

Article

Macroeconomic Impacts of Climate Change, Climate Adaptation, and Climate Mitigation in Germany

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Abstract

This study examines the effects of climate mitigation, climate change as quantifiable effects of additional extreme weather events, and adaptation investments on economic growth in Germany. First, on the basis of a comprehensive literature review and further considerations, important impact channels are discussed. Second, the macroeconomic national model PANTA RHEI is used to quantify the effects. To this end, scenarios are refined with and without additional climate change, and with and without additional climate protection to achieve national reduction targets until 2045, and defined for the first time with and without adaptation to climate change. This is also the first combination of all three climate dimensions within the model. The results show that, in the model, the quantifiable effects of extreme weather events have a negative impact on GDP that can be reduced by adaptation. By contrast, climate mitigation has a positive effect. As only monetary effects are accounted for, negative effects of climate change and positive impacts of climate policy are underestimated in broader terms. The model results help to understand the interaction between mitigation and adaptation: without mitigation, the impact of the climate crisis will increase significantly. Adaptation measures may then have less impact or even become ineffective.

Keywords: macroeconomic effects; climate change; climate adaptation; climate mitigation; extreme weather events; macroeconomic modeling; economic growth; scenario analysis



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1. Introduction

Climate change, climate change adaptation, and climate change mitigation are still mostly analyzed separately when assessing impact channels; interactions are often not considered [1]. At the EU level, for example, separate impact assessments are conducted for climate change [2] and adaptation [3] on the one hand, and for climate mitigation on the other, whereby the respective other aspect is not included in the analysis. In addition to institutional responsibilities, another reason for this separate consideration is that climate change, adaptation, and mitigation differ strongly in their temporal and spatial effects. Due to various inertias in natural systems, greenhouse gas (GHG) emissions affect the climate—and, ultimately, economic development in terms of GDP—only with a time lag. The effects of climate change are complex, highly region-specific, and, in the case of acute damage from extreme weather events, always tied to the question of attribution to climate change (for research on attribution, see [Klicken oder tippen Sie hier, um Text einzugeben.](#), e.g., [4,5]). In contrast, mitigation and adaptation measures have immediate economic effects and can be geographically localized. However, adaptation measures are spatially

limited, and there are many challenges to the assessment of their benefits—especially as, unlike mitigation, targets are currently rare. For these reasons, a direct comparison between mitigation and adaptation measures is difficult.

In global considerations and modeling, there has been a long debate about the “optimal” climate policy mix between mitigation and adaptation, which is strongly linked to the assessment of future damage and the discount rate suitable for its assessment as well as the uncertainty about future available mitigation and adaptation measures. Many environmental economists have argued in favor of less climate mitigation in the short term (e.g., Nordhaus [6]), while Stern [7], among others, has emphasized the high costs of climate change and the comparatively low costs of ambitious mitigation, thus calling for comprehensive mitigation efforts in the short term. This debate was primarily based on rather simple global impact assessment models that are not differentiated by sector and often consider long time periods. In many cases, high discount rates have been used. The assumption of high discount rates means that long-term damage caused by climate change has hardly been considered in the calculations because its current value has been estimated to be very low. As a result, the benefits of climate mitigation measures have been significantly underestimated. Recent analysis determines a greater benefit of climate mitigation and sees mitigation and adaptation as being more complementary. According to the synthesis report of the 6th Assessment Report of the IPCC [8], successful adaptation reduces the effects of climate change. At the same time, successful global climate mitigation facilitates adaptation to climate change.

Studies conducted for the Network of Greening the Financial System (NGFS) [9] distinguish between the economic risks (effects) of climate mitigation policy—so-called transition risks—on the one hand, and the risks of climate change itself on the other, which occur acutely in the form of extreme weather events or chronically due to the long-term rise in temperature, such as long-term sea level rise. Climate mitigation policy therefore endangers or changes economic growth through higher energy prices, the devaluation of the capital stock, a possible mismatch in the labor market, changes in investments and consumption and innovations. Acute physical risks of climate change, on the other hand, have an impact through the destruction of capital, supply disruptions on the labor market due to falling productivity in hot weather, lower agricultural production, the disruption of production chains, and increased insurance costs or migration. Model results for a Net Zero 2050 scenario with the NiGEM model show that the global effects of acute climate change compared to a reference scenario are significantly greater by 2050 than the chronic costs of climate change, which in turn are greater than the costs of climate mitigation, i.e., achieving the global GHG reduction target [10]. In a scenario without additional climate mitigation, the costs of climate change could more than double by 2050 compared to the climate mitigation scenario in which GHG neutrality (Net Zero 2050) is achieved. (Globally) successful climate mitigation can therefore greatly reduce the costs of climate change. Adaptation measures are not considered in this model analysis.

The different levels, i.e., temporal, spatial and those regarding the affected sectors at which climate mitigation and adaptation to climate change take place, are probably the reason macroeconomic analyses with sectoral differentiation have not yet dealt with all three effects simultaneously. For Germany, for example, there has so far been only an assessment at the level of municipal concepts and strategies [11]. This assessment clearly shows that there can be synergies and conflicting objectives. While individual measures are aimed solely at climate mitigation or adaptation, there are also measures that combine both. There are adaptation measures that have a negative impact on climate mitigation (so-called maladaptation) and climate mitigation measures that are detrimental for adaptation

to climate change. An assessment therefore depends on the specific implementation of individual measures and cannot be generalized.

At the level of economic sectors, there currently exists no joint analysis of the economic impacts of climate change, adaptation to climate change, and climate mitigation in Germany. Various analyses are available on the impact of mitigation measures, most of which show slightly positive effects [12–14]. Quantifications of the economic effects of climate change at the national level indicate negative effects in the range of less than 1% of GDP by 2050 [15,16]. Initial quantifications of the macroeconomic effects of selected adaptation measures are available [17]. The literature suggests that the three dimensions will mainly affect different sectors of the economy, meaning that there will only be limited overlap in impacts, while climate policy should be as comprehensive as possible.

Given the limited research on the joint analysis of the macroeconomic impacts of climate change, adaptation, and mitigation, there is a need for research to analyze these three dimensions in an integrated manner. Knowledge of economic trade-offs, synergies and interdependencies is necessary for the development of effective and efficient climate policy. We will investigate the following research questions: What are the individual and combined macroeconomic effects of climate change, adaptation to climate change, and climate protection measures in Germany until 2045? Which economic sectors are particularly affected, both individually and overall? What synergies and trade-offs are evident between the three dimensions, and what insights can be gained for a comprehensive and consistent climate policy?

The aim of this paper is therefore to contribute to filling this research gap through the differentiated modeling of the individual climate aspects, which are embedded in a common model framework, and to quantify the joint impact on economic development in terms of GDP and other macroeconomic indicators for Germany. The main new contributions of our paper are, for Germany, further refinements to the modeling of climate change beyond the current state of research, the first quantification of concrete adaptation measures within a macroeconomic model, an update of previous models on the macroeconomic effects of climate protection, and, most importantly, the first combination of all three climate aspects within the macroeconometric model. In the following, the model used and the modeling approaches for the three climate aspects are first presented (Section 2). The results are then described in detail (Section 3) and discussed (Section 4). Section 5, which is brief, with conclusions closes the paper.

2. Materials and Methods

2.1. Macroeconomic Model PANTA RHEI

The national model PANTA RHEI for Germany is used for the analysis presented here [14,18] which is the environmental extension of the simulation and forecasting model INFORGE [19,20]. A comprehensive model description is provided by [18]. According to the classification of climate–economy models of [21], it is a macroeconometric model. Macroeconometric and computable general equilibrium (CGE) models differentiate multiple economic sectors in contrast to impact assessment models. Long-term intersectoral structural change in economic growth over time is mapped at the level of economic industries using input–output tables. Economy and energy systems are described in detail. One advantage of macroeconometric models is the ability to track the time path of the economy through short-run disequilibrium adjustments. Macroeconometric models such as PANTA RHEI have long been used to simulate energy and climate policy [21].

In addition to comprehensive economic modeling, energy, emissions, and transport and housing are covered in PANTA RHEI in detail. The entire model is solved iteratively year by year and simultaneously, i.e., the mutual impact of model variables is considered

simultaneously. The simulations run until 2050. For different applications of the model regarding climate mitigation and adaption, see [17,22,23].

The model contains a large number of macroeconomic variables from national accounts and input–output tables and provides sectoral information according to 63 economic industries. The economic database is supplemented by energy balances [24] and emission data [25] to represent the energy and environmental dimension in the model. The behavioral parameters are estimated econometrically using time series data. This implies, in contrast to CGE models, that the actors only have myopic expectations and make decisions according to patterns observed in the past. Thus, no optimizing behavior is assumed, so that the markets are not necessarily in equilibrium.

Adjustments to an intrasectoral structural change can be implemented through exogenous specifications, e.g., if technological changes such as the transformation of the steel industry towards green hydrogen or the shift in car production from combustion engines to electric cars are to be included in the scenario.

It should always be kept in mind that all these models are simplified representations of reality, so the assumptions and limitations must be considered carefully ([26]). At the same time, however, the model types including macroeconomic models are established instruments that are often used to analyze the interaction between climate and economy. The literature overviews include model comparisons and highlight characteristics of different model types including macroeconomic models ([21,27]).

2.2. Modeling Approaches for Climate Change, Climate Adaptation, and Climate Mitigation

Scenario analysis is used to assess the impact of climate change on the German economy and the effects of countermeasures. Scenario analysis shows possible developments for the future and helps to evaluate policy measures in advance of these possible developments. Table 1 shows the different scenario projections used, which have been agreed upon with the Federal Ministry of Economic Affairs and Climate Protection. There is a reference (scenario 1) in which climate change does not continue and no further policy action is taken on climate change mitigation or adaptation. Scenario 2 represents the impacts of climate change in the form of extreme weather events, in addition to the impacts of climate change already observed in the past. As the future effects of climate change are very uncertain, we have assumed, in sensitivity calculation 2a, that the losses will be twice as high by 2050 as in scenario 2. Scenario 3 includes additional extreme weather events and climate adaptation measures; a comparison with scenarios 1 and 2 shows the effect of climate adaptation measures. In scenario 4, climate mitigation measures are implemented, that will ensure a climate neutral Germany in 2045 according to national targets, so the impact of mitigation measures can be quantified in comparison with scenario 1. Sensitivity 4a does not assume the additionality of investments but examines complete crowding out. Scenario 5 is a combination of scenarios 3 and 4 and allows for an evaluation of climate change and the combined climate change policies in comparison with scenario 1.

Table 1. An overview of the scenarios analyzed.

	Scenario	Extreme Weather Events	Mitigation	Adaptation
1	Reference	Status 2024	Policy status 2020	Policy status 2020
2	Extreme weather events (EW)	Yes	Policy status 2020	Policy status 2020
3	EW and adaptation (EWA)	Yes	Policy status 2020	Yes
3a	Sensitivity of 2 and 3	Doubled	Policy status 2020	Yes
4	Climate mitigation (CM)	Status 2024	Target achievement	Policy status 2020

Table 1. Cont.

	Scenario	Extreme Weather Events	Mitigation	Adaptation
4a	Sensitivity of 4	Status 2024	Target achievement (full crowding out)	Policy status 2020
5	EW, A, CM (EWACM)	Yes	Target achievement	Yes

2.2.1. Climate Change

According to current knowledge, the extreme weather events that can be linked to climate change in Germany are heavy rainfall, floods, heatwaves and droughts [28]. Heatwaves and droughts are expected to increase in frequency and intensity, existing trends towards low water levels will intensify, and heavy rainfall will become more frequent and intense [29,30]. On the basis of climate projections for Germany, it can therefore be assumed that the number of extreme weather events in Germany will increase—with a further increase in the intensity of damage.

Based on these expected future extreme weather events, narratives on the economic consequences are developed and scenario variables are derived, which make it possible to estimate the impact of the quantifiable effects of extreme weather events on economic and socio-economic variables. The focus is on effects that occur locally in Germany. Global effects, which are likely to have a very strong impact on the German economy, are mapped indirectly via interrelationships in international markets.

On the basis of the extreme weather events expected for Germany and a comprehensive literature analysis, the fields of action and impact chains for modeling the climate change scenario were selected for which valid and reliable parameters can be derived, which are relevant for Germany in the future and are likely to be affected by climate change, and for which monetary values can be derived. The scenario settings are summarized in Table 2. Unless otherwise stated, changes between today and 2050 are interpolated linearly.

Table 2. Scenario settings for scenario 2 EW (extreme weather events).

Field of Action	Climate Hazard and Impact	Parameter	References
Agriculture	Hazard: Heat, drought, heavy rain, flood Impact: Yield losses	Increase in import prices by 20% in 2050 (compared to reference) combined with unchanged import volumes, price increase in food products of 5% (downstream industry), higher rents for agricultural land due to competition for land of 50% in 2050	[31–35]
Forestry	Hazard: Heat, drought, heavy rain, flood, storm Impact: Lower yields	Higher prices of 30% in 2050, price increase in wood products of 8% (downstream industry), doubling of depreciation (broken and damaged timber), higher rents due to competition for land of 50% in 2050	[36–42]
Fishery	Hazard: Temperature rise Impact: Biodiversity loss, fish diseases, algae, changes in breeding behavior	Increase in import prices by 25% in 2050	[43–47]

Table 2. *Cont.*

Field of Action	Climate Hazard and Impact	Parameter	References
Water (management)	Hazard: Heat, drought, heavy rain, flood Impact: Higher efforts to guarantee groundwater quality, functionality of networks and sewage treatment plants	Increase in water demand by 10% until 2050, higher production prices due to +45% more use of electricity, construction measures and administration as well as +30% of engineering services	[48–51]
Navigability of inland waterways	Hazard: Heat, drought Impact: Reduced navigability, impairment of goods traffic	Intermediate input from wholesale services to inland water transport will triple by 2050 to meet delivery obligations	[52–56]
International sales markets (industry and commerce)	Hazard: Heat, drought, heavy rain, flood Impact: Disruption of supply chains, lower quantities of goods and higher import prices	Return to the average annual growth rate over last 22 years of import prices for goods in textiles and clothing, printing, chemicals and pharmaceuticals, rubber and plastic products, glass, metal products, electrical equipment, transport equipment and furniture, and repair and installation of machinery and equipment, lowering exports by 0.3% in 2050	[31,56–60]
Buildings	Hazard: Heavy rain, flood Impact: Damage to and destruction of buildings, settlements and infrastructure	Depreciation of insurance industry is 50% higher in 2050, reduction in the lifespan of all buildings by two years and private households' savings by 15 bn. EUR higher until 2050, companies will increase their depreciation by 0.2% by 2050	[16]
Human health and healthcare system	Hazard: Heat Impact: Heat stress on human health, increase in emergency cases and pressure on healthcare system	Increase in heat-related hospital admissions of 60% by 2050	[30,51,61–69]

2.2.2. Climate Adaptation

Adaptation can reduce the negative impacts of the climate crisis. Table 3 shows the adaptation measures implemented in the scenario. The measures listed were assigned to the fields of action of the German Climate Adaptation Strategy (DAS) including estimated implementation horizons and translated into scenario parameters using the following assumptions.

The climate damage of scenario 2 EW remain unchanged until adaptation measures are fully implemented. The implementation horizon corresponds to the last column in Table 3. It is assumed that changes in the production structure or price adjustments that have already been implemented remain unchanged after the adaptation measure has taken effect. Other losses, such as depreciation or health costs, slowly return to their original path when the adjustment takes effect. Once the adaptation measures have been fully implemented, they will unfold their full effect. The adaptation measures are implemented domestically and thus address domestic climate impacts. The costs and negative impacts on domestic industries caused by climate impacts abroad therefore remain unchanged.

This is the case for all climate impacts that are expected to result in higher import prices due to climate change. For international trade and fisheries, no adaptation measures are specified, as the climate impacts and their effects on domestic industries occur exclusively abroad. Summarizing, the adaptation scenario is an approximation and abstraction, i.e., it is not a complete determination of the additional adaptation costs actually incurred. Rather, the approximation is intended to estimate the direction and magnitude of the impact of adaptation measures.

Table 3. Adaptation measures by field of action and implementation horizon.

Field of Action	Adaptation Measure	Implementation Horizon (Years)	Mean Implementation Horizon (Years)
Agriculture	Adaptation to heat waves	5	3.4
	Renaturation	5	
	Measures to increase water efficiency	1	
	Soil protection through mats	1	
	Early warning systems and information services	5	
Forestry	Adaptation to heat waves	5	3.4
	Renaturation	5	
	Measures to increase water efficiency	1	
	Soil protection through mats	1	
	Early warning systems and information services	5	
Fishery/international sales markets	-		
Water (management)	Low water protection measures	5	4.2
	Adaptation to heat waves	5	
	Renaturation	5	
	Measures to increase water efficiency	1	
	Soil protection through mats	1	
Navigability of inland waterways	Early warning systems and information services	5	5
	Low water protection measures	5	
	Early warning systems and information services	5	
Buildings	Green roofs	1	6.2
	Renaturation	5	
	Climate-adapted spatial planning	5	
	Flood protection	15	
	Early warning systems and information services	5	
Human health and healthcare system	Adaptation to heat waves	5	4.2
	Renaturation	5	
	Climate-adapted spatial planning	5	
	Open space greening	1	
	Early warning systems and information services	5	

A total of around EUR 50 billion will be invested until 2050. At 85%, the lion's share is accounted for by construction investment, with only 15% going to equipment investment. This ratio remains unchanged throughout the observation period.

The exact nature of climate change, i.e., the frequency, extent and intensity of extreme weather events, is uncertain. To better understand the implications of a more severe climate change and to assess the effectiveness of adaptation measures, we conducted sensitivity analysis 3a. More precisely, the sensitivity calculation assumes that the originally assumed direct consequences of climate change (scenario 2 EW) are doubled. This was then compared with the initial level of climate adaptation in scenario 3 EWA and the impact of doubling the adaptation measures.

2.2.3. Climate Mitigation

To model climate mitigation, the macroeconomic PANTA RHEI model is coupled with data on the energy system from bottom-up models [14]. Supplement S1 provides an overview of the input parameters. The additional investments in corresponding mitigation measures, which are determined as the deviation from the reference development in the bottom-up models and set in PANTA RHEI, are crucial in this context. We have therefore calculated sensitivity 4a that does not assume the additionality of investments but examines complete crowding out.

In PANTA RHEI, gross fixed capital formation is modeled separately for equipment, buildings and other assets (particularly in the form of intellectual property). At the level of economic industries, it is estimated as a function of the respective production, and for certain industries, the capital stock and time trend are also included as explanatory variables. Higher investments directly increase demand and thus gross domestic product. In subsequent years, this is associated with higher depreciation, which increases the costs of the industries, which therefore raise their prices *ceteris paribus*.

In addition to higher investments, the climate protection scenario also requires higher carbon prices, which influence the level of energy prices and therefore lead to cost and price increases, particularly in energy-intensive sectors of the economy. The higher revenues from carbon pricing flow into the public budget and are not returned. However, they are used to finance higher government investment, whereby the level of differential investment does not depend on carbon revenues. In the model, the government's financing balance according to the national accounts results from higher revenues, higher government investment on the expenditure side and an improved general economic situation, which in turn leads to higher revenues and lower government expenditure.

An electricity market model was also used to determine the effects of higher carbon prices, changes in electricity supply, and changes in electricity demand compared to the reference scenario on electricity prices for different consumer groups. According to this analysis, prices in the first few years are significantly higher than in the reference scenario, but this difference decreases over time and is only minor in 2045.

The higher energy efficiency achieved through mitigation measures and the increased expansion of renewable energies will lead to a significant decline in imports of fossil fuels compared to the reference scenario in the 2030s. Hydrogen and synthetic fuel imports will only increase after 2035, so the monetary impact on energy imports will largely offset each other again by 2045. Higher energy efficiency results in a permanent reduction in energy costs.

3. Results

The following results are each presented as a deviation from the reference development (scenario 1), which shows the effect of the assumed settings in the other scenarios (scenarios 2 to 5). The individual effects are described first (Sections 3.1–3.3), followed by the overall effects caused jointly by climate change, climate change adaptation and climate mitigation (Section 3.4).

3.1. Impacts of Climate Change (Scenario 2 Compared to 1)

The results depicted in Figure 1 show that additional climate change in the form of more severe extreme weather events would have a clear negative impact on economic output and that the damage would increase as climate change progresses. In 2035, price-adjusted GDP is 0.4% lower than in the reference case and 0.8% lower in 2045. In total, the losses in price-adjusted GDP amount to EUR 300 billion by 2045. To put this in context, the costs of the Ahr and Erft floods in 2021 are estimated at around EUR 40.5 billion [70]. This would mean that costs similar to those of this costly single event could be expected approximately every three years.

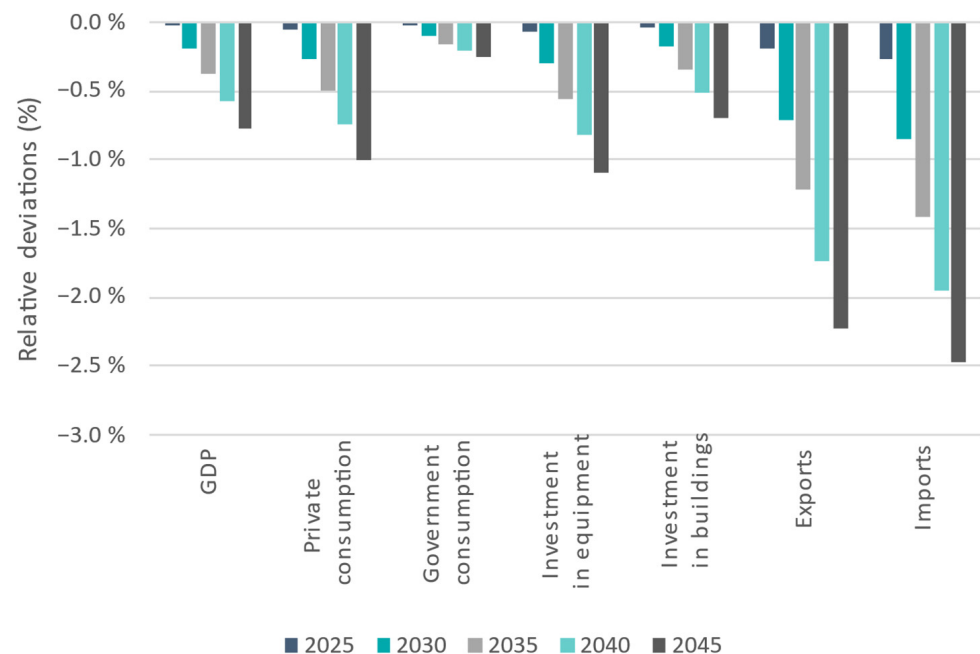


Figure 1. Percentage change in price-adjusted GDP and its components (scenario 2 EW compared to reference scenario).

The impact on the individual components of GDP is in some cases much greater than for GDP in total. International trade in particular shows large deviations. Both exports and imports will be more than EUR 500 billion lower in real terms by 2045 (−2.2% for exports and −2.5% for imports). This is mainly due to the effects of climate change, which occurs abroad and also affects domestic prices via trade structures. In addition to trade, private consumption would also be negatively affected: private households would consume EUR 200 bn less in price-adjusted terms by 2045 (−1% in 2045) due to the climate change impacts. This is partly due to higher living costs (especially food and rent) and partly to a higher propensity to save (provisions for claims). Increased provisions and write-downs by companies for possible claims as a result of advancing climate change are reflected in a decline in investment. There is also a price-increasing effect of climate change impacts: overall, inflation rises by an average of 0.1 percentage points per year more than in the reference scenario.

Output will fall by 1.2% in 2045 across all sectors of the economy, resulting in a lower demand for around 120,000 workers. Compared to the reference scenario, the number of employees in business-related services and public services will decrease the most. Their numbers will fall according to Figure 2 by almost 50 thousand and just over 20 thousand people, respectively, in 2045.



Figure 2. Change in employment (scenario 2 EW compared to reference scenario) across economic activities.

3.2. Impacts of Climate Change and Adaptation (Scenario 3 Compared to 1)

Investing in climate change adaptation helps to mitigate the effects of climate change while having a positive impact on GDP. However, Figure 3 shows that not all losses can be compensated: Price-adjusted GDP will still fall by just under 0.5% in 2045, respectively, or EUR 210 billion cumulative over the entire period (in the climate change scenario without adaptation, price-adjusted GDP will be 0.8% lower in 2045 or EUR 300 billion cumulative). The comparatively low effect of adaptation in the scenario is due to the fact that climate impacts occurring abroad and “imported” into Germany via trade cannot be addressed by national adaptation measures. Accordingly, the relative deviations in trade remain high. The adaptation measures have a clearly positive effect on investment in construction. Private consumption, government consumption and investment in machinery and equipment are at least less affected than without adjustment measures.

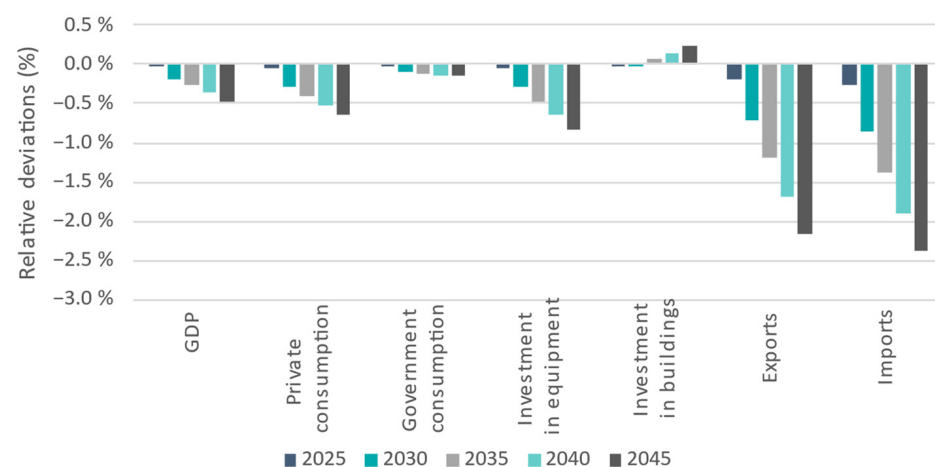


Figure 3. Percentage change in price-adjusted GDP and its components (scenario 3 EWA compared to 1).

The assumption of higher climate damage in sensitivity 3a means that the economic effects more than double. Despite existing climate change adaptation measures, increased climate change will reduce GDP by a cumulative EUR 590 billion by 2045, resulting in additional losses of EUR 380 billion. If increased climate adaptation measures are implemented in anticipation of a more severe climate change, some of the newly incurred costs can be offset: cumulatively, GDP will be reduced by EUR 410 billion by 2045.

3.3. Impacts of Climate Mitigation (Scenario 4 Compared to 1)

At a macroeconomic level, there are positive effects from the climate mitigation measures. Compared to scenario 1, price-adjusted GDP in scenario 4 is higher over the entire analysis period, but the effects are high until 2035 and tend to weaken in the longer term; while the deviation is 2.3% in 2030, it falls to 0.8% in 2045. Figure 4 also shows effects for expenditure components of GDP, which provide information on which parts of the economy benefit more from climate mitigation and which benefit less or are even weakened. In particular, the relative effects on investments in equipment and buildings stand out and are higher than in the reference scenario up to 2040. The climate mitigation scenario assumes that the transformation towards climate neutrality will be largely completed by 2045, which means that less investment will be required in the climate protection scenario in 2045 than in the reference development. There is also a positive effect on private and government consumption: as a result of the higher overall economic output, disposable incomes are higher, which drives consumption spending.

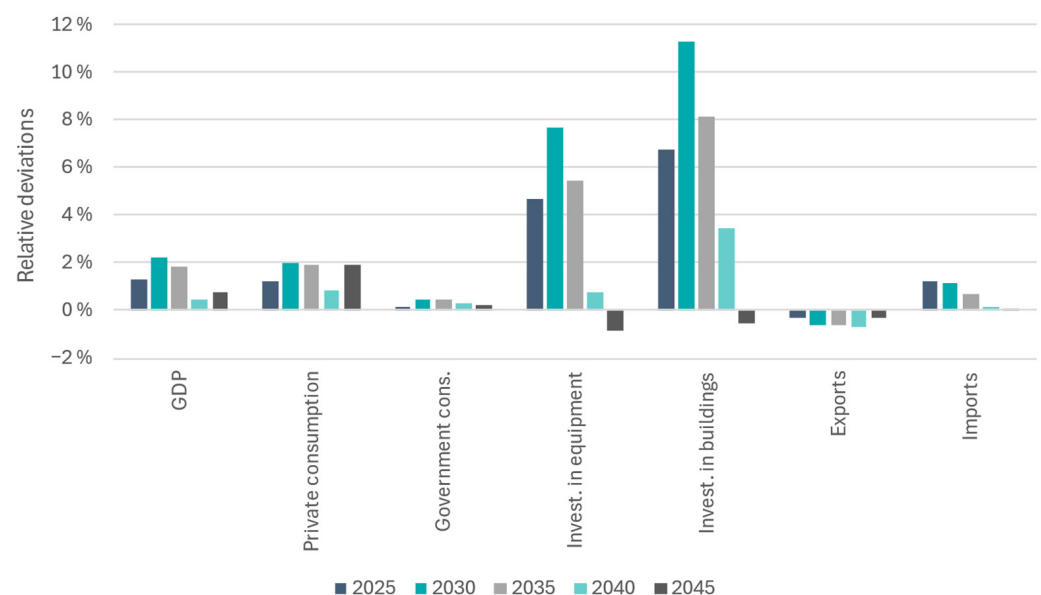


Figure 4. Relative deviations of price-adjusted GDP and its components in scenario 4 CM compared to the reference.

Slightly higher electricity and carbon prices will have a slightly negative impact on GDP, which will be particularly evident in exports. The trade balance deteriorates in the climate mitigation scenario compared to the reference case: the higher price level due to the carbon price paths has a lowering effect on exports and an increasing effect on imports, while the latter are also increased by the additional demand. On the other hand, imports of fossil fuels will decline significantly in the climate mitigation scenario. These negative effects on the trade balance can be explained by the model limitations of PANTA RHEI, as it is a national model that does not map changes in the rest of the world. If comparable

climate mitigation efforts were implemented by Germany's trading partners, this negative competitive effect would be less pronounced or disappear.

In general, it should be noted that in the PANTA RHEI model, labor demand depends on production and real wages. At the industry level, employment in the construction sector benefits most from higher investment demand and the associated increase in production. Related service sectors such as architectural services also grow visibly. In manufacturing, the higher demand effect initially prevails, while rising prices later cause employment to fall slightly. Higher production and rising prices drive real wages, which tend to have a downward effect on employment. The total employment effect amounts to over 160,000 jobs in 2030 (Figure 5). At the end of the transformation in 2045, the overall employment effect is therefore only slight compared to the reference scenario. Slightly higher production is largely offset by higher price levels.

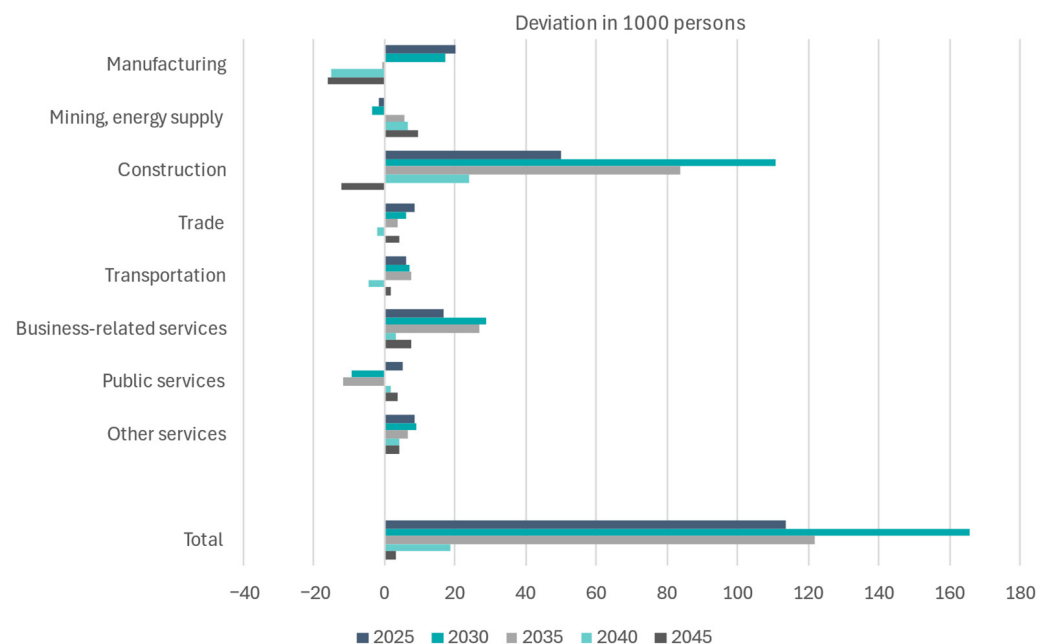


Figure 5. Absolute deviations of employment in scenario 4 CM compared to the reference.

In the sensitivity calculation with complete crowding out, there is a somewhat different time course for the macroeconomic results, which are less positive in the first few years than in Scenario 2.

3.4. Impacts of Climate Change, Adaptation, and Mitigation (Scenario 5 Compared to 1)

The total effect of additional climate change in the form of extreme events, adaptation, and mitigation (EWACM) is shown in Figure 6. Climate change will have increasingly negative effects on GDP, which can be partially offset by adaptation measures. However, these effects will increase significantly after 2045, especially if no effective climate protection is achieved worldwide. In the short term, the effects of mitigation will dominate due to the high additional investments required. However, the trade balance deteriorates, on the one hand, due to the effects of climate mitigation (see Section 3.3) and, on the other hand, because climate change impedes international trade. Until 2045, the overall effect of EWACM will be small, as adaptation and mitigation can compensate negative impacts of climate change. In the longer term however, the negative effects of climate change will dominate.

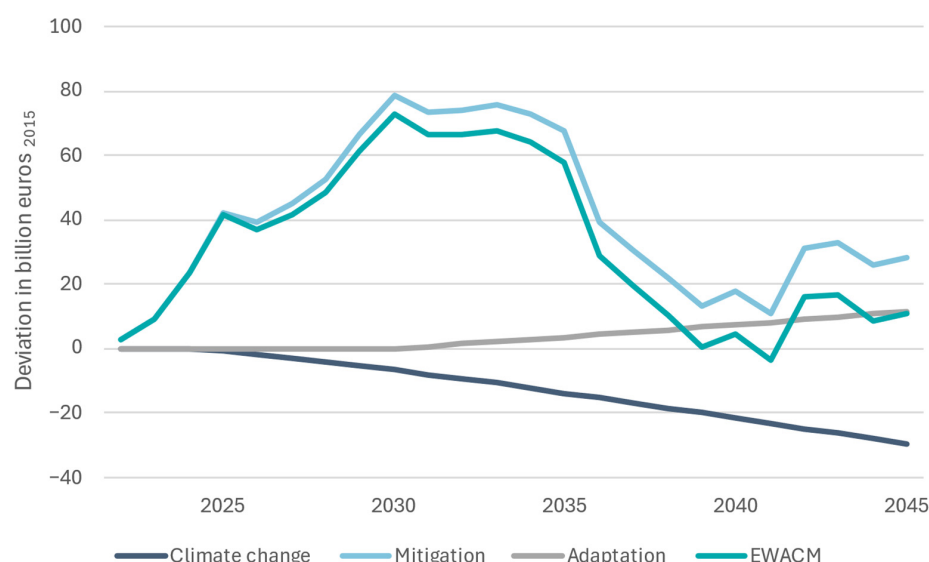


Figure 6. Absolute deviations of GDP in the different scenarios compared to the reference.

4. Discussion

The results describe for the first time the combined macroeconomic effects of additional acute climate change, adaptation, and climate protection in Germany up to 2045, when the country aims to be climate neutral.

A comparison of the economic sectors heavily affected by climate change, adaptation and climate mitigation shows that the overlaps are limited. Climate change primarily affects agriculture, transportation, healthcare, insurance and infrastructure. Adaptation aims to reduce the damages caused by climate change, while the investments required to adapt to the consequences of climate change are mainly made in the construction industry. Climate mitigation leads to major changes in the energy sector, energy-intensive industry, vehicles and building technology. The construction industry also plays a central role in climate mitigation. This industry will be the major winner of climate mitigation in terms of production and jobs, which could be a challenge with regard to labor supply and skill needs. In agriculture, there may be competition for land due to biofuels, organic farming, PV and wind power plants or the rewatering of peatlands, among other things.

It is important to note that the estimates of damages and losses caused by climate change represent a lower bound: on the one hand, only damages on top of existing climate costs from 2024 onwards were considered, and on the other hand, only climate impacts that can be monetized were taken into account. That is, negative impacts that are difficult or impossible to quantify in monetary terms, such as the loss of the quality of life, long-term psychological effects, trauma, the loss of biodiversity, etc., were not included in the estimated costs. The actual impact on the economy is therefore likely to be much more negative and will become even more significant for Germany, especially after 2050 with increased chronic climate impacts. Climate models, including for the IPCC [8], show that global warming, and thus the risks and impacts of climate change, will increase in intensity and severity, particularly after 2050, depending on the extent of climate protection efforts. If climate tipping points are exceeded, the costs of extreme weather events for Germany could be considerably higher. Multi-criteria analysis offers a framework to capture these aspects more effectively. However, this would require a separate analysis that goes beyond the scope of this paper.

The costs of climate change represented by quantifiable impacts of extreme weather events estimated here are comparable to the results of similar macroeconomic models that focus on Germany and provide a detailed description of the economic structure in a macroeconomic context (see Table 4).

Table 4. Results on quantifiable effects of extreme weather events in various studies.

Model	Analysis Period	Damage Costs (Losses in GDP)	Damage Costs p.a.
PANTA RHEI (this study)	2025–2045	2045: −0.8% until 2045: EUR −300 bn	EUR 14.3 bn
PANTA RHEI [16]	2022–2050	until 2050: EUR −280, −530, −910 bn	EUR 9.7/18.2/31.4 bn
D.CLIMATE [15]	2020–2070	2070: EUR −1.2% until 2070: EUR −730 bn	EUR 14.3 bn
WIAGEM [71]	2026–2050	until 2050: EUR −410 bn	EUR 17 bn

In contrast, the results from Kotz et al. [72] show much higher negative effects of climate change, with a larger proportion of these already occurring in the reference scenario regardless of the further scope of climate mitigation on a global level. A study for the EU Commission, on the other hand, arrives at quantifiable effects of additional climate change for Europe that are in good agreement with the presented results [2]. Depending on the method used and the scenario design, the results vary greatly, so further research is needed in any case.

In the literature on climate adaptation, the subject is often examined purely in terms of damage reduction. Additionally, the literature primarily examines the cost–benefit effects of specific, regionally tailored measures. Assessments of packages of measures, especially at a national level, and their classification in terms of economic effects are rarely carried out. This is largely because the impacts of climate change can vary greatly at a local level, requiring regionally tailored adaptation measures. This local focus makes it difficult to apply the results of specific models of regionally implemented individual measures to a generally valid nationwide level. In other words, it is challenging to derive generally valid, literature-based cost–benefit effects of climate adaptation measures.

Due to the lack of information on damage cost avoidance curves, we opted for a simplified approach, estimating the total investment required for climate change adaptation based on the total expected damages of climate change and cost–benefit analyses of various adaptation measures. Based on the expected level of damage, the necessary investments were estimated on the basis of static cost–benefit ratios while also assuming that all damages can be completely avoided by the proposed set of adaptation measures. This leads to a potential underestimation of actual adaptation costs.

In contrast, the literature on climate mitigation lists various channels through which climate mitigation measures can have an impact on the economy as a whole. There is a broad consensus that higher carbon prices and additional investments in the energy transition are necessary to achieve ambitious climate targets. However, investments in mitigation carry the risk of stranded assets if the capital stock is replaced prematurely. In addition to investment effects, there are also substitution and price effects, which in turn depend on elasticities and impact mechanisms. Climate mitigation investments are generally aimed at either increasing energy efficiency or generating renewable energy. The underlying transmission mechanisms for the expansion of renewable energies and increased energy efficiency can vary significantly. The availability of qualified skilled workers is crucial for the output effect of investments due to shortages in the labor market. Climate mitigation should be implemented internationally and designed to be predictable as far as possible, as this reduces the costs of (national) climate mitigation.

The macroeconomic effects of such mitigation measures are not clear-cut and depend on many factors. More supply-oriented approaches tend to show slightly more negative effects than demand-oriented approaches [73]. A meta-analysis by the International Mone-

tary Fund [74] shows that there is no scientific consensus on the macroeconomic effects of climate mitigation. While *ex ante* analyses tend to show slightly negative effects of between 0 and -0.5% of GDP after five years, empirical studies examining carbon pricing measures that have actually been implemented show slightly positive effects [75].

A model study by the IMF [76] finds clear positive effects of global climate mitigation for Germany. According to the socio-economic impact assessment for the 2023 projection report, the with-further-measures scenario, which achieves the climate mitigation targets, results in positive effects on GDP of 0.2 to 0.5% per year compared to a reference [12].

In addition to the instruments used, the question of whether higher investment rates are possible so that investments in a decarbonized energy system can be made additionally, or whether they crowd out other investments (in part or in full) (crowding-out effect), plays a particularly important role. The assumption made here can be of decisive importance for the magnitude and sign of the economic effects. For the results presented above, the additionality of investments with no crowding out of other planned investments has been assumed. This is an important reason for the reported positive impacts of mitigation. The sensitivity analysis assuming complete crowding out, i.e., the displacement of other planned investments, shows that this assumption plays an important role in the short term but that the long-term economic benefits of climate protection in the form of lower energy and emission costs outweigh this.

In this context, the importance of the international context must be taken into account, which is usually ignored in national studies, while international studies often model climate mitigation policy and the structure of the economy in an overly simplified manner. International effects are primarily competitive effects when carbon costs increase in one country relative to others and opportunities to export climate mitigation goods when other countries pursue more stringent climate targets. At the same time, costs of climate mitigation technologies decline with global expansion.

Climate change, adaptation, and climate mitigation are, of course, also linked to questions of social equity and environmental discount. This applies to the effects between countries and also within individual countries between different social groups. Other analyses have shown that poorer households spend a larger share of their income on energy goods and are more exposed to extreme weather events and other consequences of climate change than richer households. These aspects are very important for climate policy-making and acceptance. However, a more detailed analysis of justice issues is beyond the scope of this paper.

5. Conclusions

The following conclusions can be drawn for future research: The effects of mitigation should always be considered together with the effects of climate change. This is because mitigation in the sense of preventing climate change damage leads to significant positive economic effects in the long term. However, due to the limitations in modeling climate change impacts outlined above, the time lag between climate protection and climate change damage, and the nature of climate mitigation as an international public good, this is not easily possible. The focus is therefore generally on mapping direct, nationally effective macroeconomic effects of climate mitigation in terms of changes in GDP or employment. Given the importance of climate change, adaptation, and mitigation, it seems reasonable to bring together the analyses that have so far been largely separate and to consider their combined effects.

For policymakers, the scenario results show, despite all the uncertainties, that the negative consequences of extreme weather events can be reduced through adaptation measures and that climate mitigation can even have a positive macroeconomic impact under certain assumptions. According to these results, it therefore makes sense to jointly promote and implement climate mitigation and adaptation measures. Considering climate

aspects together can also be important in terms of sectoral impacts in order to identify industries that are more affected and those that benefit more from climate policy and to take this into account in policy-making.

Future analyses could focus more on the non-monetary aspects of climate change and distributional justice in relation to the three climate dimensions, rather than considering effects that are limited to quantifiable monetary impacts. It should be highlighted that the effects of climate change and the positive effects of adaptation and climate mitigation are therefore underestimated. Complementary methods such as multi-criteria analysis can supplement the model results and thus also better incorporate social and environmental impacts. This will be central to the acceptance and implementation of climate policy.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su17136175/s1>, Figure S1: Percentage change in price-adjusted GDP and its components (scenario 2 EW compared to reference scenario); Figure S2: Change in employment (scenario 2 EW compared to reference scenario) across economic activities; Figure S3: Percentage change in price-adjusted GDP and its components (scenario 3 EWA compared to 1); Figure S4: Relative deviations of price-adjusted GDP and its components in scenario 4 CM compared to the reference; Figure S5: Absolute deviations of employment in scenario 4 CM compared to the reference; Figure S6: Absolute deviations of GDP in scenario 5 EWACM compared to the reference; Supplement S1: Overview of parameters set in PANTA RHEI from the energy system modeling.

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Abbreviations

The following abbreviations are used in this manuscript:

Bn	Billion
CM	Climate mitigation
DAS	Deutsche Anpassungsstrategie an den Klimawandel (German Climate Adaptation Strategy)
EU	European Union
EUR	Euro
EW	Extreme weather event
EWA	Extreme weather event and adaptation
EWACM	Climate change, adaptation and mitigation
GDP	Gross domestic product

GHG	Greenhouse gas
GWS	Gesellschaft für Wirtschaftliche Strukturforschung (Institute of Economic Structures Research)
INFORGE	INterindustry FORecasting Germany
IPCC	Intergovernmental Panel on Climate Change
NGFS	Network for Greening the Financial System
NiGEM	National Institute Global Econometric Model
PV	Photovoltaic

References

- Howarth, C.; Robinson, E.J.Z. Effective climate action must integrate climate adaptation and mitigation. *Nat. Clim. Change* **2024**, *14*, 300–301. [\[CrossRef\]](#)
- Tröltzsch, J.; Tarpey, J.; Attström, K.; Caspani, M.; Boitier, B.; Le Mouél, P.; Zagamé, P. *Macro-Economic/Top-Down Assessment of Climate Impacts on the EU Economy: Final Report*; Publications Office of the European Union European Commission: Luxembourg, 2025; ISBN 978-92-68-25698-5.
- European Commission. *Forging a Climate-Resilient Europe: The New EU Strategy on Adaptation to Climate Change*; Impact Assessment Report; European Commission: Brüssel, Belgium, 2021; Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN#document1> (accessed on 20 February 2024).
- Otto, F.E. Attribution of Weather and Climate Events. *Annu. Rev. Environ. Resour.* **2017**, *42*, 627–646. [\[CrossRef\]](#)
- Hirschfeld, J.; Schulze, N.; Hock, A.-L.; Trenczek, J.; Flaute, M.; Eiserbeck, L.; Sandhövel, M.; Reuschel, S.; Lühr, O.; Hoffmann, E.; et al. Kostendimensionen von Klimaschäden—Eine Systematische Kategorisierung: Studie im Rahmen des Projektes Kosten durch Klimawandelfolgen in Deutschland. 2021. Available online: https://www.ioew.de/fileadmin/user_upload/BILDER_und_Downloadateien/Publikationen/2022/Hirschfeld_et_al._2021_Kostendimensionen_von_Klimaschaeden.pdf (accessed on 26 May 2022).
- Nordhaus, W.D. An optimal transition path for controlling greenhouse gases. *Science* **1992**, *258*, 1315–1319. Available online: <https://www.nobelprize.org/uploads/2018/10/nordhaus-lecture.pdf> (accessed on 10 July 2024). [\[CrossRef\]](#)
- Stern, N.H. *The Economics of Climate Change: The Stern Review*, 30th ed.; Cambridge University Press: Cambridge, UK, 2007; ISBN 9780521700801.
- Intergovernmental Panel on Climate Change. *Climate Change 2023: Synthesis Report: Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2023.
- Network for Greening the Financial System. *Conceptual Note on Short-Term Climate Scenarios: Technical Document*; Network for Greening the Financial System: Paris, France, 2023.
- Network for Greening the Financial System. *NGFS Climate Scenarios: Technical Dokumentation*; Network for Greening the Financial System: Paris, France, 2023.
- Bender, S.; Groth, M.; Seipold, P.; Gehrke, J.-M. Klimaschutz und Anpassung an die Folgen des Klimawandels: Synergien und Zielkonflikte im Rahmen Kommunalen Konzepte und Strategien. 2022. Available online: https://www.helmholtz-klima.de/sites/default/files/medien/dokumente/gerics_netto-null_repot_anpassung_klimaschutz-final-screen-1_1.pdf (accessed on 2 October 2024).
- Sievers, L.; Grimm, A.; Siegle, J.; Fahl, U.; Kaiser, M.; Pietzcker, R.; Rehfeldt, M. *Gesamtwirtschaftliche Wirkung der Energiewende*; Potsdam Institute for Climate Impact Research: Potsdam, Germany, 2023.
- Umweltbundesamt. *Sozio-Ökonomische Folgenabschätzung zum Projektionsbericht 2023*. Climate Change 17/24. 2024. Available online: <https://www.umweltbundesamt.de/publikationen/sozio-oekonomische-folgenabschaetzung> (accessed on 2 October 2024).
- Lutz, C.; Becker, L.; Kemmler, A. Socioeconomic Effects of Ambitious Climate Mitigation Policies in Germany. *Sustainability* **2021**, *13*, 6247. [\[CrossRef\]](#)
- Philip, P.; Ibrahim, C.; Hodges, C. Germany's Turning Point: Accelerating New Growth on the Path to Net Zero. 2021. Available online: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/821098-02_Germany's-Turning-Point.pdf (accessed on 23 May 2022).
- Flaute, M.; Reuschel, S.; Stöver, B. *Volkswirtschaftliche Folgekosten durch Klimawandel: Szenarioanalyse Bis 2050: Studie im Rahmen des Projektes Kosten durch Klimawandelfolgen in Deutschland*; GWS Research Report 2022/02; Gesellschaft für Wirtschaftliche Strukturforschung: Osnabrück, Germany, 2022.
- Flaute, M.; Reuschel, S.; Lutz, C. Economic Impacts of Exemplary Climate Change and Adaptation Effects Under Different Socio-Economic Developments in Germany. *GLCE* **2024**, *2*, 184–192. [\[CrossRef\]](#)

18. Lutz, C.; Banning, M.; Ahmann, L.; Flaute, M. Energy efficiency and rebound effects in German industry: Evidence from macroeconomic modeling. *Econ. Syst. Res.* **2021**, *34*, 253–272. [CrossRef]
19. Maier, T.; Mönnig, A.; Zika, G. Labour demand in Germany by industrial sector, occupational field and qualification until 2025—Model calculations using the IAB/INFORGE model. *Econ. Syst. Res.* **2015**, *27*, 19–42. [CrossRef]
20. Becker, L.; Bernardt, F.; Bieritz, L.; Mönnig, A.; Parton, F.; Ulrich, P.; Wolter, M.I. *INFORGE in a Pocket*; GWS-Kurzmitteilung; Osnabrück, Germany, 2022; Available online: <https://www.gws-os.com/de/publikationen/gws-kurzmitteilungen/detail/inforge-in-a-pocket> (accessed on 27 September 2023).
21. Nikas, A.; Doukas, H.; Papandreou, A. A Detailed Overview and Consistent Classification of Climate-Economy Models. In *Understanding Risks and Uncertainties in Energy and Climate Policy*; Doukas, H., Flamos, A., Lieu, J., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 1–54. ISBN 978-3-030-03151-0.
22. Ulrich, P.; Naegler, T.; Becker, L.; Lehr, U.; Simon, S.; Sutardhio, C.; Weidlich, A. Comparison of macroeconomic developments in ten scenarios of energy system transformation in Germany: National and regional results. *Energy Sustain. Soc.* **2022**, *12*, 35. [CrossRef]
23. Lutz, C.; Becker, L. Effects of Energy Price Shocks on Germany's Economy and Private Households. In *Vulnerable Households in the Energy Transition: Energy Poverty, Demographics and Policies*; Bardazzi, R., Pazienza, M.G., Eds.; Springer: Cham, Switzerland, 2023; pp. 11–28.
24. AG Energiebilanzen e. V. Bilanzen 1990 Bis 2030. Available online: https://ag-energiebilanzen.de/daten-und-fakten/bilanzen-1990-bis-2030/?_jahresbereich-bilanz=2021-2030 (accessed on 8 May 2025).
25. Umweltbundesamt. Kohlendioxid-Emissionsfaktoren für die Deutsche Berichterstattung Atmosphärischer Emissionen. 1990–2023. 2025. Available online: https://view.officeapps.live.com/op/view.aspx?src=https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/co2_ef_liste_2025_brennstoffe_und_industrie_final.xlsx&wdOrigin=BROWSELINK (accessed on 8 May 2025).
26. Box, G.E.P. Science and Statistics. *J. Am. Stat. Assoc.* **1976**, *71*, 791–799. [CrossRef]
27. Colmenares, G.; Löschel, A.; Madlener, R. The rebound effect representation in climate and energy models. *Environ. Res. Lett.* **2020**, *15*, 123010. [CrossRef]
28. Trenczek, J.; Lühr, O.; Eiserbeck, L.; Sandhövel, M.; Ibens, D. *Auswahlprozess zur Detailuntersuchung eines Klimawandelbezogenen Extremereignisses: Methodisches Konzept und Anwendung*; Projektbericht “Kosten durch Klimawandelfolgen”; Prognos AG: Düsseldorf, Germany, 2022; Available online: https://www.prognos.com/sites/default/files/2022-07/Prognos_KlimawandelfolgenDeutschland_%20Auswahl_Untersuchungsereignisse_AP2_2.pdf (accessed on 7 May 2025).
29. Brienens, S.; Walter, A.; Brendel, C.; Fleischer, C.; Ganske, A.; Haller, M.; Helms, M.; Höpp, S.; Jensen, C.; Jochumsen, K.; et al. Klimawandelbedingte Änderungen in Atmosphäre und Hydrosphäre: Schlussbericht des Schwerpunktthemas Szenarienbildung (SP-101) im Themenfeld 1 des BMVI-Expertenetzwerks. 2020. Available online: <https://www.bmdv-expertenetzwerk.bund.de/DE/Publikationen/TFSPTBerichte/SPT101.pdf> (accessed on 15 June 2023).
30. Pfeifer, S.; Rechid, D.; Bathiany, S. Klimaausblick Deutschland. 2020. Available online: https://gerics.de/imperia/md/content/csc/projekte/klimasignalkarten/gerics_klimaausblick_germany_version1.2_deutsch.pdf (accessed on 19 May 2022).
31. Peter, M.; Guyer, M.; Füssler, J.; Bednar-Friedl, B.; Knittel, N.; Gabriel, B.; Schwarze, R.; von Unger, M. Folgen des Globalen Klimawandels für Deutschland: Abschlussbericht: Analysen und Politikempfehlungen. 2020. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/2020-05-06_cc_15-2020_impactchain.pdf (accessed on 19 May 2022).
32. Ren, X.; Weitzel, M.; O'Neill, B.C.; Lawrence, P.; Meiyappan, P.; Levis, S.; Balistreri, E.J.; Dalton, M. Avoided economic impacts of climate change on agriculture: Integrating a land surface model (CLM) with a global economic model (iPETS). *Clim. Change* **2018**, *146*, 517–531. [CrossRef]
33. Wang, J.; Vanga, S.K.; Saxena, R.; Orsat, V.; Raghavan, V. Effect of Climate Change on the Yield of Cereal Crops: A Review. *Climate* **2018**, *6*, 41. [CrossRef]
34. Batten, S.; Sowerbutts, R.; Tanaka, M. Climate Change: Macroeconomic Impact and Implications for Monetary Policy. In *Ecological, Societal, and Technological Risks and the Financial Sector*; Palgrave Macmillan Cham: London, UK, 2020.
35. de Winne, J.; Peersman, G. The adverse consequences of global harvest and weather disruptions on economic activity. *Nat. Clim. Change* **2021**, *11*, 665–672. [CrossRef]
36. Allen, C.D.; Breshears, D.D.; McDowell, N.G. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* **2015**, *6*, art129. [CrossRef]
37. Buth, M.; Kahlenborn, W.; Savelsberg, J.; Becker, N.; Bubeck, P.; Kabisch, S.; Kind, C.; Tempel, A.; Tucci, F.; Greiving, S.; et al. *Vulnerabilität Deutschlands Gegenüber dem Klimawandel*; Umweltbundesamt: Dessau-Roßlau, Germany, 2015; Available online: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_24_2015_vulnerabilitaet_deutschlands_gegenueber_dem_klimawandel_1.pdf (accessed on 22 May 2023).

38. Renner, K.; Fritsch, U.; Zebisch, M.; Wolf, M.; Schmuck, A.; Ölmez, C.; Schönthaler, K.; Porst, L.; Voß, M.; Wolff, A.; et al. *Klimawirkungs- und Risikoanalyse 2021 für Deutschland: Teilbericht 2: Risiken und Anpassung im Cluster Land*; Umweltbundesamt: Dessau-Roßlau, Germany, 2021; Available online: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_2_cluster_land_bf_211027_0.pdf (accessed on 30 May 2022).
39. Lantz, V.; McMonagle, G.; Hennigar, C.; Sharma, C.; Withey, P.; Ochuodho, T. Forest succession, management and the economy under a changing climate: Coupling economic and forest management models to assess impacts and adaptation options. *For. Policy Econ.* **2022**, *142*, 102781. [CrossRef]
40. Tei, S.; Sugimoto, A.; Yonenobu, H.; Matsuura, Y.; Osawa, A.; Sato, H.; Fujinuma, J.; Maximov, T. Tree-ring analysis and modeling approaches yield contrary response of circumboreal forest productivity to climate change. *Glob. Change Biol.* **2017**, *23*, 5179–5188. [CrossRef]
41. Bosello, F.; Standardi, G.; Parado, R.; Dasgupta, S.; Guastella, G.; Rizzati, M.; Pareglio, S.; Schleyden, J.; Boere, E.; Batka, M.; et al. D2.7. Macroeconomic, Spatially-Resolved Impact Assessment: Deliverable of the H2020 COACCH Project. 2020. Available online: https://www.coacch.eu/wp-content/uploads/2020/10/D2.7_final.pdf (accessed on 28 November 2023).
42. Alegria, C.; Roque, N.; Albuquerque, T.; Gerassis, S.; Fernandez, P.; Ribeiro, M.M. Species Ecological Envelopes under Climate Change Scenarios: A Case Study for the Main Two Wood-Production Forest Species in Portugal. *Forests* **2020**, *11*, 880. [CrossRef]
43. Dee, L.E.; Miller, S.J.; Peavey, L.E.; Bradley, D.; Gentry, R.R.; Startz, R.; Gaines, S.D.; Lester, S.E. Functional diversity of catch mitigates negative effects of temperature variability on fisheries yields. *Proc. Biol. Sci.* **2016**, *283*, 20161435. [CrossRef]
44. ESKP. Biodiversität und Artenvielfalt. Available online: <https://www.eskp.de/grundlagen/klimawandel/biodiversitaet-artenvielfalt-935291/> (accessed on 15 July 2024).
45. Tilman, D. Functional Diversity. In *Encyclopedia of Biodiversity*; Levin, S.A., Ed.; Academic Press: San Diego, CA, USA, 2001; pp. 109–120, ISBN 9780122268656.
46. Barange, M.; Merino, G.; Blanchard, J.L.; Scholtens, J.; Harle, J.; Allison, E.H.; Allen, J.I.; Holt, J.; Jennings, S. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Clim. Change* **2014**, *4*, 211–216. [CrossRef]
47. Froehlich, H.E.; Gentry, R.R.; Halpern, B.S. Global change in marine aquaculture production potential under climate change. *Nat. Ecol. Evol.* **2018**, *2*, 1745–1750. [CrossRef]
48. Egerer, S.; Puente, A.F.; Peichl, M.; Rakovec, O.; Samaniego, L.; Schneider, U.A. Limited potential of irrigation to prevent potato yield losses in Germany under climate change. *Agric. Syst.* **2023**, *207*, 103633. [CrossRef]
49. Bender, S.; Groth, M.; Viktor, E. Auswirkungen des Klimawandels auf die zukünftige Grundwassernutzung: Betroffenheiten, Handlungsbedarfe und Lösungsansätze. *Grund.-Z. Fachsekt. Hydrogeol. (Grund.)* **2021**, *26*, 61–72. [CrossRef]
50. Fliß, R.; Baumeister, C.; Gudera, T.; Hergesell, M.; Kopp, B.; Neumann, J.; Posselt, M. Auswirkungen des Klimawandels auf das Grundwasser und die Wasserversorgung in Süddeutschland. *Grund.-Z. Fachsekt. Hydrogeol. (Grund.)* **2021**, *26*, 33–45. [CrossRef]
51. Barrage, L. Fiscal Costs of Climate Change in the United States. 2023. Available online: https://ethz.ch/content/dam/ethz/special-interest/mtec/cer-eth/cer-eth-dam/documents/working-papers/wp_23_380.pdf (accessed on 9 June 2023).
52. Voß, M.; Kahlenborn, W.; Porst, L.; Dorsch, L.; Nilson, E.; Rudolph, E.; Lohrengel, A.-F. *Klimawirkungs- und Risikoanalyse 2021 für Deutschland: Teilbericht 4: Risiken und Anpassung im Cluster Infrastruktur*; Umweltbundesamt: Dessau-Roßlau, Germany, 2021; Available online: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_4_cluster_infrastruktur_bf_211027_0.pdf (accessed on 10 April 2024).
53. Nilson, E.; Astor, B.; Fischer, H.; Fleischer, C.; Haunert, G.; Helms, M.; Hillebrand, G.; Labadz, M.; Mannfeld, M.; Riedel, A.; et al. Beiträge zu einer verkehrsträgerübergreifenden Klimawirkungsanalyse: Wasserstraßenspezifische Wirkungszusammenhänge—Schlussbericht des Schwerpunktthemas Schifffbarkeit und Wasserbeschaffenheit (SP-106) im Themenfeld 1 des BMVI-Expertenetzwerks. 2020. Available online: https://www.bmv-forschungsnetzwerk.bund.de/DE/Publikationen/TFSPtBerichte/SPT106.pdf?__blob=publicationFile&v=2 (accessed on 24 January 2022).
54. Hänsel, S.; Hillebrand, G.; Nilson, E.; Rauthe, M.; Lohrengel, A.-F.; Meine, L.; Herrmann, C.; Brendel, C.; Forbriger, M.; Kirsten, J.; et al. Klimawirkungsanalyse für die Bundesverkehrswege: Methodik und erste Ergebnisse. Schlussbericht des Schwerpunktthemas Klimawirkungsanalyse (SP-102) im Themenfeld 1 des BMVI-Expertenetzwerks. 2020. Available online: https://www.bmv-forschungsnetzwerk.bund.de/DE/Publikationen/TFSPtBerichte/SPT102.pdf?__blob=publicationFile&v=2 (accessed on 10 April 2024).
55. Ademmer, M.; Jannsen, N.; Kooths, S.; Möse, S. *Zum Einfluss des Niedrigwassers auf die Konjunktur*; Kieler Konjunkturberichte IfW-Box 2018.17; Institut für Weltwirtschaft: Kiel, Germany, 2018; Available online: <https://www.ifw-kiel.de/de/publikationen/zum-einfluss-des-niedrigwassers-auf-die-konjunktur-27883/> (accessed on 22 May 2023).
56. Ademmer, M.; Jannsen, N.; Möse, S. Extreme weather events and economic activity: The case of low water levels on the Rhine river. *Ger. Econ. Rev.* **2023**, *24*, 121–144. [CrossRef]
57. Knittel, N.; Jury, M.W.; Bednar-Friedl, B.; Bachner, G.; Steiner, A.K. A global analysis of heat-related labour productivity losses under climate change—Implications for Germany’s foreign trade. *Clim. Change* **2020**, *160*, 251–269. [CrossRef]

58. Wolf, M.; Ölmez, C.; Schönthaler, K.; Porst, L.; Voß, M.; Linsenmeier, M.; Kahlenborn, W.; Dorsch, L.; Dudda, L. Klimawirkungs- und Risikoanalyse 2021 für Deutschland: Teilbericht 5: Risiken und Anpassung in den Clustern Wirtschaft und Gesundheit. 2021. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_5_cluster_wirtschaft_gesundheit_bf_211027_0.pdf (accessed on 30 May 2022).
59. Er-Kara, M.; Ghadge, A.; Bititci, U.S. Modelling the impact of climate change risk on supply chain performance. *Int. J. Prod. Res.* **2020**, *24*, 7317–7335. [CrossRef]
60. Rüttinger, L.; van Ackern, P.; Lepold, T.; Vogt, R.; Auberger, A. Impacts of Climate Change on Mining, Related Environmental Risks and Raw Material Supply. Final Report. 2020. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/texte_106-2020_impacts_of_climate_change_on_mining_related_environmental_risks_and_raw_material_supply.pdf (accessed on 22 May 2023).
61. Karlsson, M.; Ziebarth, N.R. Population health effects and health-related costs of extreme temperatures: Comprehensive evidence from Germany. *J. Environ. Econ. Manag.* **2018**, *91*, 93–117. [CrossRef]
62. Statistisches Bundesamt. Gesundheit: Kostennachweis der Krankenhäuser 2019. Fachserie 12, Reihe 6.3. 2021. Available online: https://www.statistischebibliothek.de/mir/servlets/MCRFileNodeServlet/DEHeft_derivate_00074017/21206301970_04.pdf (accessed on 4 July 2025).
63. Bobb, J.F.; Obermeyer, Z.; Wang, Y.; Dominici, F. Cause-Specific Risk of Hospital Admission Related to Extreme Heat in Older Adults: Original Investigation. *JAMA* **2014**, *312*, 2659–2667. [CrossRef]
64. Ebi, K.L.; Capon, A.; Berry, P.; Broderick, C.; de Dear, R.; Havenith, G.; Honda, Y.; Kovats, R.S.; Ma, W.; Malik, A.; et al. Hot weather and heat extremes: Health risks. *Lancet* **2021**, *398*, 698–708. [CrossRef]
65. Kjellstrom, T. Impact of Climate Conditions on Occupational Health and Related Economic Losses: A New Feature of Global and Urban Health in the Context of Climate Change. *Asia Pac. J. Public Health* **2016**, *28* (Suppl. S2), 28S–37S. [CrossRef]
66. Schmuker, C. Klimawandel: Extremtemperaturen Gefährden die Gesundheit. G+G Wissenschaft 21(3). 2021. Available online: <https://www.wido.de/publikationen-produkte/ggw-gesundheit-gesellschaft-wissenschaft/ausgabe-3-2021/> (accessed on 22 May 2023).
67. Hübler, M.; Klepper, G.; Peterson, S. Costs of climate change: The effects of rising temperatures on health and productivity in Germany. *Ecol. Econ.* **2008**, *68*, 381–393. [CrossRef]
68. Hübler, M. Sozio-ökonomische Bewertung von Gesundheitseffekten des Klimawandels in Deutschland. In *Warnsignal Klima: Gesundheitsrisiken—Gefahren für Pflanzen, Tiere und Menschen*, 2nd ed.; Lozán, J.L., Graßl, H., Jendritzky, G., Karbe, L., Reise, K., Eds.; 2014; pp. 299–306. Available online: https://www.klima-warnsignale.uni-hamburg.de/wp-content/uploads/pdf/de/gesundheitsrisiken/warnsignal_klima-gesundheitsrisiken-kapitel-4_13.pdf (accessed on 4 July 2025).
69. Limaye, V.S.; Max, W.; Constible, J.; Knowlton, K. Estimating the Health-Related Costs of 10 Climate-Sensitive U.S. Events During 2012. *Geohealth* **2019**, *3*, 245–265. [CrossRef]
70. Trenczek, J.; Lühr, O.; Eiserbeck, L.; Leuschner, V. *Schäden der Sturzfluten und Überschwemmungen im Juli 2021 in Deutschland: Eine ex-Post-Analyse*; Projektbericht “Kosten durch Klimawandelfolgen”; Prognos AG: Düsseldorf, Germany, 2022.
71. Kemfert, C. *Klimawandel Kostet die Deutsche Volkswirtschaft Milliarden*; Wochenbericht 11/2007; DIW: Berlin, Germany, 2007.
72. Kotz, M.; Levermann, A.; Wenz, L. The economic commitment of climate change. *Nature* **2024**, *628*, 551–557. [CrossRef]
73. Mercure, J.-F.; Knobloch, F.; Pollitt, H.; Paroussos, L.; Scricciu, S.S.; Lewney, R. Modelling innovation and the macroeconomics of low-carbon transitions: Theory, perspectives and practical use. *Clim. Policy* **2019**, *19*, 1019–1037. [CrossRef]
74. International Monetary Fund. *Fiscal Monitor: Climate Crossroads: Fiscal Policies in a Warming World*; International Monetary Fund: Washington, DC, USA, 2023.
75. Metcalf, G.E.; Stock, J.H. The Macroeconomic Impact of Europe’s Carbon Taxes. *Am. Econ. J. Macroecon.* **2023**, *15*, 265–286. [CrossRef]
76. Espagne, E.; Oman, W.; Mercure, J.-F.; Svartzman, R.; Volz, U.; Pollitt, H.; Semieniuk, G.; Campiglio, E. *Cross-Border Risks of a Global Economy in Mid-Transition*; IMF Working Papers 2023/184; International Monetary Fund: Washington, DC, USA, 2023.
77. Lutz, C.; Reuschel, S.; Stöver, B.; Becker, L.; Kemmler, A.; Eiserbeck, L.; Leuschner, V.; Limbers, J. *Szenarien der Gesamtwirtschaftlichen Entwicklung in Deutschland im Kontext von Klimaschutz, Klimawandel und Klimaanpassung: Endbericht zum Forschungsauftrag “Auswirkungen des Klimawandels, des Klimaschutzes und der Klimaanpassung auf Die Gesamtwirtschaftliche Entwicklung in Deutschland (FA 05/22)”*; Studie im Auftrag des Bundesministeriums für Wirtschaft und Klimaschutz; GWS mbH: Osnabrück, Germany, 2025; Available online: https://gws-os.com/fileadmin/downloads/endbericht_bmwk_klima_fa0255.pdf (accessed on 9 April 2025).

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