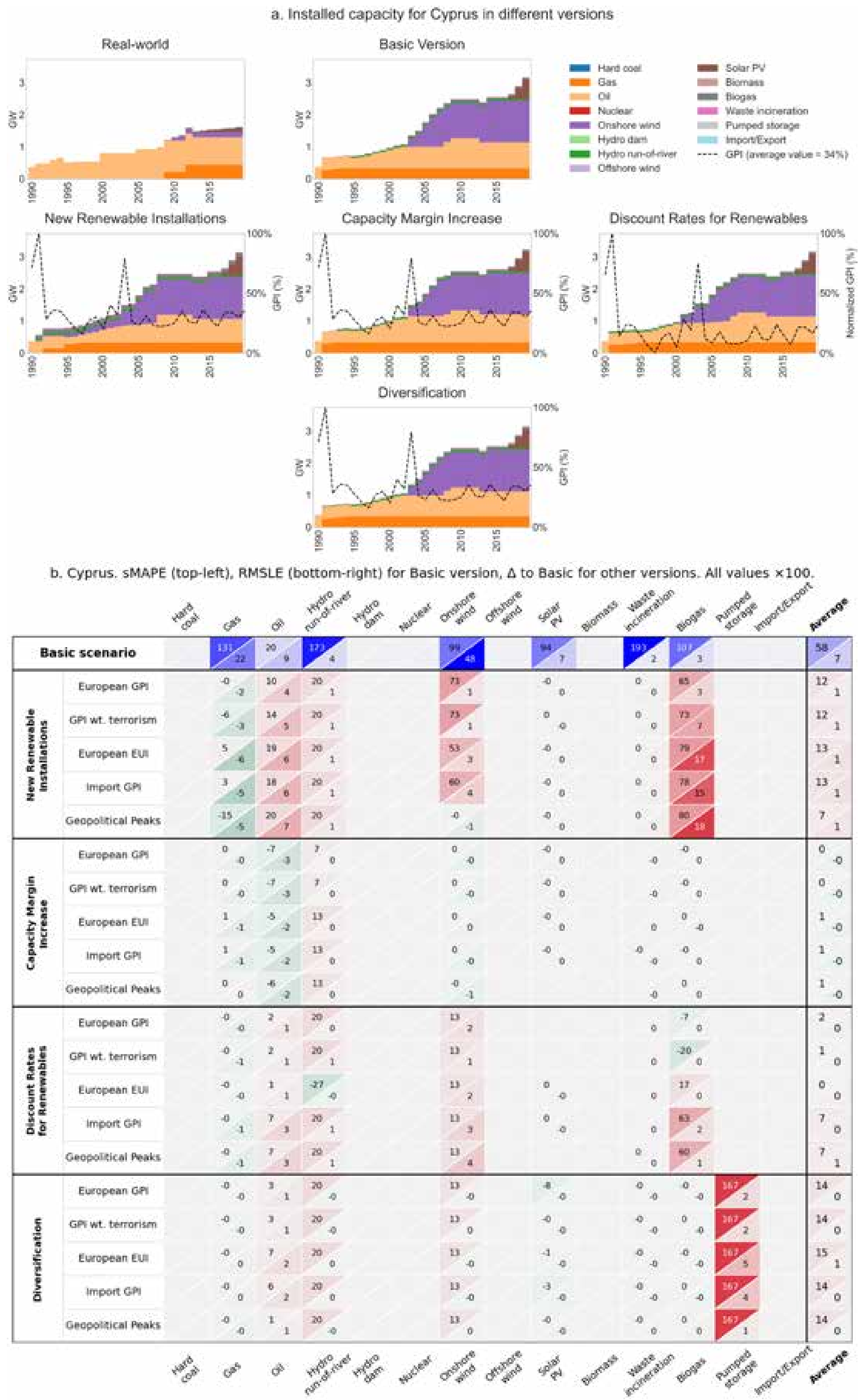

Figure. B8-5. Cyprus

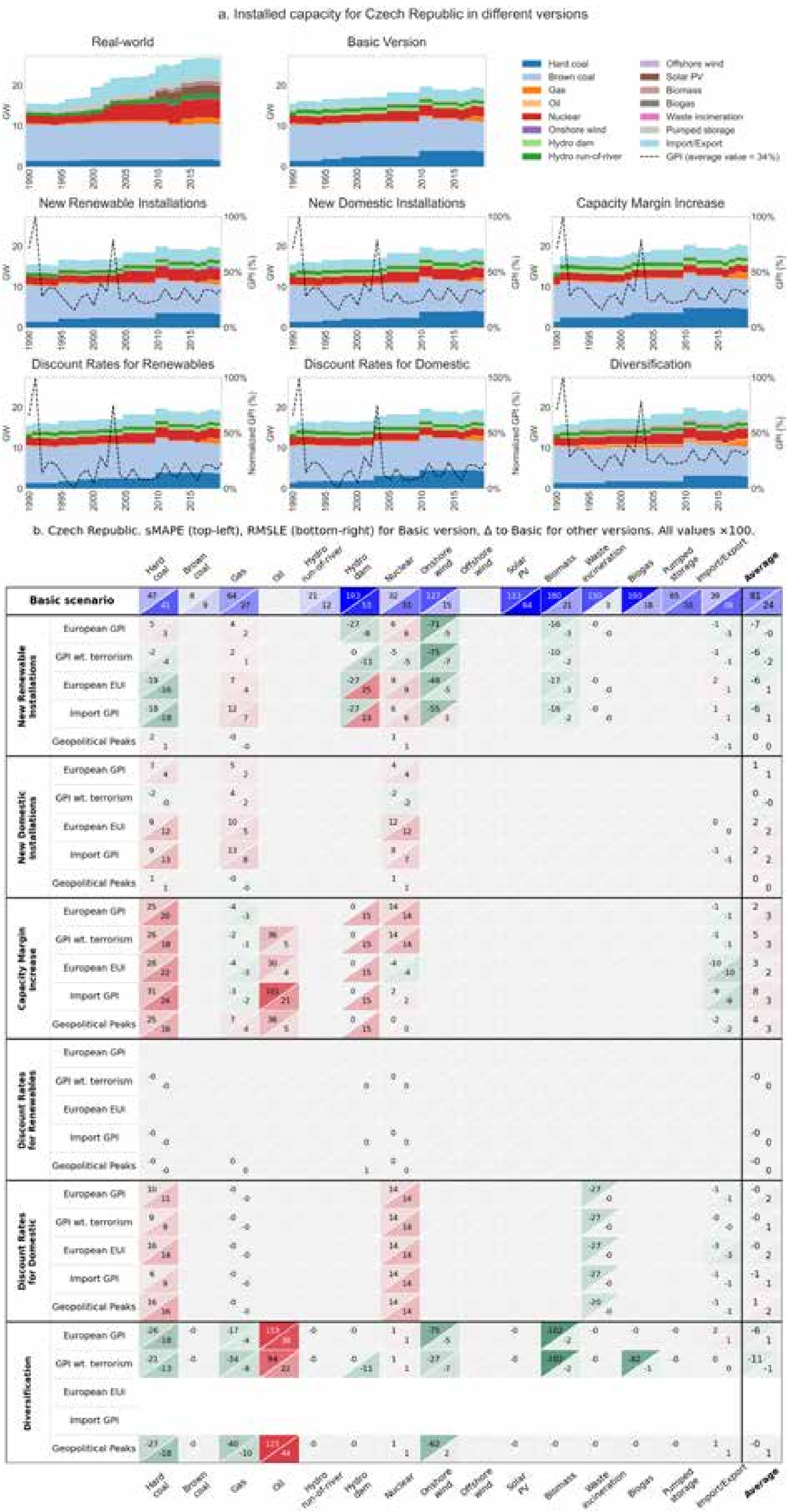

Figure. B8-6. Czech Republic

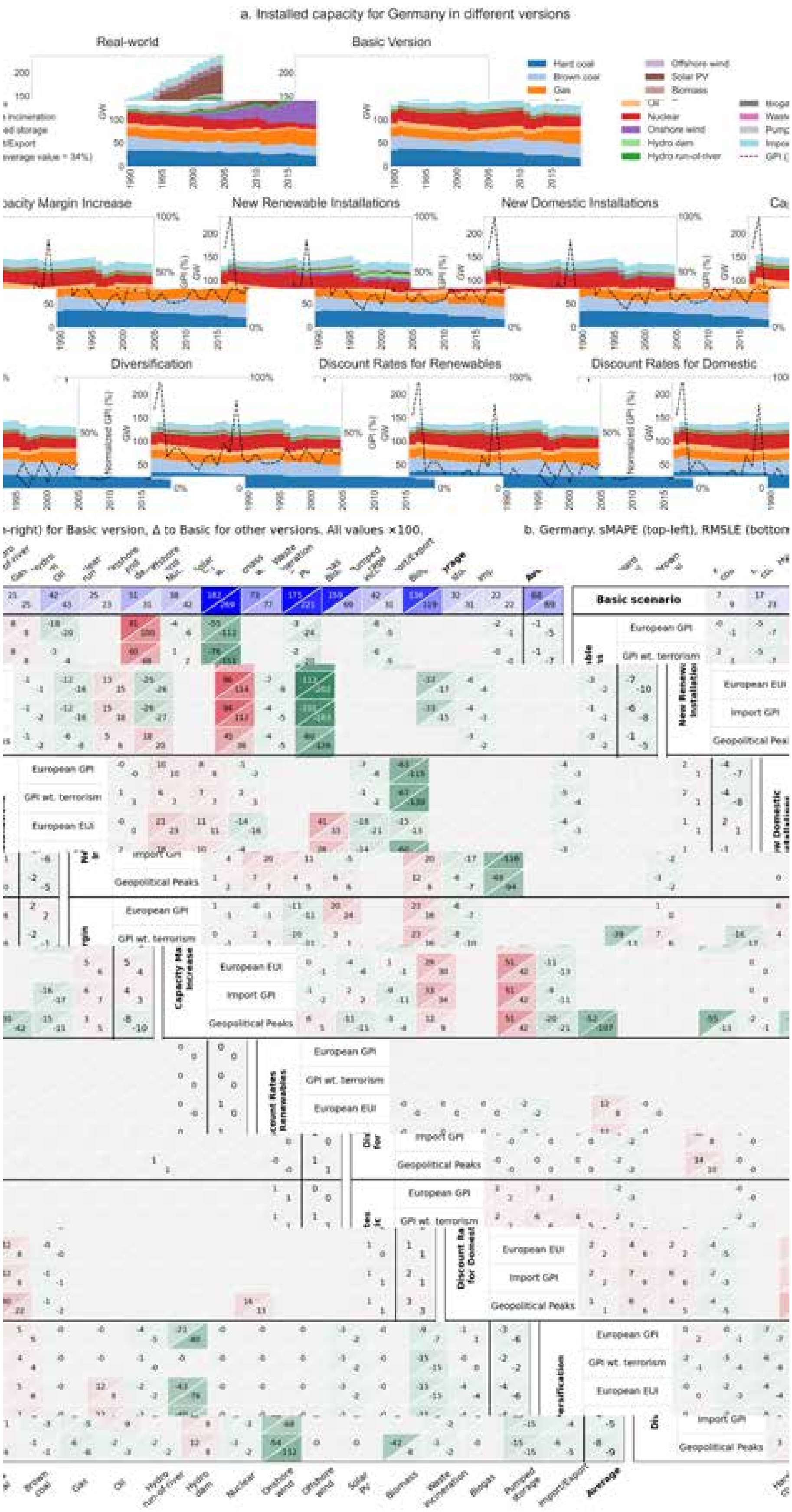

Figure. B8-7. Germany

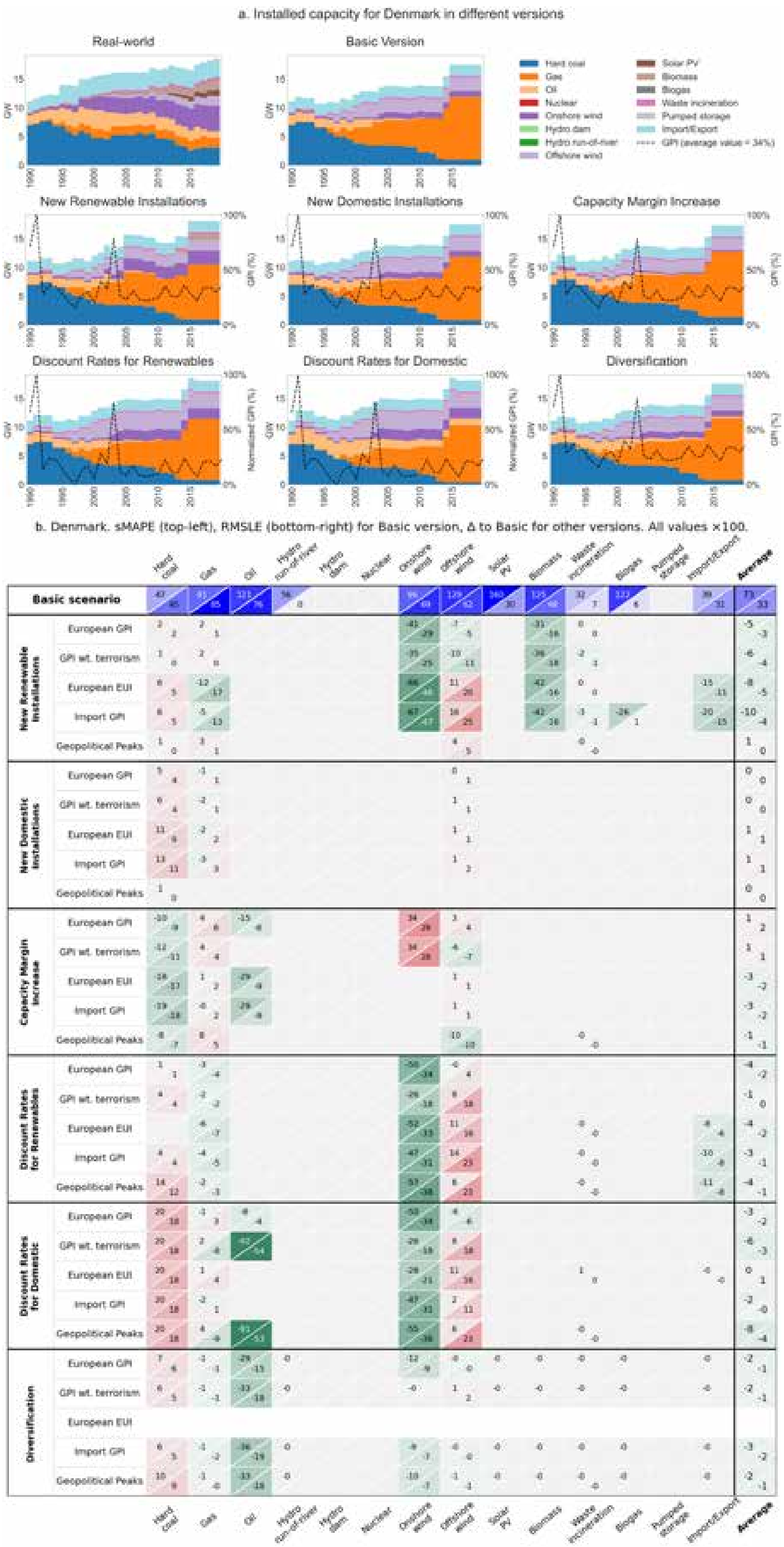

Figure. B8-8. Denmark

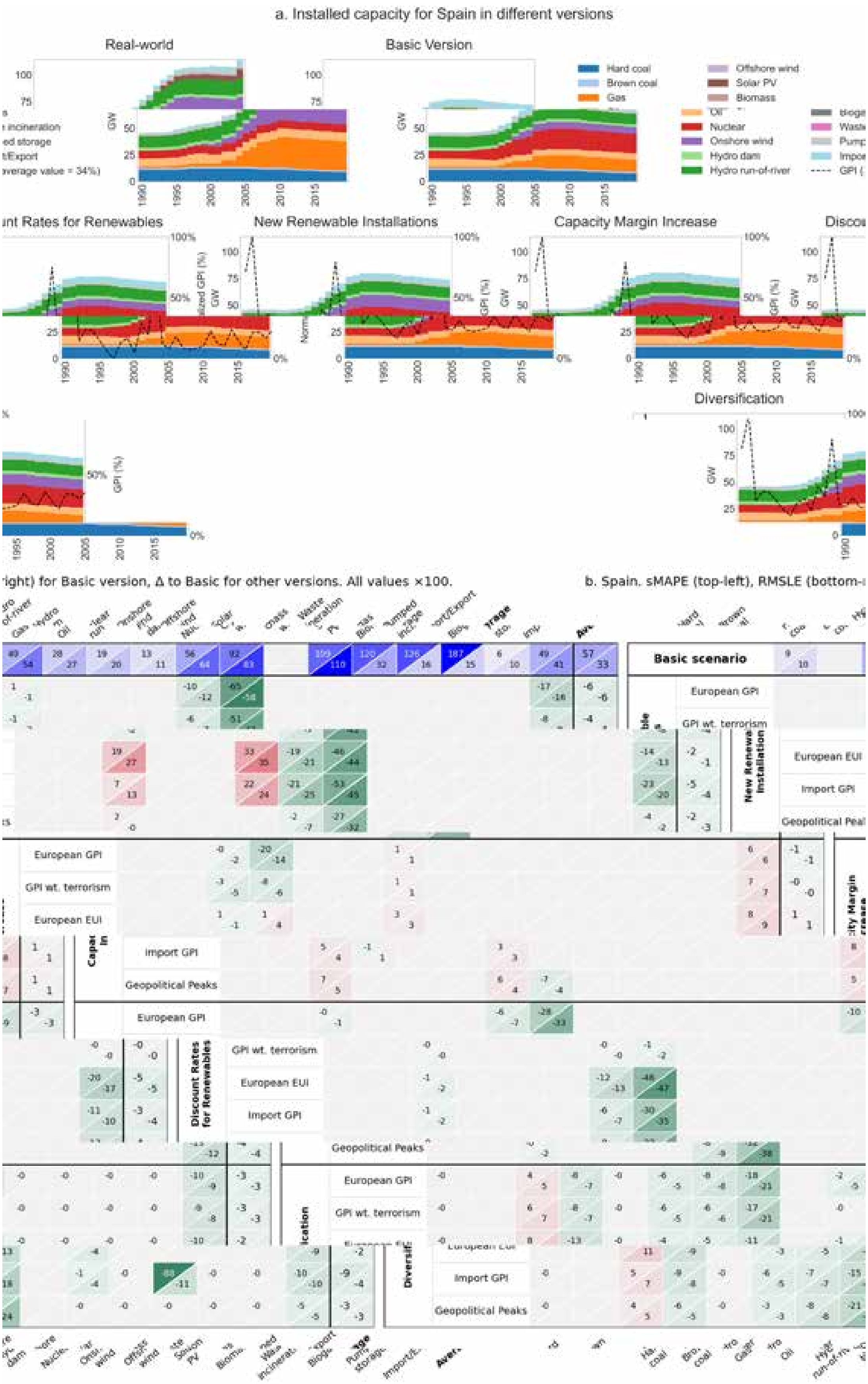

Figure. B8-9. Spain

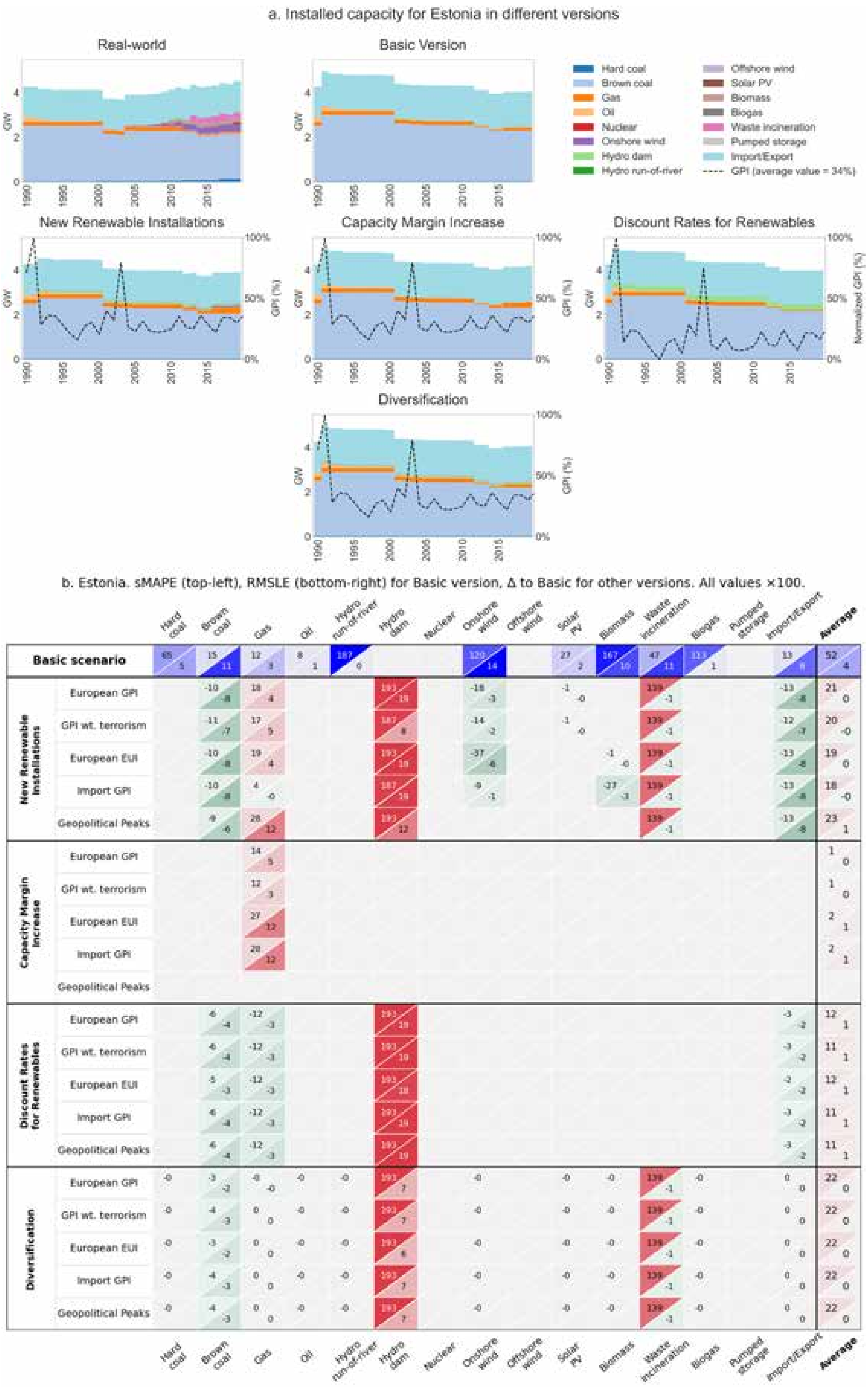

Figure. B8-10. Estonia

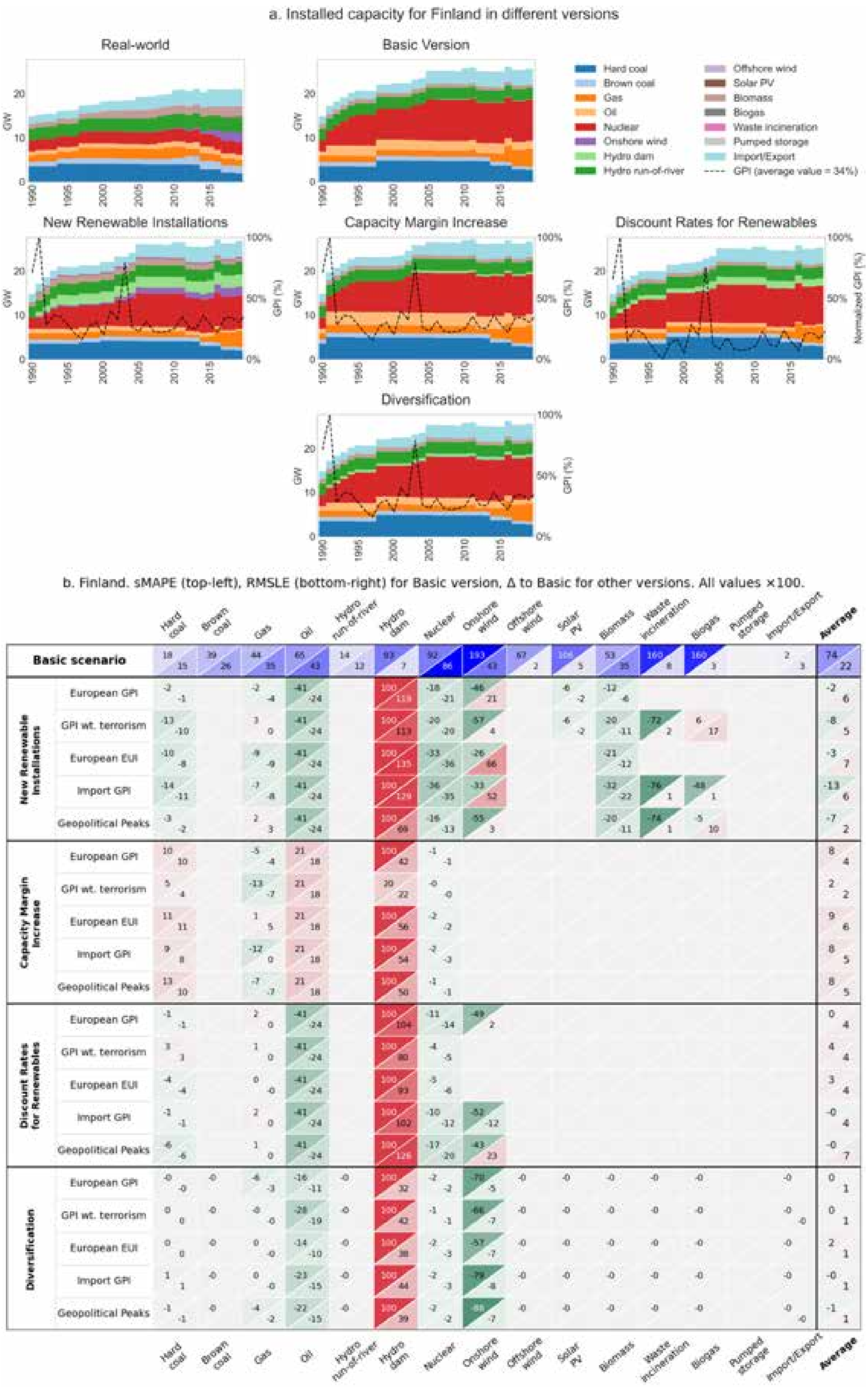

Figure. B8-11. Finland

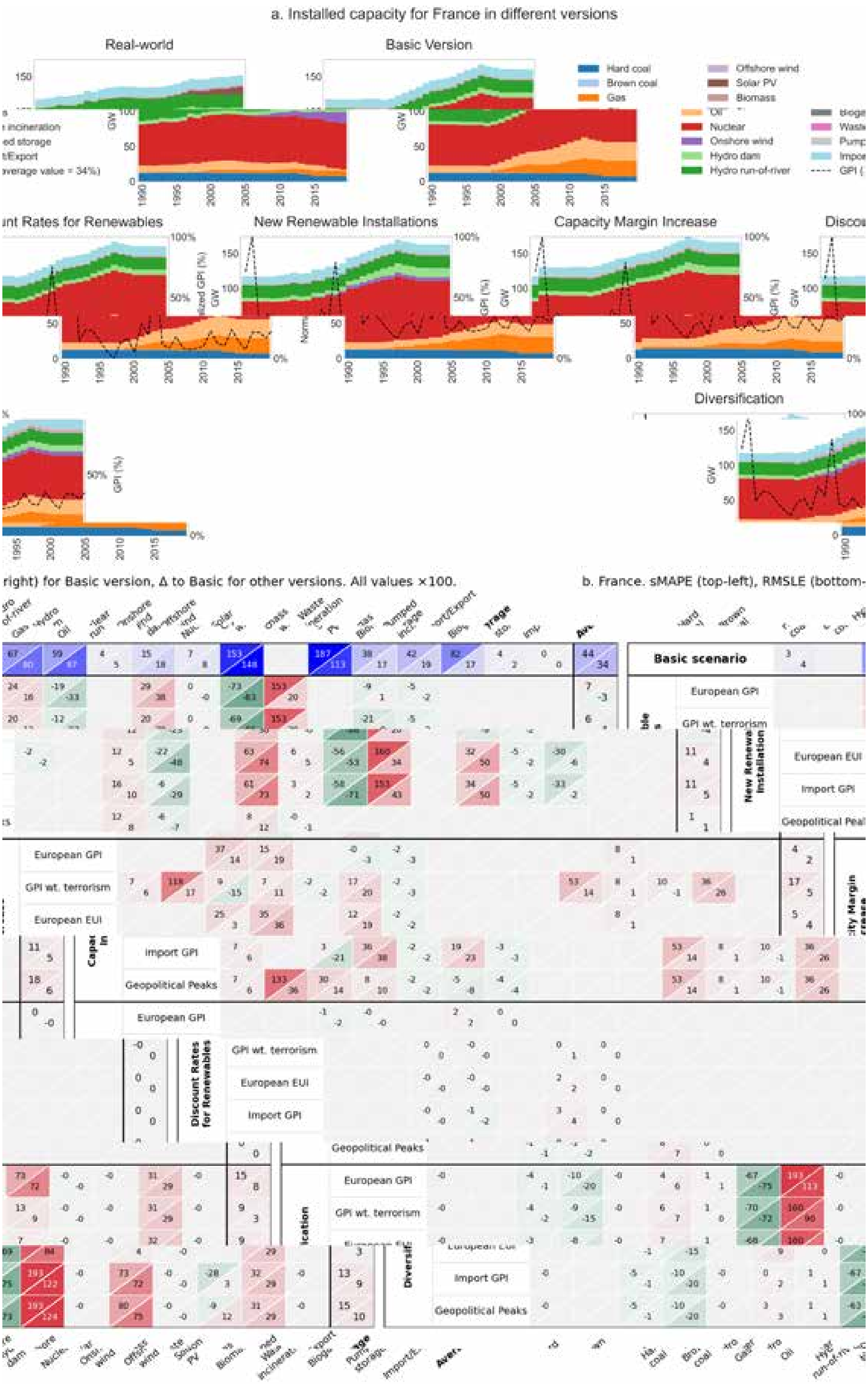

Figure. B8-12. France

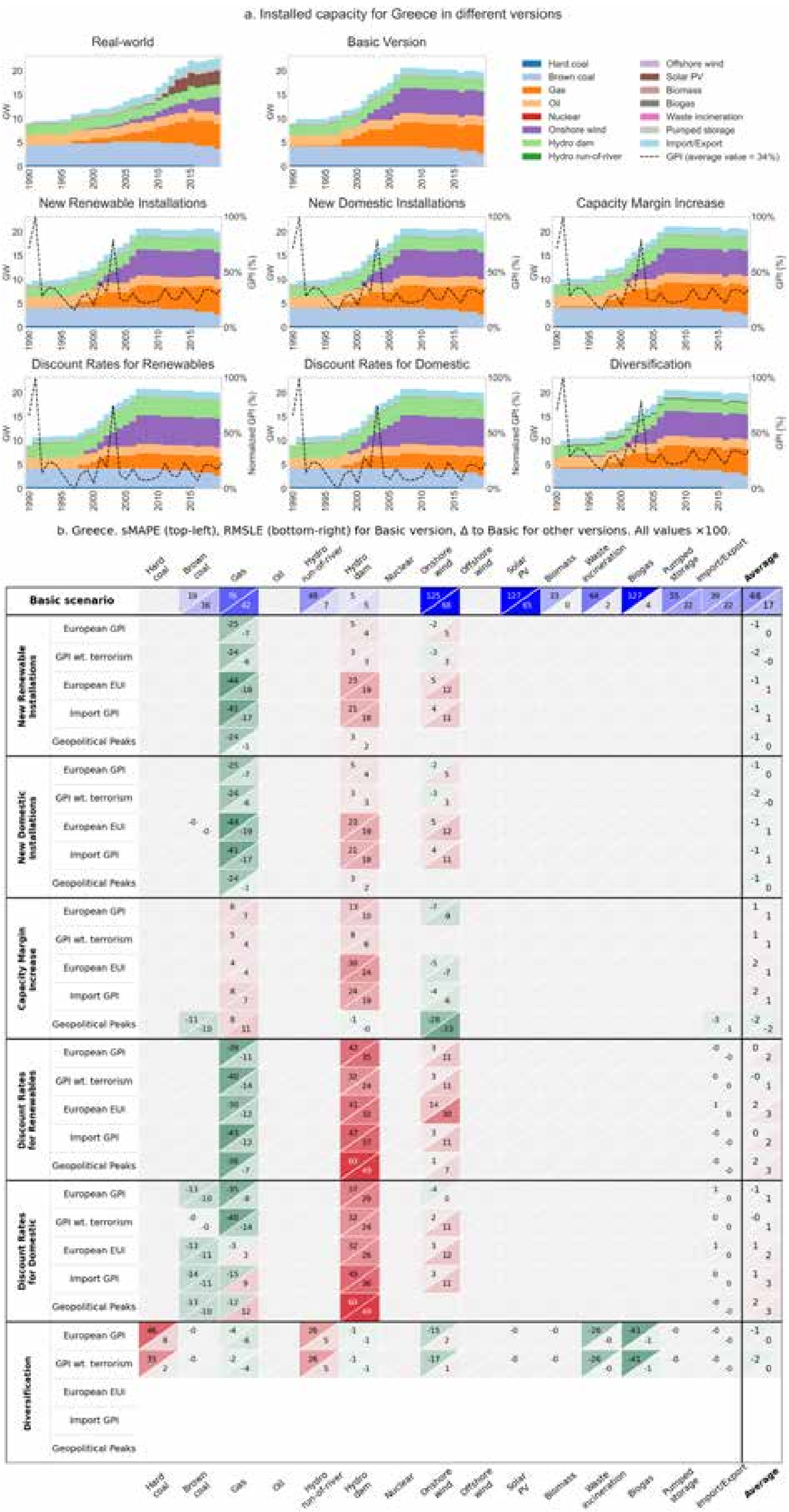

Figure. B8-13. Greece

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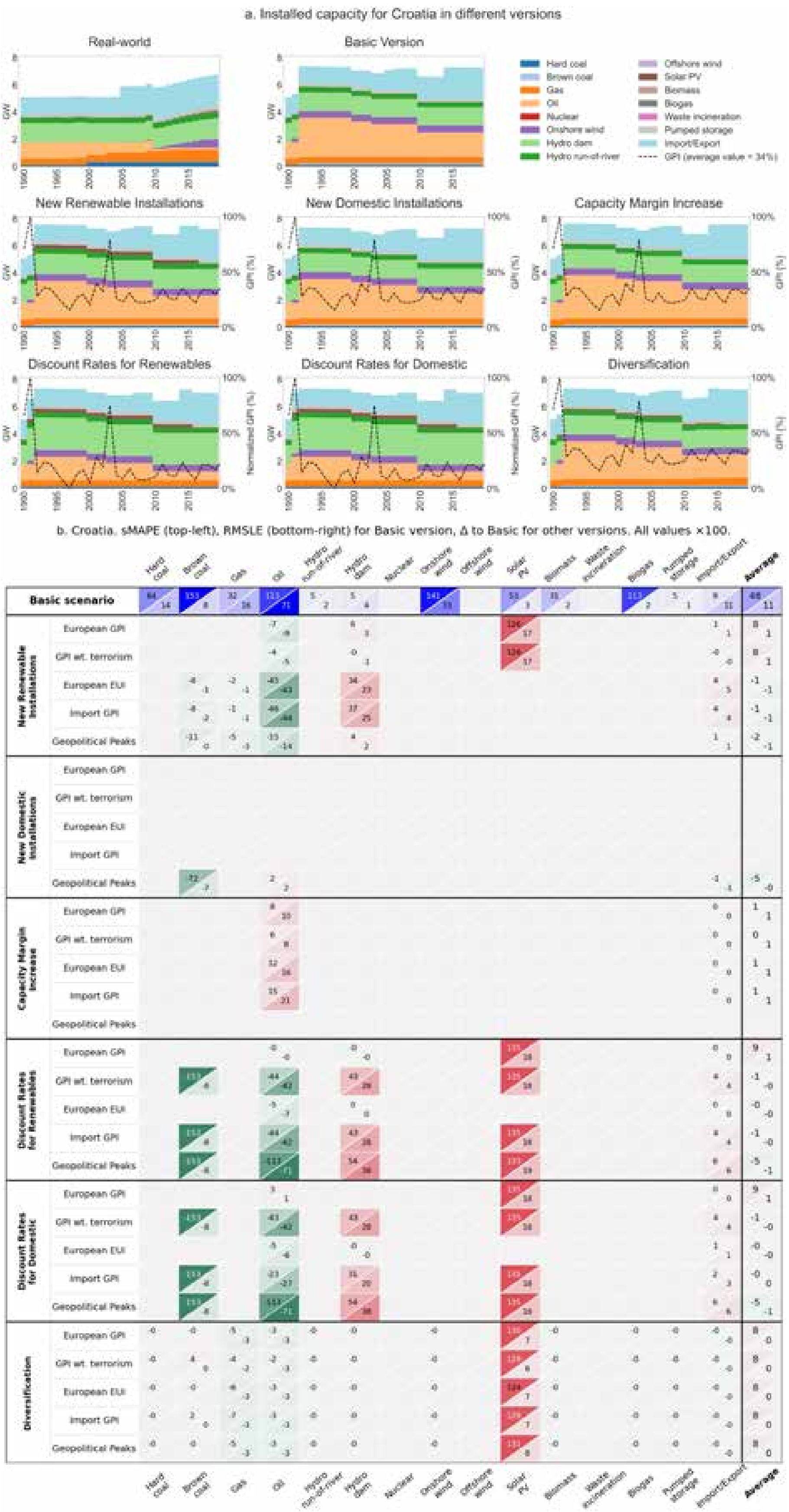

Figure. B8-14. Croatia

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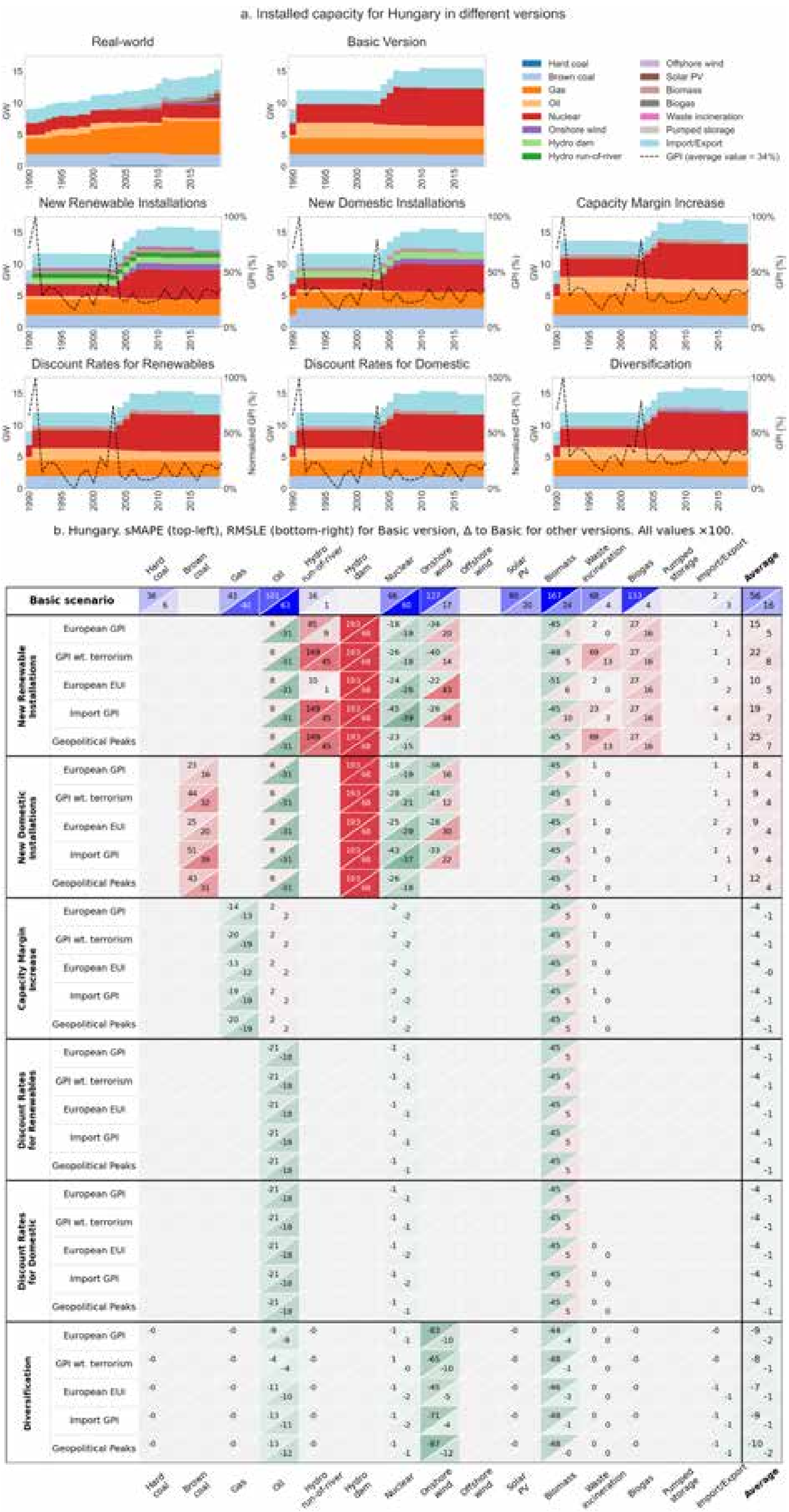

Figure. B8-15. Hungary

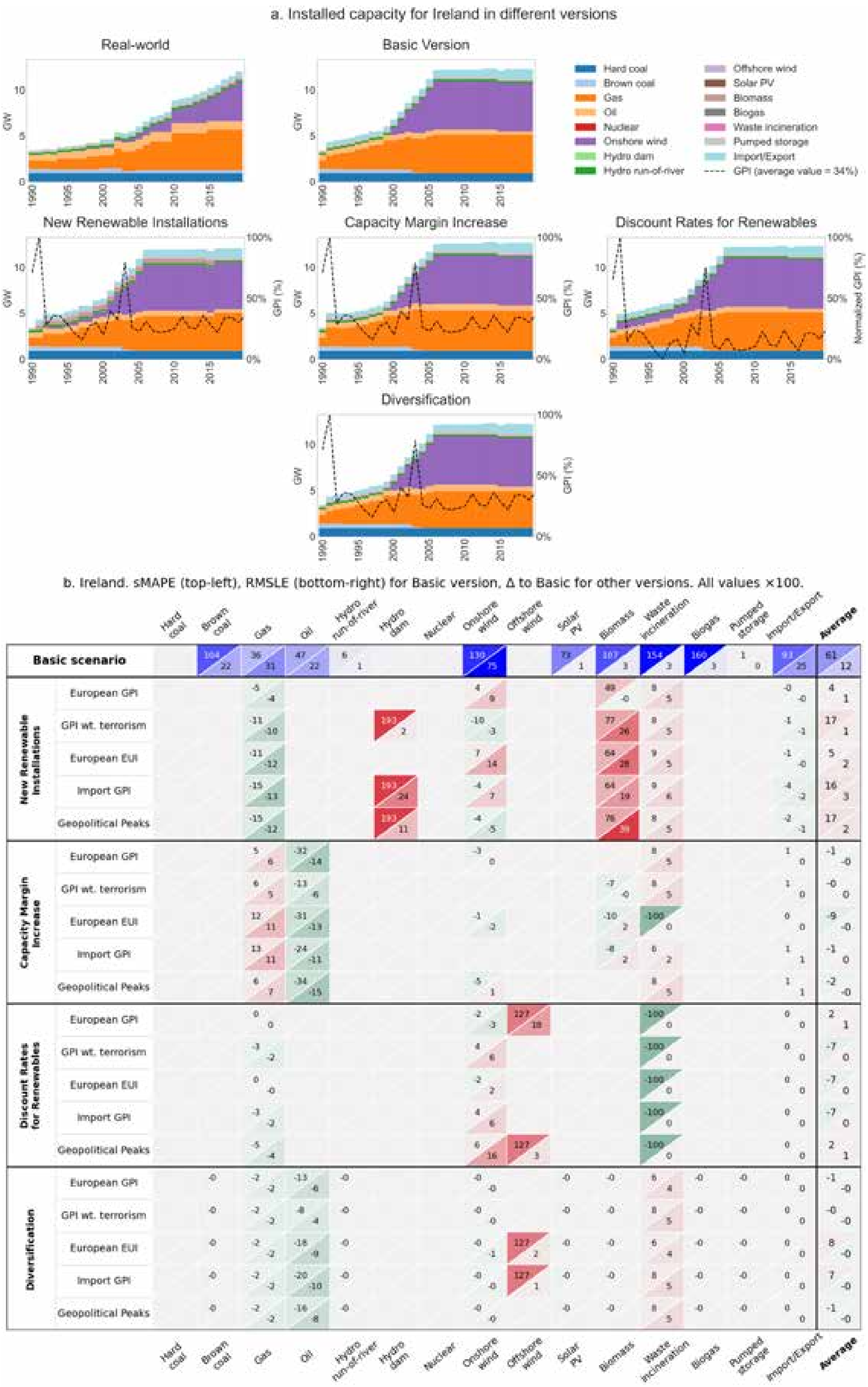

Figure. B8-16. Ireland

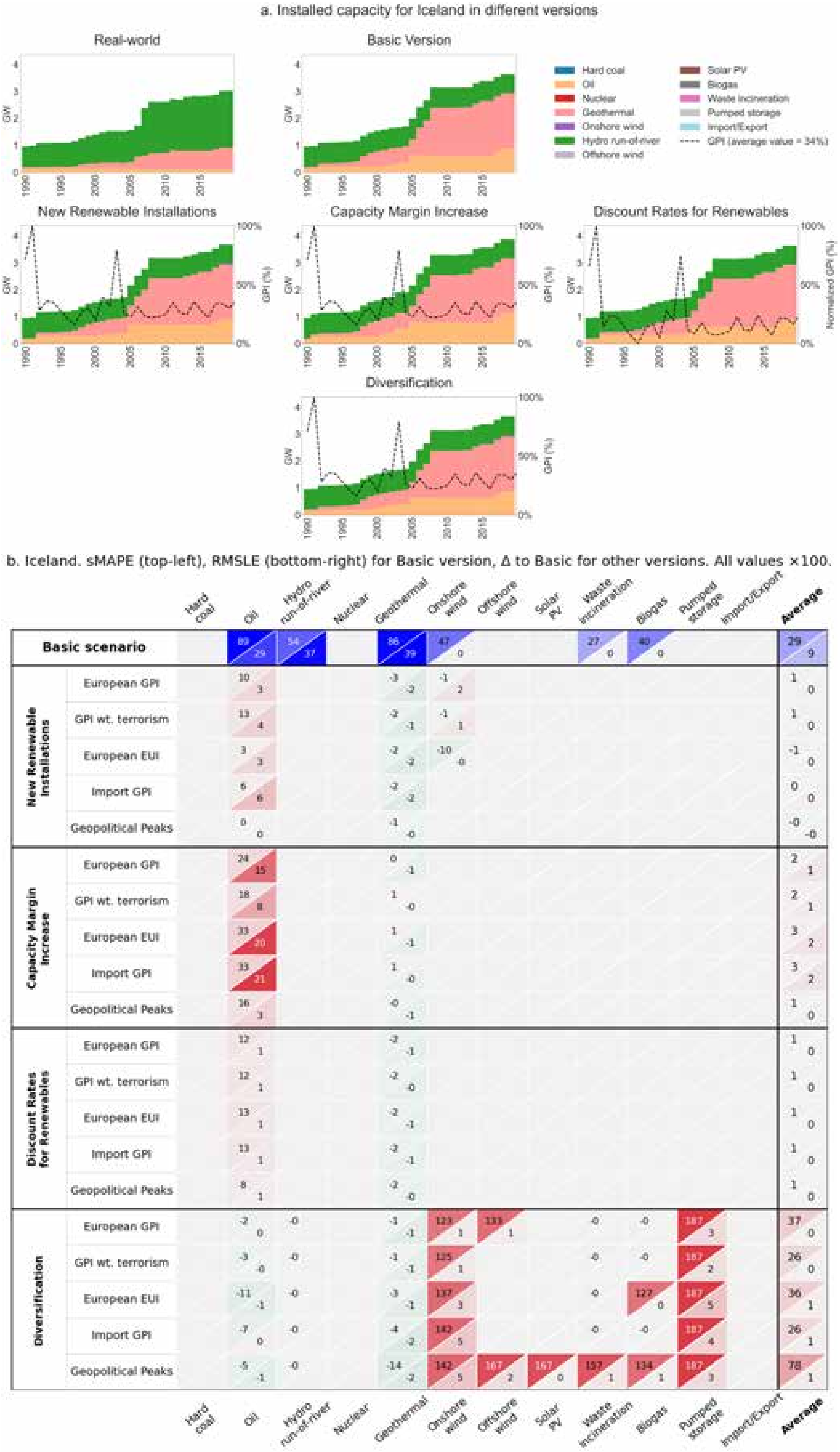

Figure. B8-17. Iceland

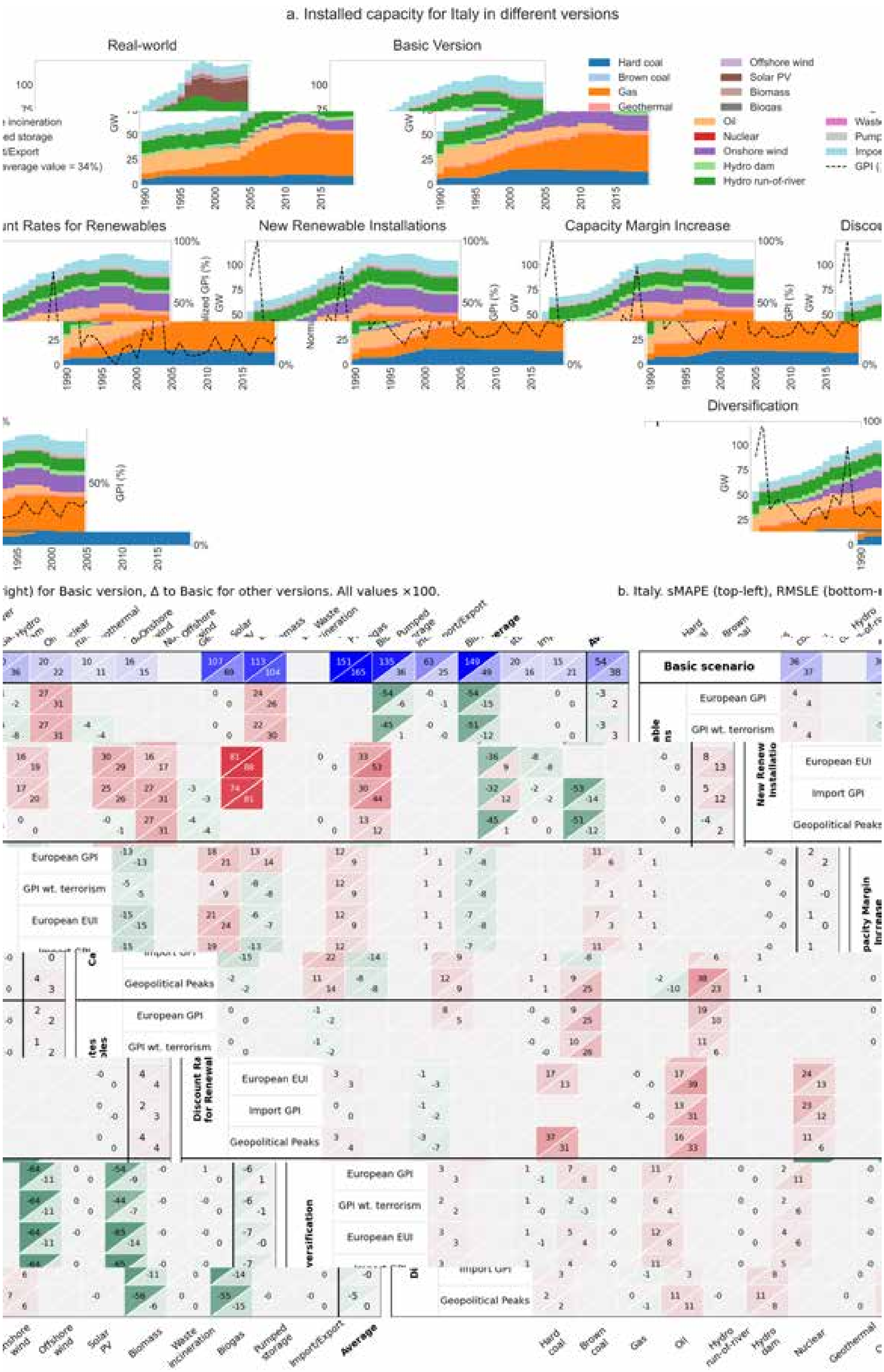

Figure. B8-18. Italy

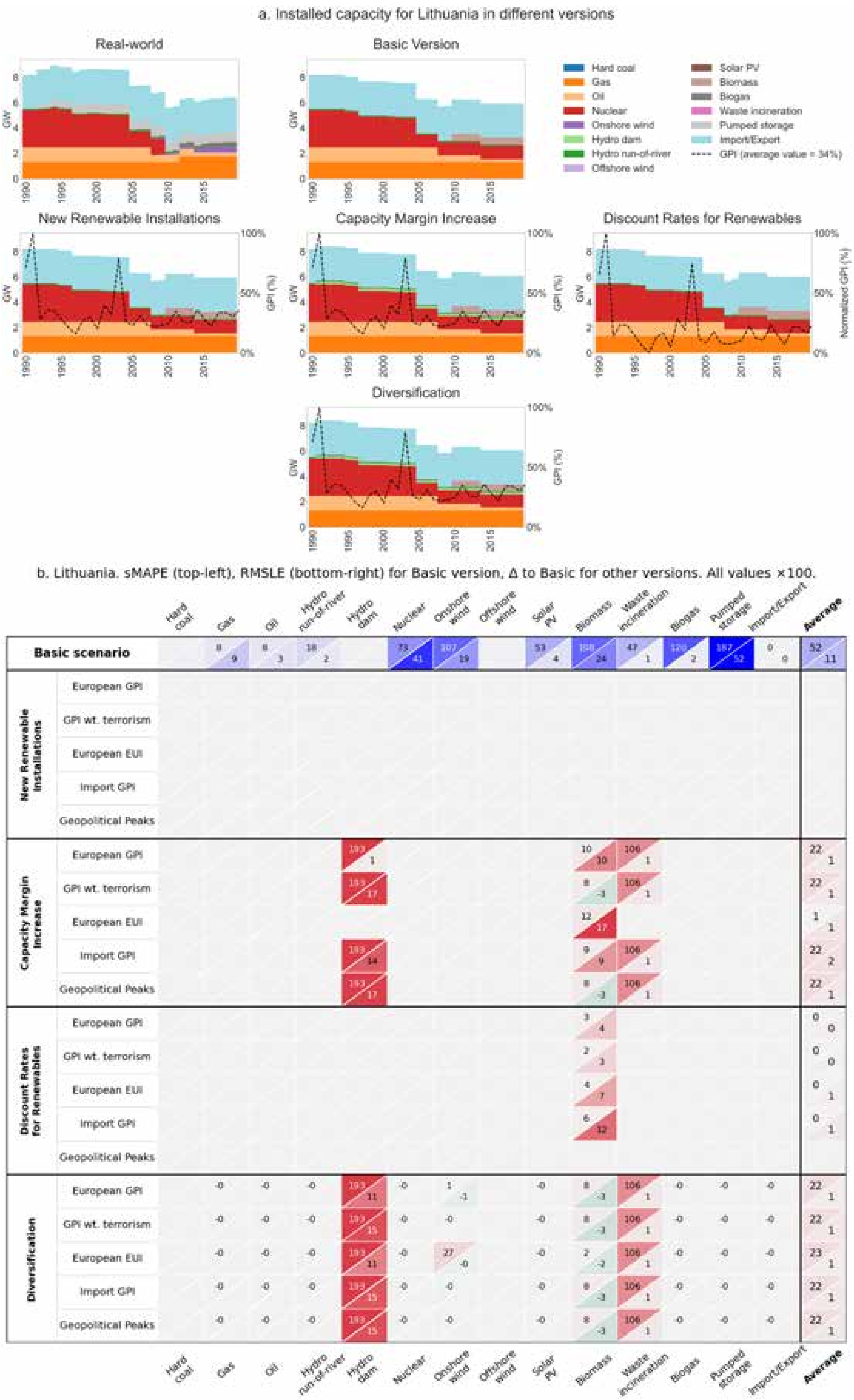

Figure. B8-19. Lithuania

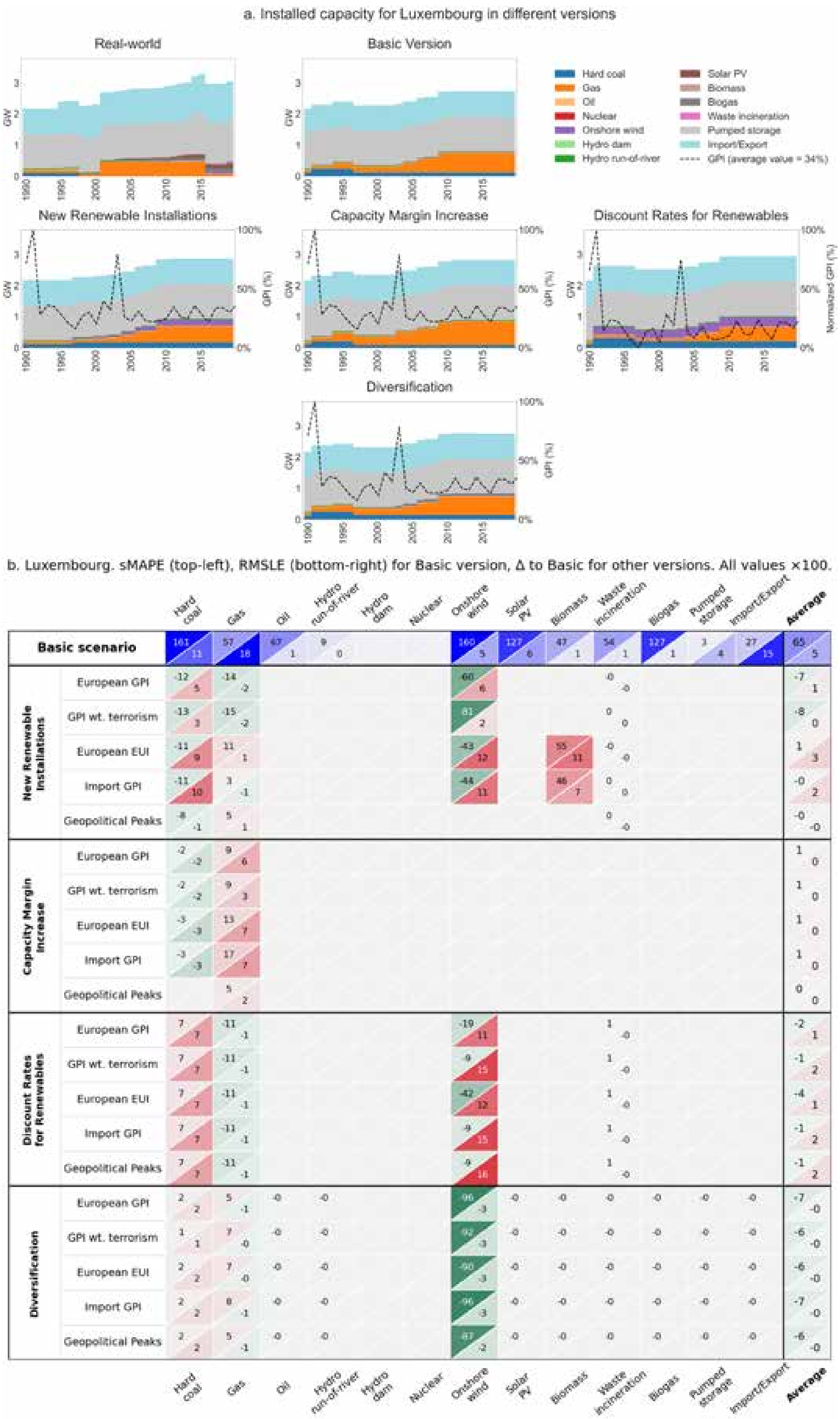

Figure. B8-20. Luxembourg

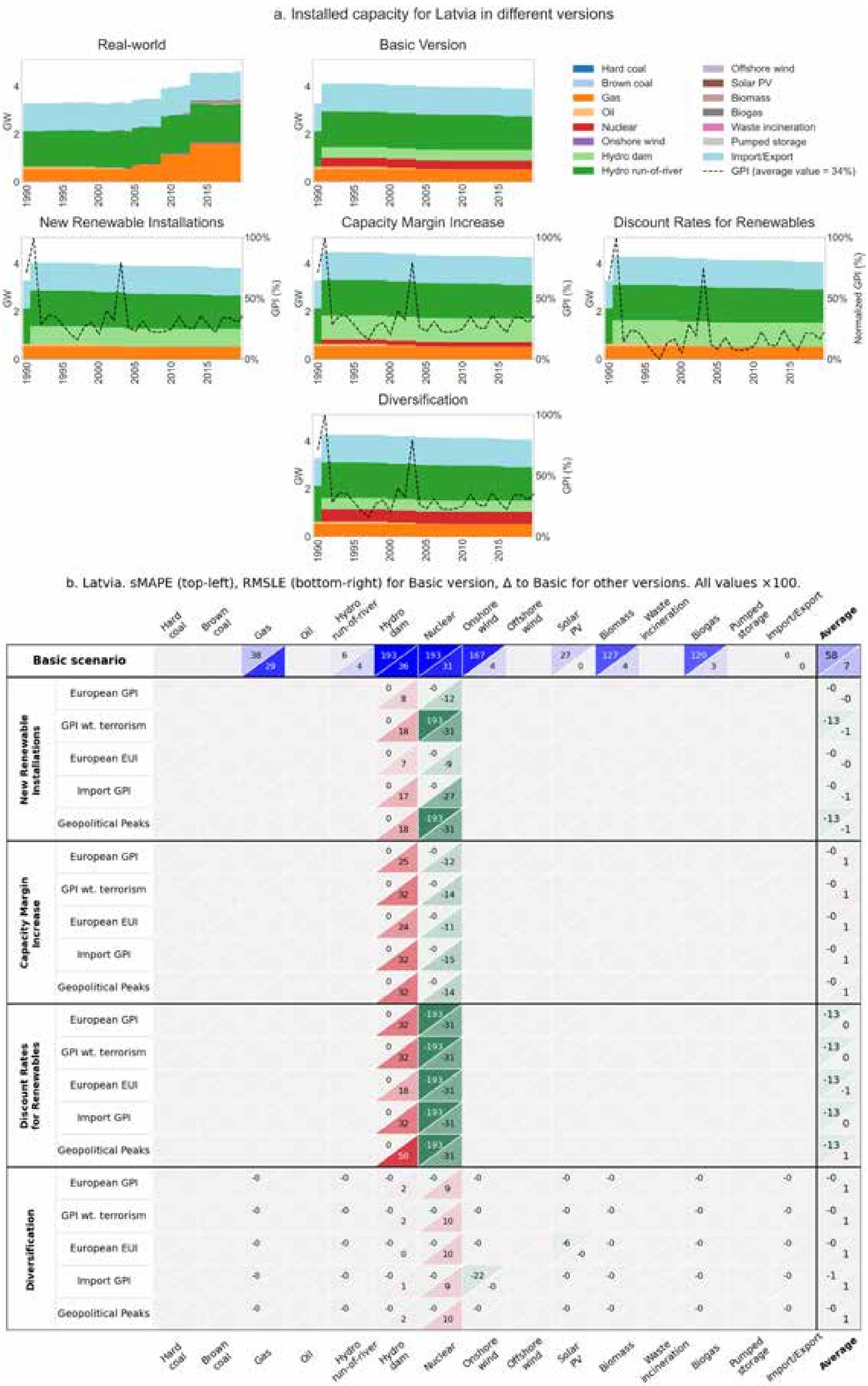

Figure. B8-21. Latvia

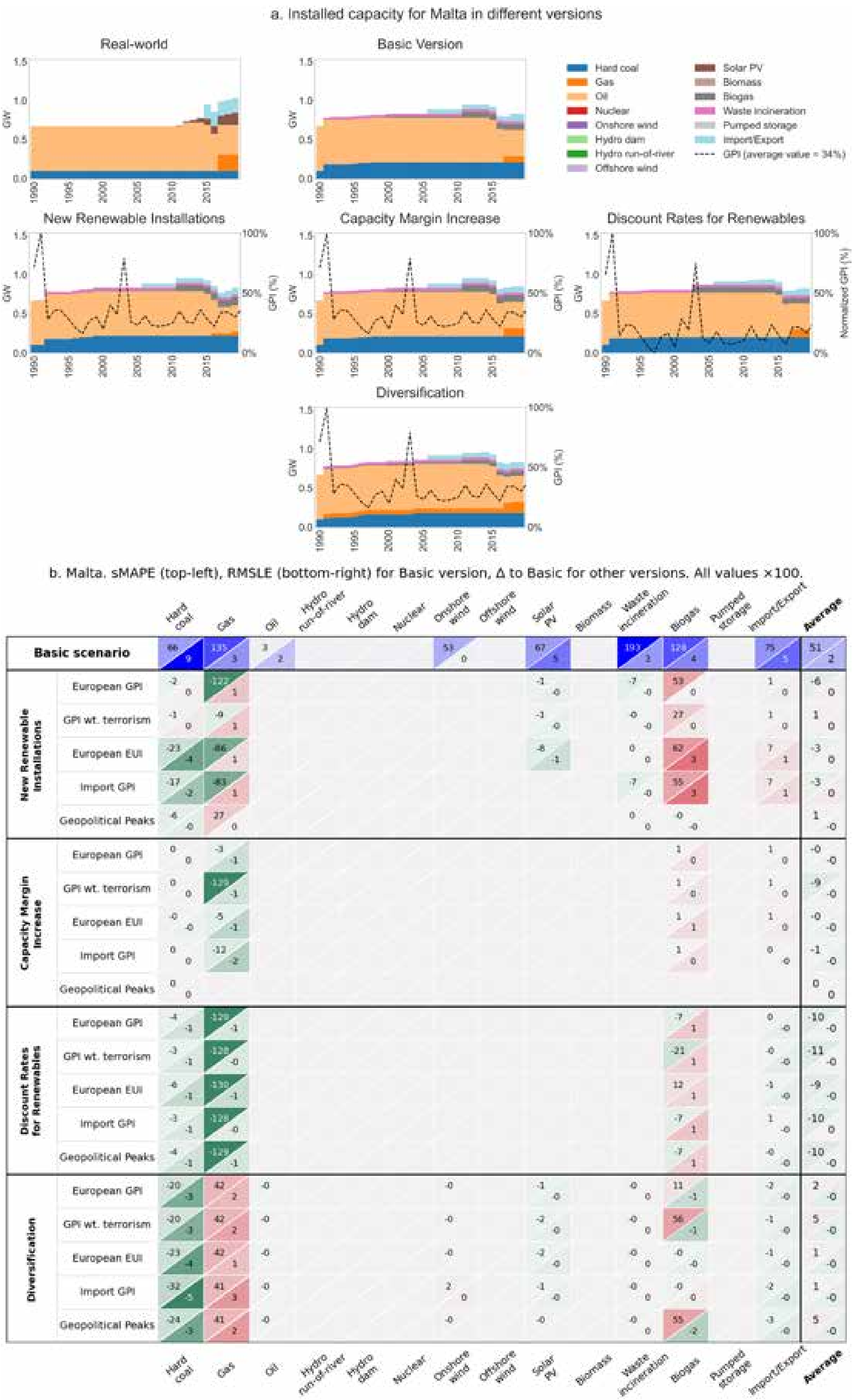

Figure. B8-22. Malta

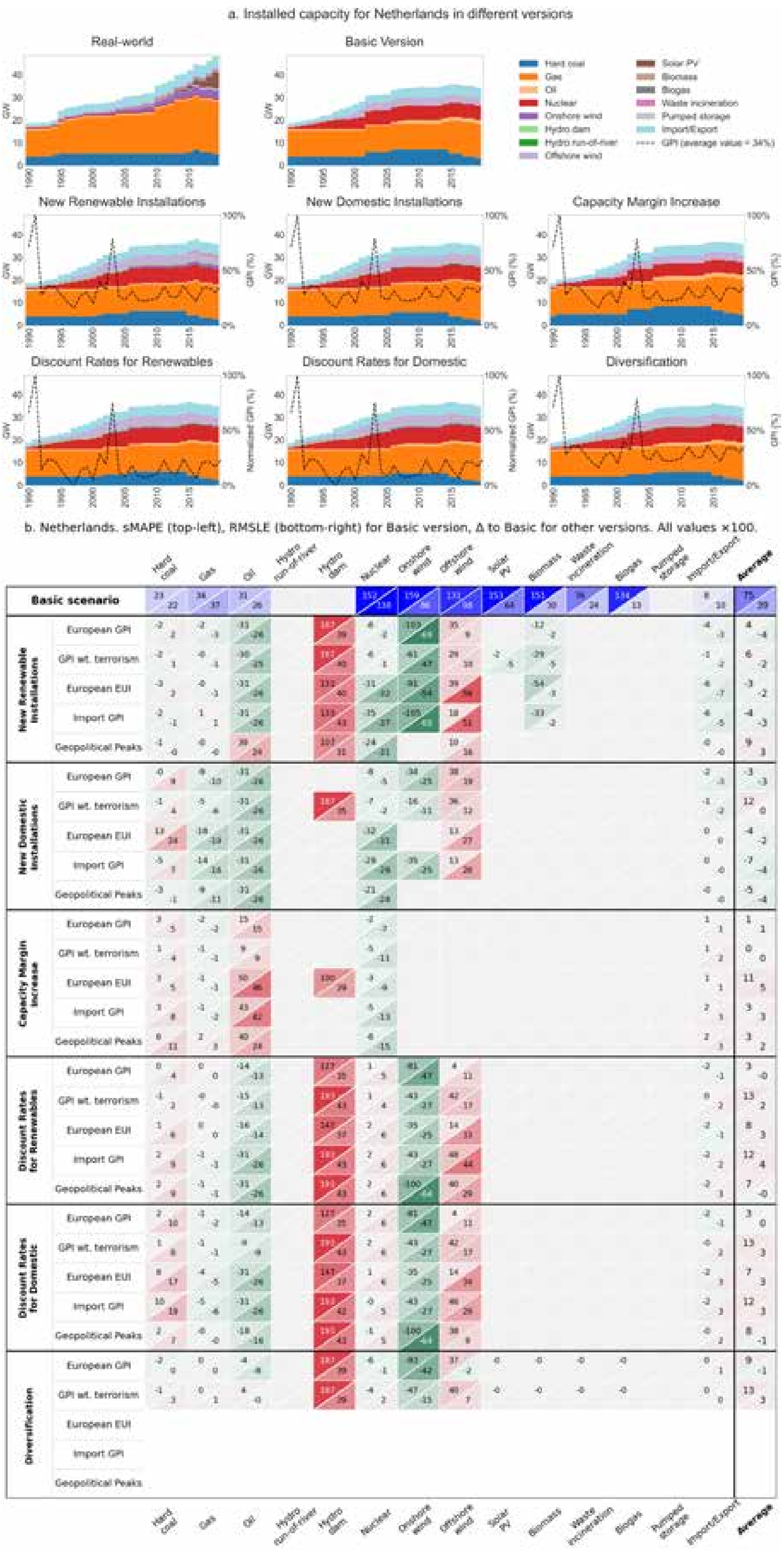

Figure. B8-23. The Netherlands

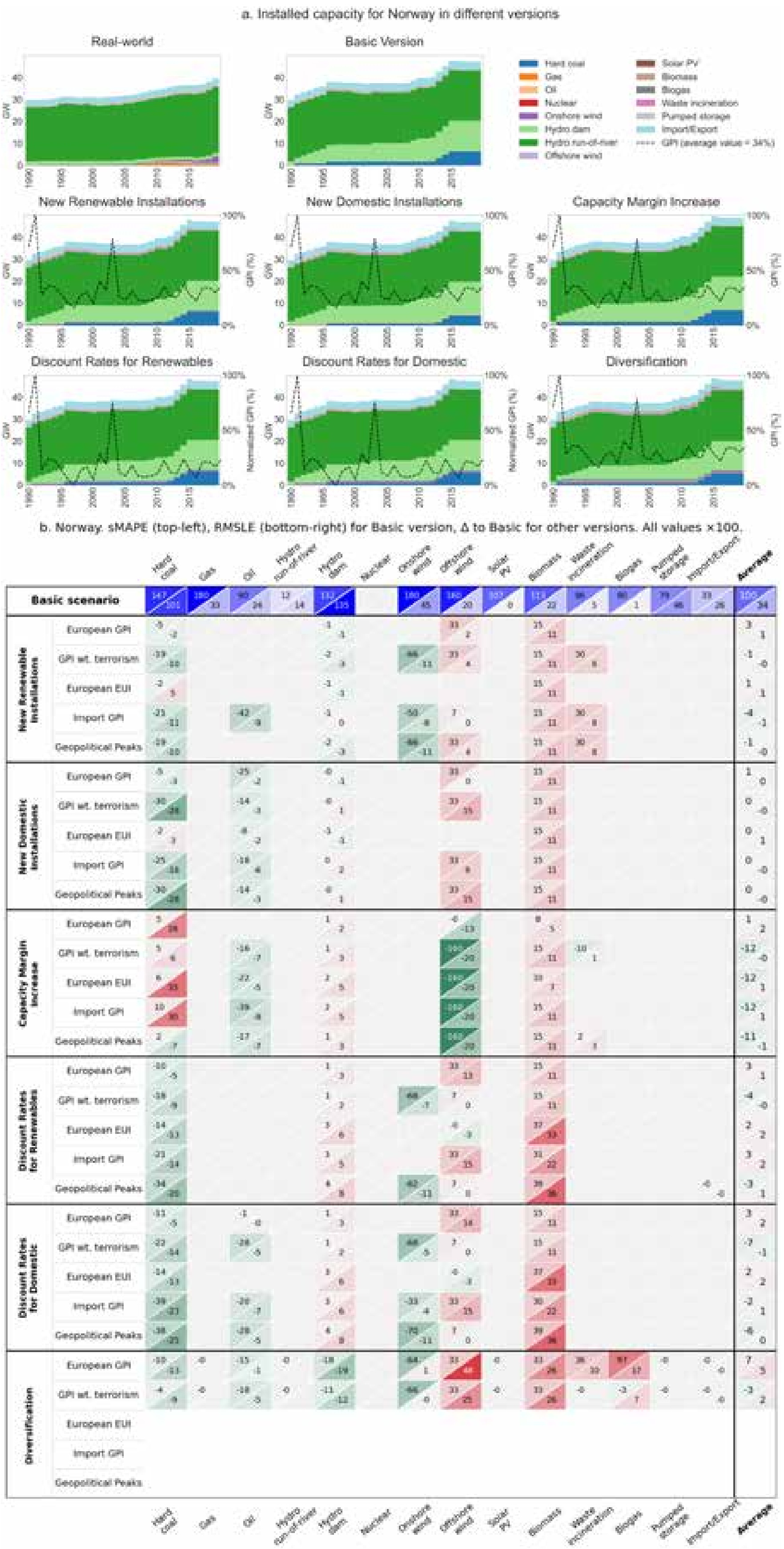

Figure. B8-24. Norway

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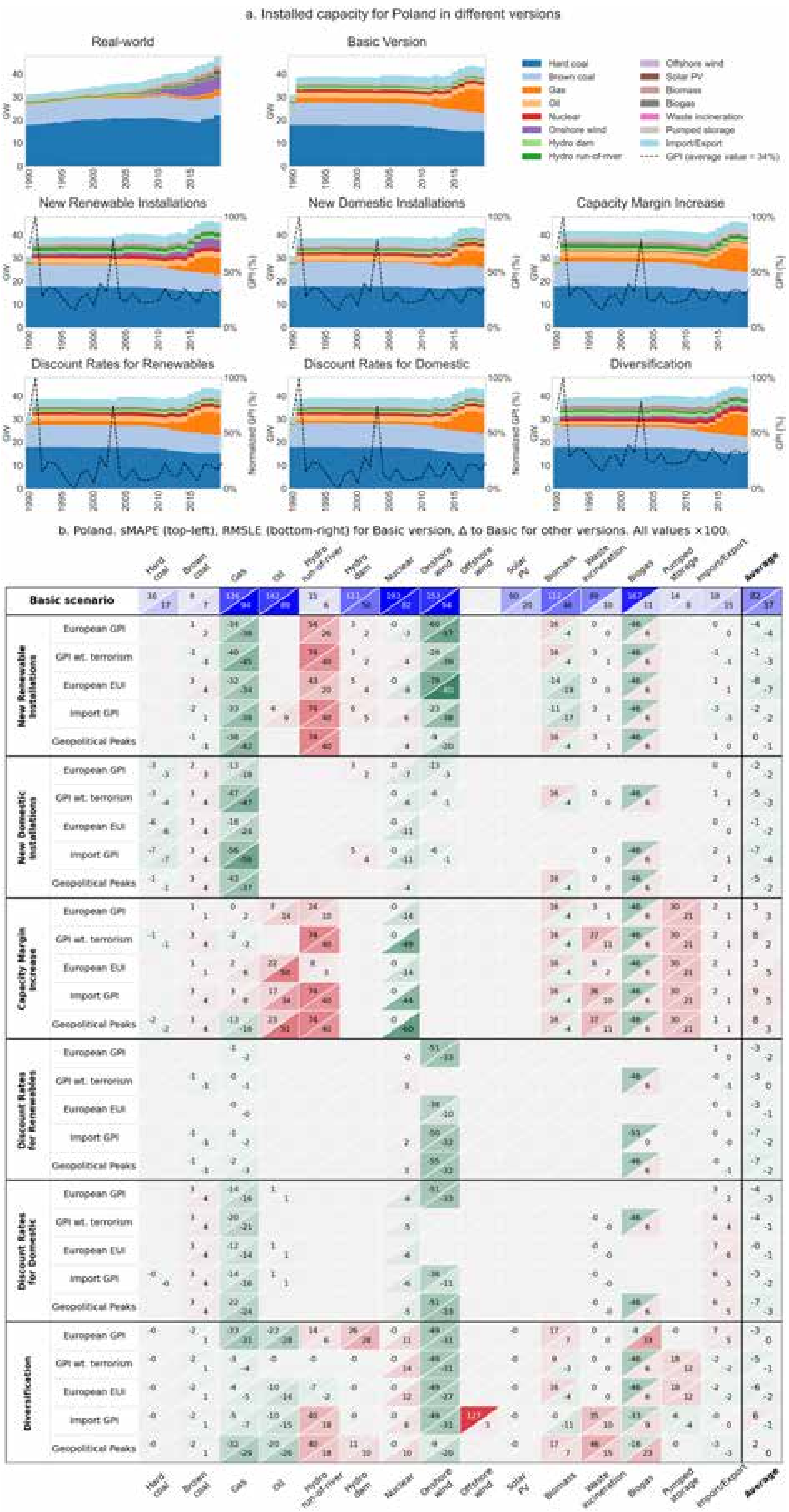

Figure. B8-25. Poland

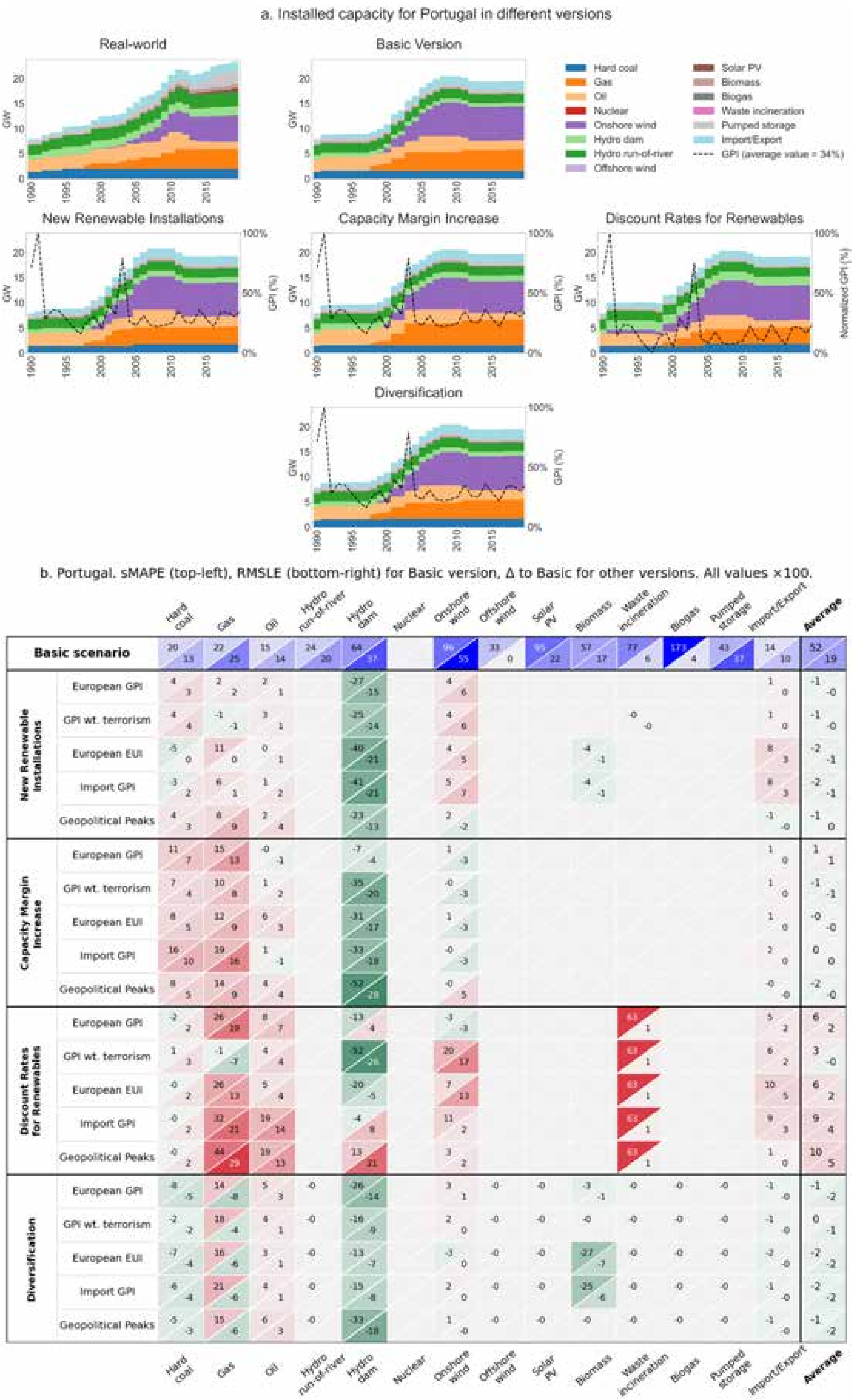

Figure. B8-26. Portugal

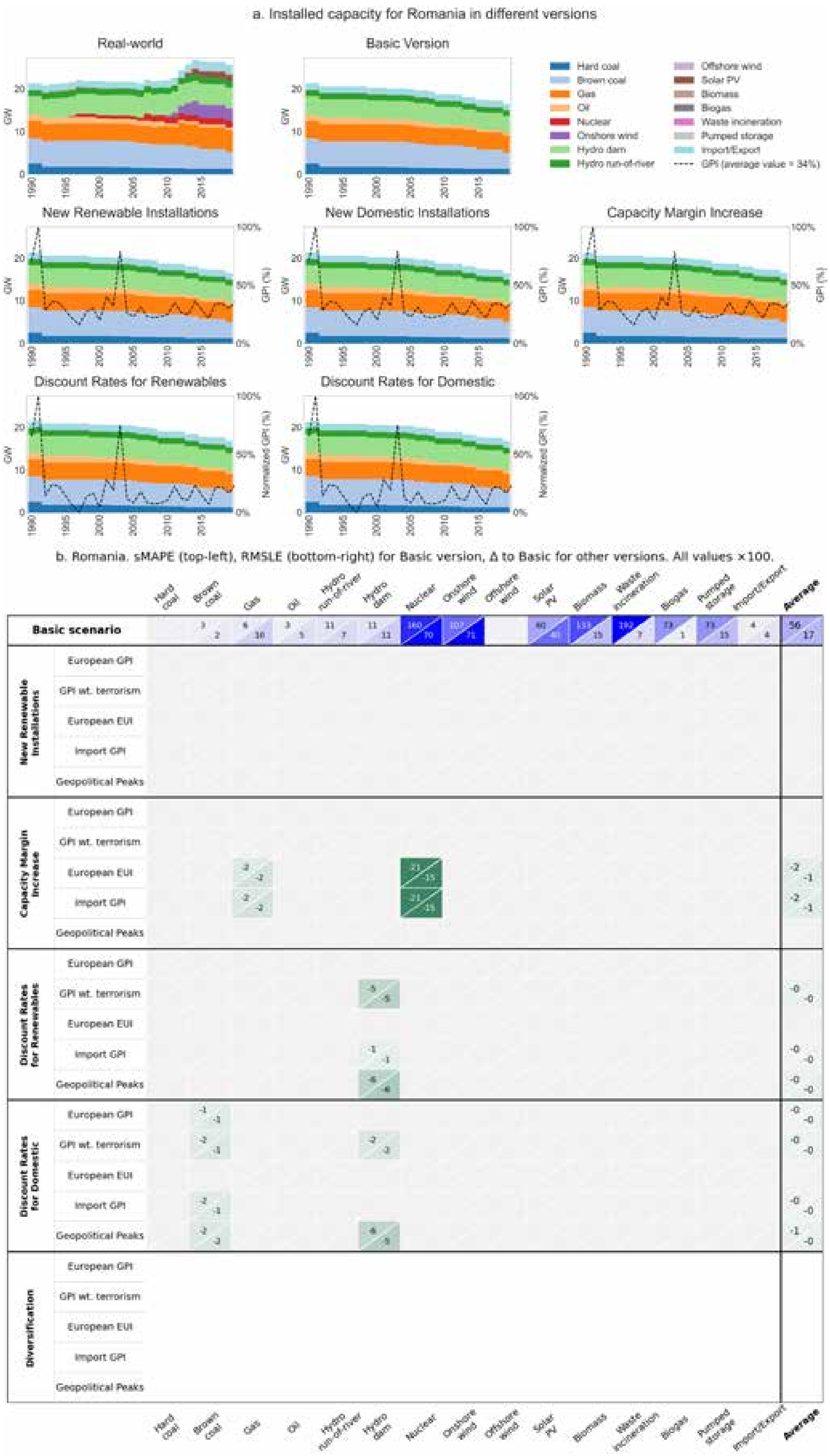

Figure. B8-27. Romania

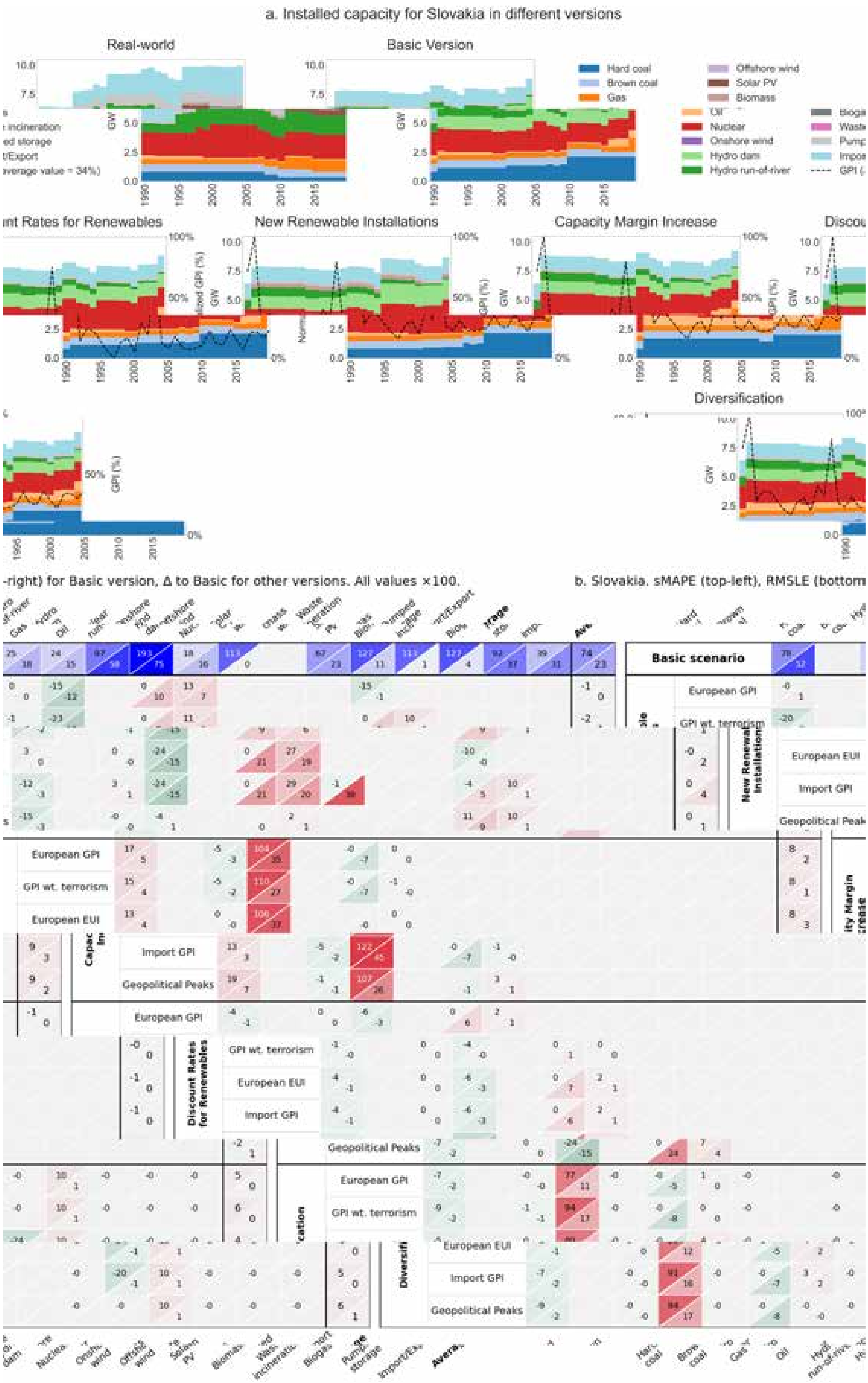

Figure. B8-28. Slovakia

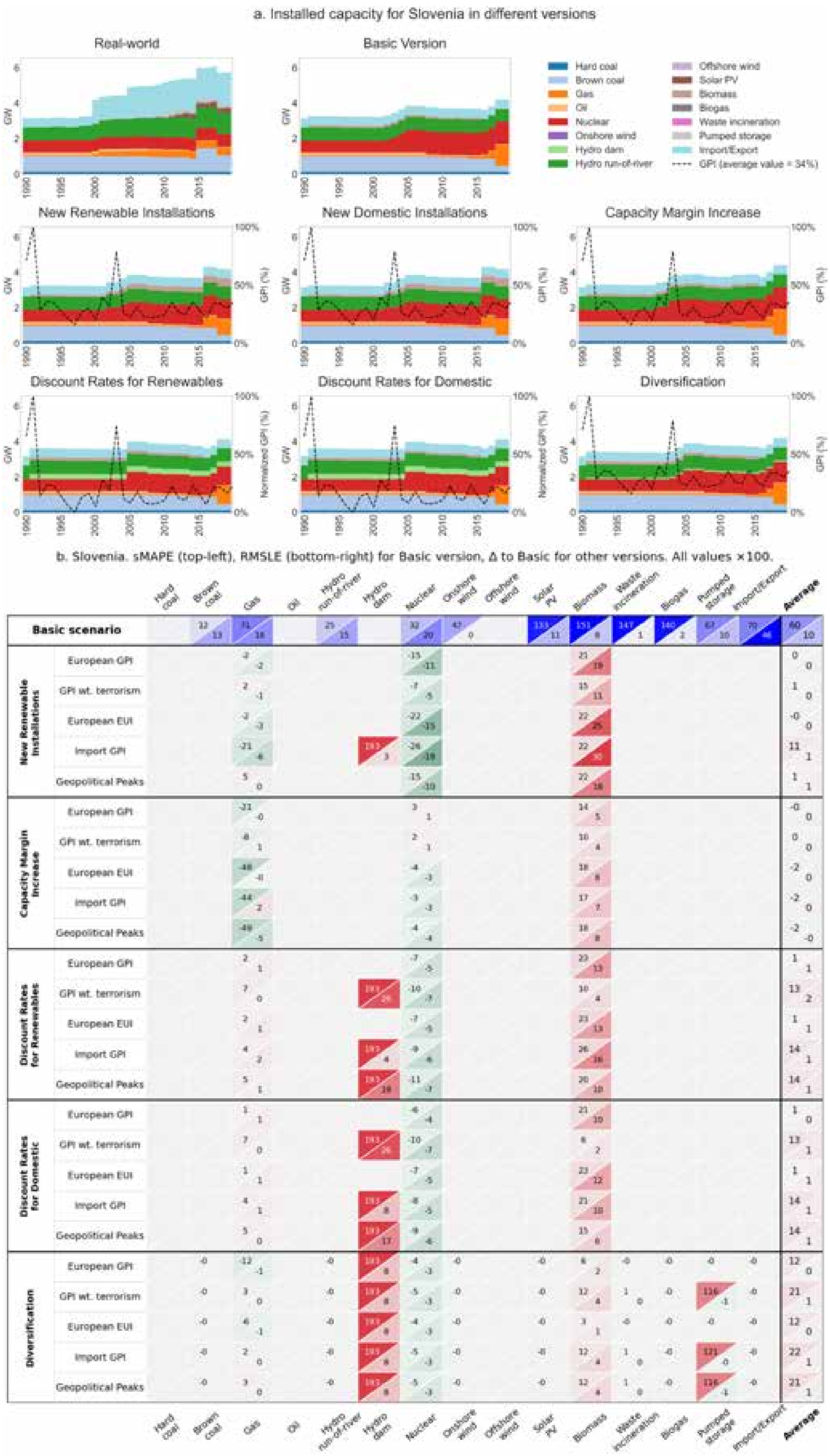

Figure. B8-29. Slovenia

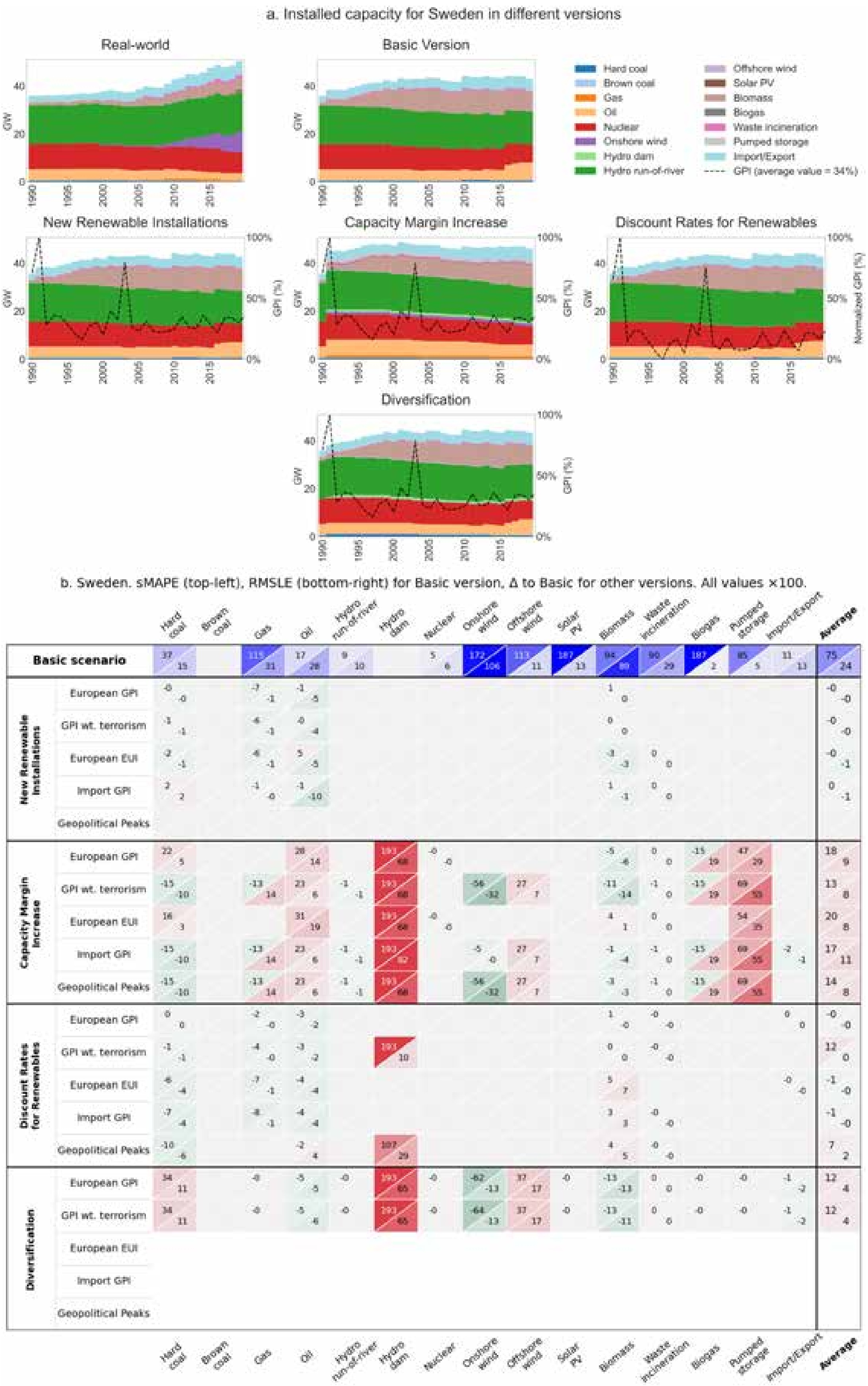

Figure. B8-30. Sweden

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