Received: 1 September 2023 | Revised: 19 December 2023 | Accepted: 26 January 2024 | Published online: 31 January 2024

Green and Low-Carbon Economy
2024, Vol. 2(3) 184–192
DOI: 10.47852/bonviewGLCE42021658

RESEARCH ARTICLE

# Economic Impacts of Exemplary Climate Change and Adaptation Effects Under Different Socio-Economic Developments in Germany

**Markus Flaute[1], Saskia Reuschel[1,*] and Christian Lutz[1]**

[1]*Institute of Economic Structures Research (GWS), Germany*

**Abstract:** Three different socioeconomic developments are implemented at the national level in the macroeconometric model PANTA RHEI. While one scenario is oriented toward sustainability, a second one continues current trends. The third scenario is characterized by more dynamic socioeconomic development. This paper extends the impact chain methodology. Exemplary climate impacts and adaptation measures from literature are quantified for the transport, energy, and health sectors based on literature analyses and entered into the model. These are the interruption of a road due to flooding, cooling water scarcity for power plants due to drought, and higher health expenditures. Their quantifications are linked to the three different socioeconomic developments. The findings indicate that the economic costs of climate change may vary significantly across different socioeconomic scenarios. Climate impacts generate socioeconomic costs that can be reduced by adaptation measures. In the sustainability scenario, the negative economic impacts of climate change are significantly lower than in the other scenarios, especially in the energy and transport sectors. The effects are higher in the case of dynamic socioeconomic development. In contrast, socioeconomic development plays only a minor role for the effects in the health sector, which are mainly driven by demographic trends. The adaptation measures considered have positive macroeconomic effects, mainly due to lower damages, but also because of the additional investment activity. The model calculations quantify some impacts of climate change under different socioeconomic scenarios and assess the effects of climate risks and adaptation on critical infrastructure.

**Keywords:** climate impact chain, climate risk and vulnerability assessment, climate change adaptation, macroeconomic modeling, socioeconomic scenarios

## Abbreviations

| | |
|---|---|
| AR5 | Fifth Assessment Report |
| CGE | Computable general equilibrium |
| COACCH | Fifth CO-designing the Assessment of Climate CHange costs |
| COIN | COst of INaction |
| CRED | Climate Resilient Economic Development |
| GDP | Gross domestic product |
| GIZ | Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH |
| IAM | Integrated assessment models |
| IC | Impact chain |
| IPCC | Intergovernmental Panel on Climate Change |
| PESETA | Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis |
| SSP | Shared Socioeconomic Pathway |

*Corresponding author: Saskia Reuschel, Institute of Economic Structures Research (GWS), Germany. Email: reuschel@gws-os.com

## 1. Introduction

The growing interest in the economic costs of climate change and adaptation is attended by a number of studies that use macroeconomic models to assess climate change impacts and risks. Probably, the best-known calculations of the macroeconomic impacts of climate change have been made since the early 1990s by Nordhaus [1], who mapped the linkages between climate change and the global economy in a dynamic model. Based on this, various approaches of integrated assessment models have been developed and refined to better assess and regionalize damages. For example, Hsiang et al. [2] use a micro-founded sectoral bottom-up approach to identify the economic damages of climate change in the USA.

Various models of the effects of climate change are available for the EU, which have been incorporated into the EU Adaptation Strategy [3]. As part of the PESETA Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis [4, 5] and COACCH [6] projects, biophysical effects and socioeconomic impacts were quantified, with result variables being exchanged between different models. The results have so far been examined primarily at a macroeconomic level, e.g., with regard to sea-level rise [7] and river flood risk [8]. Kahn et al. [9] investigate long-term effects on the growth of gross domestic product (GDP). Dasgupta et al. [10] analyze impacts of climate change on labor productivity and supply and find differentiated regional and sectoral effects. Heterogeneous regional response functions make it necessary to skip one-size-fits-all response functions and investigate the climate effect on labor more specifically.

Also at the national and sub-national level, climate impacts have been assessed using different economic modeling approaches. For Austria, the interdisciplinary project COIN (COst of INaction) has assessed the economic impacts of climate change for 12 key sectors [11]. In the project Policy Advice for Climate Resilient Economic Development of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), dynamic macro models were developed for Georgia, Kazakhstan, and Vietnam to map climate change and adaptation measures [12].

The intensity and frequency of extreme weather events will continue to increase in the future as global warming proceeds [13]. But not only the frequency and the intensity of extreme weather events have an impact on the loss and damages, but also the extent to which humans and assets are exposed and vulnerable to the hazards. While hazards are driven by changes in climate, the exposure and vulnerability are also influenced by a changing society, which may vary in terms of population growth and economic development [14]. For sustainable adaptation to climate change, a sound understanding of both the climate-related and the societal impacts of climate risks is necessary.

Against this background, the following case study for Germany quantifies climate damages for exemplary critical infrastructures under different socioeconomic developments. A methodology for climate change risk and vulnerability assessments is the impact chain (IC) framework, as described in the Vulnerability Sourcebook and its supplements [15–17]. Although the IC framework has been widely used for risk assessments, there are still methodological gaps for further development as the integration of dynamic elements and quantitative models [18]. For an overview of the IC methods and the other case studies within the project by Petutschnig et al. [19]. This paper extends this methodology by showing how quantitative and qualitative data can be better integrated for assessment of uncertainties, how an integrated assessment of the impacts of potential climatic and societal changes can be conducted, and how the quasi-static IC approach can be combined with ex ante simulations. The combination of the IC method with macroeconomic modeling delivers quantitative values for the qualitative strands of the ICs. Modeling supports the quantification of climate change impacts on different socioeconomic developments and assesses the effects of climate risks and adaptation on critical infrastructure.

This paper first gives an overview of the materials and methods used. The case study-relevant ICs are illustrated using the IC method. In addition, three socioeconomic scenarios for Germany are quantified in the macroeconometric model PANTA RHEI. Selected climate impacts and adaptation measures are determined for the sectors energy, transport, and health. The comparison of the different socioeconomic scenarios shows the role of socioeconomic assumptions for the macroeconomic effects of single climate impacts and adaptation measures, whereby indirect and induced effects are considered. The next section discusses the results. A main finding of this study is that the economic costs of climate change may vary significantly across different socioeconomic scenarios. Pursuing ambitious climate and energy targets may result in lower adaptation need if the underlying economic activity is strongly influenced by mitigation. This illustrates how assumptions about future socioeconomic development influence the level of climate change impacts and the effectiveness of adaptation measures. Discussion and conclusions close the paper.

## 2. Materials and Methods

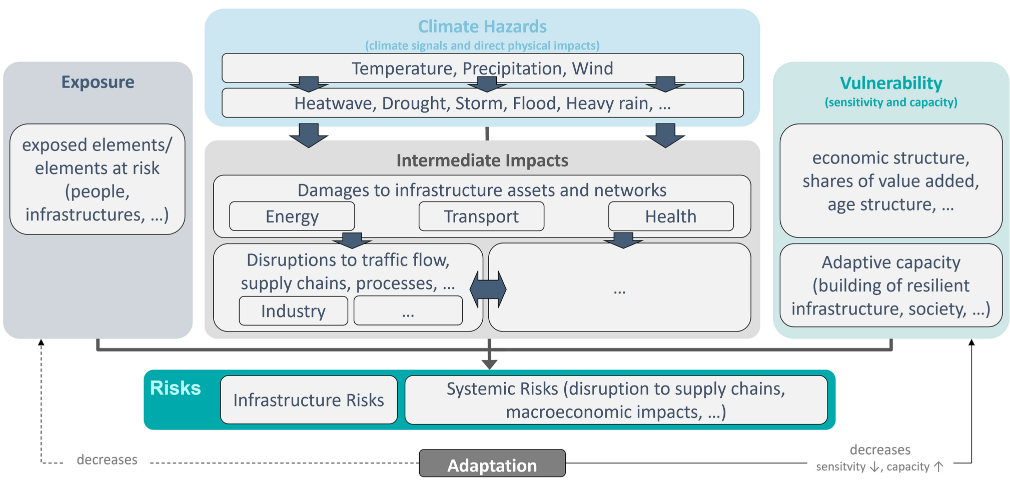
### 2.1. Application of the impact chain framework

ICs are an analytical tool that can be used for operational climate risk assessment. They provide the basic framework for systematizing the elements that determine the risks associated with climate impacts and selecting appropriate indicators. The IC method is a standard for evaluating adaptation to climate change [20] and has already been used as a conceptual basis for the climate risk and vulnerability assessment in Germany [21].

The concept of climate risk used is based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [22] and the current version of the IC framework [15, 16]. According to the IPCC AR5 concept, the risk of climate-related impacts results from the interaction of climate-related hazards, exposure, and vulnerability of human and natural systems, whereas vulnerability and exposure largely result from socioeconomic processes [22]. ICs thus consist of the three risk components hazard, vulnerability and exposure, and their underlying factors and intermediate impacts and provide a basis for identifying and selecting appropriate adaptation measures [15].

The development of ICs starts with the identification of climate impact and risk and continues with the determination of hazard and intermediate impacts, determination of vulnerability and exposure, and collection of ideas for adaptation measures [16]. They can be presented in a specific form for illustration purposes [16]. Figure 1

**Figure 1**
**Schematic illustration of the impact chains assessed in the case study**



[16] provides a schematic overview of IC elements of this case study. For the analysis, climate impacts from the energy, transport, and health sectors were selected to cover a range of infrastructures.

The analysis includes cascading effects of damages to infrastructures and considers different socioeconomic developments and adaptation. Climate change adaptation mainly reduces vulnerability, either by reducing sensitivity or increasing capacity. Operational assessments based on ICs are open to combine data and model-based approaches with expert-based approaches. Therefore, in the following, the IC approach is combined with macroeconomic modeling to provide quantitative metrics for the qualitative strands of the IC.

The frequency and intensity of heat waves and heavy precipitation are expected to increase significantly in Germany [23]. Future socioeconomic development can be represented through socioeconomic scenarios, which affect vulnerability, exposure, and thus climate change risk. Three national socioeconomic scenarios based on the Shared Socioeconomic Pathways (SSPs) are used in this case study to integrate socioeconomic model results in IC risk assessment and to address uncertainties regarding future socioeconomic development. The scenarios each depict a different socioeconomic development and thus differ in terms of economic and social structure and different energy and climate targets. The modelling, the implementation of the socio-economic scenarios and the implementation of the climate change impacts are described in the following sections.

## 2.2. Implementation of the modeling

According to the classification of climate-economy models of Nikas et al. [24], the applied model PANTA RHEI is a macroeconometric model. Macroeconometric and computable general equilibrium (CGE) models differentiate multiple economic sectors in contrast to impact assessment models. But in contrast to CGE models, optimal behavior of consumers and producers, market clearance, and short-term equilibrium are not assumed. The model explicitly includes a health sector and a transportation sector, which allows to model climate change and adaptation in sector detail. The energy sector is represented in high detail, which makes it possible to quantify impacts on different types of power plants as nuclear, coal, gas, and renewable energies. Maier et al. [25] give a detailed description of the economic part of the model especially for the labor market. An update with more detail on the energy sector can be found in Lutz et al. [26].

Umweltbundesamt [27] developed three national socioeconomic scenarios for the analysis and assessment of the impacts of climate change in Germany based on the SSPs [28, 29]: a business-as-usual scenario (“trend”), a sustainable development scenario (“stability”), and a third one as a counterpart to the sustainability scenario which assumes a higher socioeconomic development (“dynamic”). Important characteristics at the national level are population and demographic development, GDP, land use, and developments in the field of energy, climate, and transport (such as energy consumption, greenhouse gas emissions, renewable energy, passenger and freight transport services, and modal split). Table 1 [27] summarizes the key assumptions and characteristics of the three scenarios at national level.

The trend scenario is internationally comparable to the SSP2 scenario. While the development of the population and economic growth is identical compared to the stability scenario, a slower development is applied to the achievement of the energy and climate targets. The stability scenario is internationally comparable to the SSP1 scenario. For population, a long-term net immigration of 200,000 persons per year is assumed, which is in line with the variant 2a of the 13th coordinated population projection of the Federal Statistical Office [30]. However, the working-age population declines over time, which in turn has an impact on the development of the GDP: The GDP initially grows at 1.3% per year until 2020, with 1% on annual average until 2025, and at a rate of 0.8% per year afterwards. Foreign trade will continue to grow much faster than GDP in the future. The dynamic scenario contains faster socioeconomic development. The dynamic scenario is most similar to SSP5, but without a corresponding focus on the use of fossil fuels. Net migration is higher than in the other two scenarios (100,000 people p.a. more), resulting in a population that is around 3 million people larger than in the trend scenario in 2045. Likewise, GDP growth is higher than in the stability and trend scenario: In the long run, the economy grows at 1.2% annually. Thus, GDP is about 12% higher in the dynamic scenario than in the other scenarios in 2045. Higher GDP is mainly driven by higher exports, which also have positive effects on other GDP components as consumption and investment.

The model PANTA RHEI is used to analyze the effects of climate change on transport, energy, and health infrastructure for the three different socioeconomic projections at national level. In this respect, the concrete model settings and reaction modes are not the focus of the considerations. Essentially, the assumptions on the economic effects of selected climate impacts and adaptation measures are reflected in the different results of the three socioeconomic scenarios. The transport, energy, and health sectors were selected because they are of crucial importance for economic and social development, cover a wide range of types of infrastructure, and include climate impacts for which quantified data are available. The sectors also represent the respective fields of action of the national adaptation strategy [21]. Table 2 provides an overview of the climate impacts considered. The criteria for selection of examples have been quantifications of the literature.

For transport, the climate risk of the disruption of transport routes due to heavy precipitation and flooding is considered. Additional investments are needed to rebuild infrastructure. The users of the road, both passengers and freight transport, will have to take detours, which means increased time consumption plus additional mileage. The transport sector is the one potentially most affected by climate change, due to its vulnerability to damage caused by extreme weather events [31]. Detailed information on the influence of natural hazards on the availability of transport infrastructure and its traffic flows in Germany is provided by Hänsel et al. [32] and Hänsel et al.

**Table 1**
**Key assumptions and characteristics of the three scenarios at national level**

| | Trend | Stability | Dynamic |
|---|---|---|---|
| Related SSP | SSP2 | SSP1 | Economic dynamics as SSP5, but no focus on fossil fuels |
| Population development (annual net immigration) | 200,000 | | 300,000 |
| GDP (annual average growth rate) | 1.0% up to 2025<br>0.8% as of 2026 | | 1.3% up to 2025<br>1.2% as of 2026 |
| Energy and climate targets | Delayed achievement | Achieved | Missed |
| Transport | Delayed achievement | Limited transport | High transport |

**Table 2**
**Considered climate impacts**

| Sector | Climate impact and risk |
|---|---|
| Transport | Disruption of road transport due to heavy precipitation/flooding |
| Energy | Lack of cooling water for coal power plants due to heat/drought |
| Health | Increased demand for health care services due to heat |

[33]. For the calculations in this paper, a disruption of a highway for 180 days is assumed. Every day, 15,000 trucks would use the route and are thus forced to take a detour. This detour is 25 km long and it takes about 40 min to drive. Assuming an average consumption of 34l/100 km for loaded trucks, this results in additional costs for diesel of about 30 million euros. The production losses in industry are particularly difficult to quantify. The information above serves as the basis for the trend scenario. Accordingly, the assumptions for the number of affected trucks due to the road lock are adjusted in each scenario. Fewer trucks are affected by road failure in the stability scenario than in the trend scenario, but more are affected in the dynamic scenario.

For the energy sector, the case of reduced energy generation of hard-coal-fired power plants due to limited availability of cooling water because of heat and drought is considered. The physical effects can be translated into corresponding model variables. Energy supply causes 55% of the current water extraction. The problem of high temperatures and the effects on cooling water for thermal power plants become more relevant in the future if a high proportion of thermal power generation is being assumed. Thus, the risk of insufficient cooling water for the thermal power plants in Germany could be significantly reduced with the transformation toward renewable energy [31]. The reduced efficiency and production of electricity of the thermal power plants have an impact on the economy via higher wholesale electricity prices and price volatility [34]. The reduction in electricity generation by hard-coal-fired power plants must be compensated by other types of power plants or by electricity imports. The three socioeconomic pathways at the national level are all based on different assumptions concerning the development of the electricity sector. Accordingly, the higher energy demand in the dynamic scenario leads to a higher electricity generation of coal-fired power plants.

For the health sector, this case study considers the risk of heat to morbidity and associated impact on health infrastructure through hospital costs. Extreme heat increases hospitalizations, particularly of older persons. It can be assumed that this risk will increase both due to rising temperatures and the increasing number, intensity, and duration of heat waves, and due to the increasing vulnerability caused by demographic development [35]. To analyze the heat-related effects on health infrastructure, assumptions are made on the number of heat-related hospital admissions, the average costs per hospital day, and the number of hot days per year. The number of people affected depends on the population development in the respective socioeconomic scenario. It is assumed that mainly elderly people (over 65 years of age) are affected. However, the number of older persons hardly differs among the three scenarios, unlike the previously considered variables of climate impacts in the areas of transport and energy. Overall, the number of people affected in the dynamic scenario is slightly higher than in the other two scenarios. The average costs of a hospital day in Germany were calculated by dividing the average costs per treatment case by the average length of stay [36] and extrapolating them until 2050. The average costs per hospital day are slightly higher in the dynamic scenario. The assumptions on the number of hospital admissions are based on the study by Karlsson and Ziebarth [37]. For the analysis of heat events, 20 hot days are assumed for Germany in 2030 and 30 hot days in 2040.

## 3. Results

### 3.1. Transport

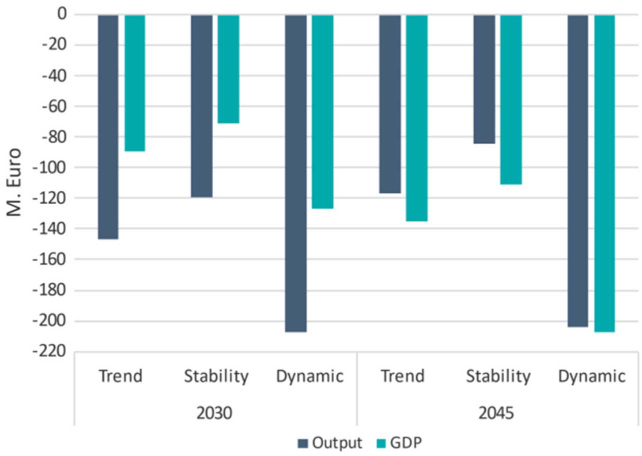
Freight transport performance will increase in all three scenarios. In the dynamic scenario, the increase is particularly strong, resulting in a freight transport performance of 1128 billion tkm in 2045. Compared to the stability scenario, this is more than 25% higher. In addition, the distribution between the modes of transport differs significantly in the stability scenario: While the increase in freight transport performance in road transport is comparatively weak, shipping and, in particular, rail transport can expand their shares [27]. These differences between the socioeconomic scenarios directly change the effects of a road closure. Since the transport performance of road transport is low in the stability scenario, the road closure only has minor macroeconomic effects. These effects are higher in the dynamic scenario with higher road transport.

The closure of a highway causes negative macroeconomic effects. The detours to be taken increase the working hours in the transport industry. While there are positive effects on gross production in this sector, the overall transport costs increase. Transport services are demanded by many other sectors as intermediate inputs, facing higher costs, which they pass on to other sectors. Increasing prices have a negative impact on demand and production. Furthermore, delays in the delivery interrupt individual production chains, leading to production losses. While some of these production losses can be offset by changes in inventories, a negative impulse remains due to the lower production. The increased demand for petrol and diesel by the transport industry is also reflected in higher prices, which are passed on to customers by the downstream sectors with negative macroeconomic effects. Figure 2 shows the total effects on gross production and GDP for the years 2030 and 2045. The highest negative impacts on GDP are caused in the dynamic scenario, while the GDP effects in the stability scenario are rather small. The negative impact on gross production is decreasing over time.

Increasing the capacity of drainage systems for roads is a suitable adaptation measure against increasing precipitation and heavy rains [38]. The investments in drainage systems are long-term issues and need to be carried out every year. A 20% increase of drainage capacity is estimated to cost additional 6.7 million euros per year [38]. The increase of the drainage system capacity is supposed to reduce potential damages from precipitation in the future. The additional drainage capacity ensures that the roads are no longer flooded and therefore the roads do not have to be closed or only for a shorter period, and thus, reducing detours, additional mileage, and additional fuel consumption. In addition to the reduction of damage, there is also a positive effect of the additional investment.

To illustrate the effects of adaptation, it is assumed that implementing the adaptation measure "20% increase of drainage capacity" reduces the damages from precipitation by 20%. Figure 3 shows the changes in real GDP between the climate change scenario (without adaptation) and the adaptation scenario in 2030 and 2045. Compared to the climate change scenario, there is a positive effect on GDP due to the additional investment

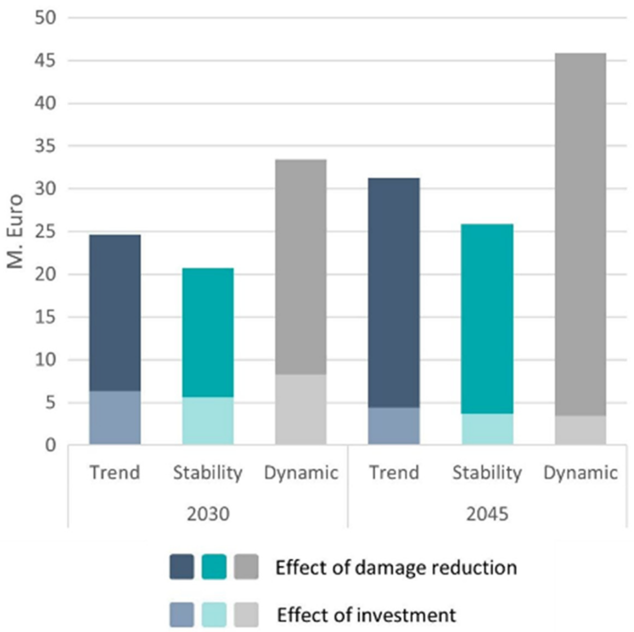
**Figure 2**
**Gross production and GDP – Changes due to disruption of road transport for 2030 and 2045 in M. Euro, real values**




(lighter part) and the reduced damages (darker part). Compared to the trend and stability scenario, the absolute effects are higher in the dynamic scenario due to the higher transport performance and the higher shares of road transport in freight. Damage reduction accounts for most of the effect.

In this adaptation scenario, residual damages remain. The highest residual damages for the respective years occur in the dynamic scenario, the lowest in the stability scenario. The annual adaptation investments of 6.7 million Euro do not only have an impact in the damage years. Figure 4 therefore shows the cumulative effects of the adaptation scenario and the climate change scenario throughout the period from 2021 to 2050. The adaptation scenario includes climate change and the considered adaptation measure (20% increase of drainage capacity and 20% damage reduction). Adaptation will more than halve the negative effects on cumulative GDP in all three SSP scenarios.

**Figure 3**
**Real GDP – Changes from the adaptation measure "Increase of drainage capacity (20%)" for 2030 and 2045 in M. Euro**




## 3.2. Energy

Figure 5 shows the changes in wholesale electricity prices due to the temperature-induced reduction in hard-coal-fired electricity generation for the years 2030 and 2045. For the years shown, the prices for industry increase by up to 0.3% in the year 2030 in the trend scenario and in the dynamic scenario. The prices for households are only marginally changed. In the year 2045, the price increases are significantly lower due to the coal phase-out. However, the higher share of coal-generated electricity and its vulnerability to hot cooling water in the dynamic scenario still induce an increase of more than 0.1% for the prices in industry.

**Figure 4**
**Cumulative effect on real GDP from disruption of road transport for 2021–2050 in M. Euro**

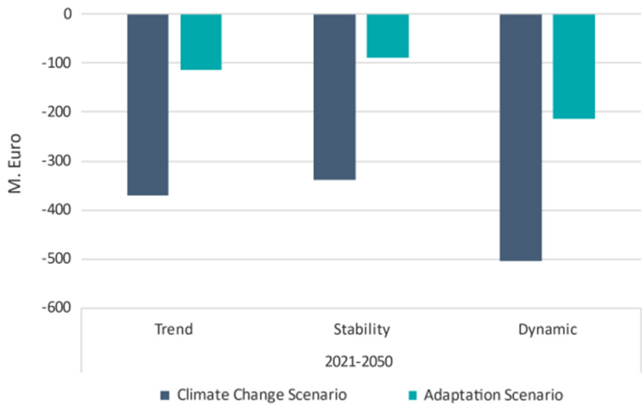



Figure 6 illustrates the temperature-induced reduction in hard-coal-fired electricity generation assumed for analyzing the effects of cooling-water availability in the three respective scenarios. For this purpose, the respective scenario is used as a basis so that the depicted climate change reflects the different impacts of climate change depending on the socioeconomic development. In the stability scenario with the coal phase-out, no further cooling water-related outages occur after 2038. In the dynamic scenario, however, coal-fired power plants will still be in operation in 2050, so that there will still be effects of climate change via electricity generation from coal.

The resulting macroeconomic effects on gross production and GDP are shown in Figure 7. While production in the energy sector decreases due to the reduced electricity generation of coal-fired power plants, production in other industries decreases due to the higher electricity prices. GDP is being influenced by several effects. Both consumption expenditures of the government and households decrease. Further, there are negative effects on the GDP from reduced investment activities and a reduced level of exports. Additionally, more electricity is being imported from abroad. Imports of other products also increase due to higher domestic prices. Total effects are rather small, but negative. As electricity price increases and demand effects are higher in the dynamic scenario, the negative impacts on the GDP are larger but decreasing over time in all three scenarios.

**Figure 5**
**Temperature-induced effects on wholesale electricity prices for 2030 and 2045 in %**

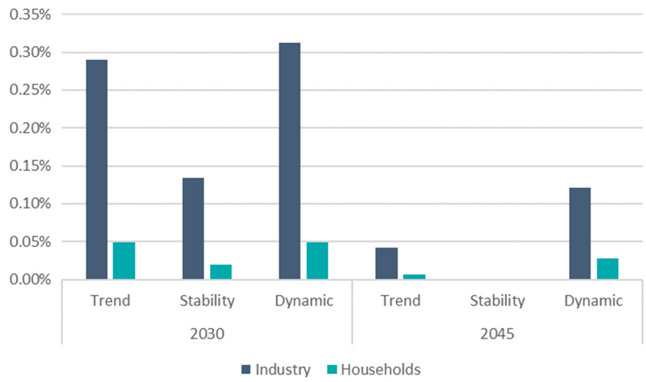



**Figure 6**
**Temperature-induced reduction in hard-coal-fired electricity generation for 2025 to 2050 in GWh**

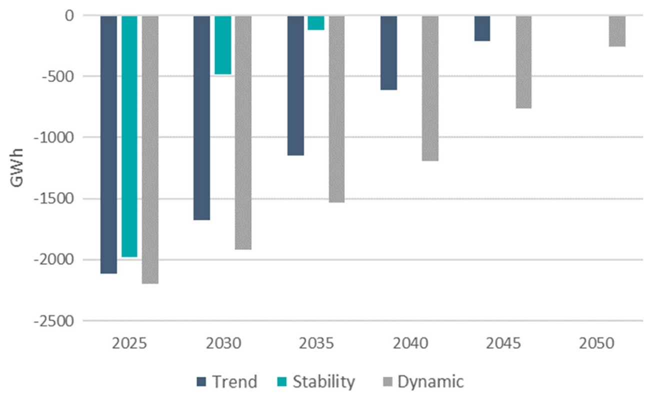
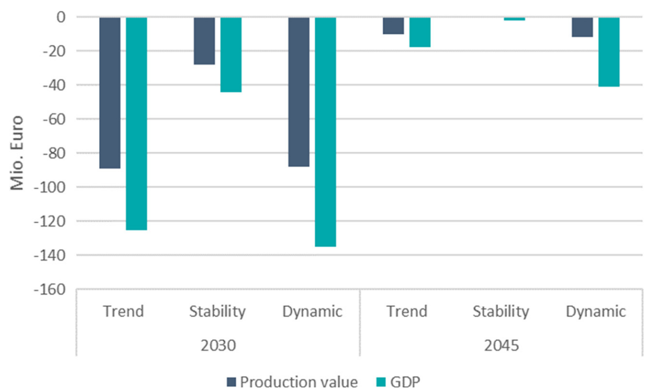



**Figure 7**
**Gross production and GDP – Temperature-induced effects for 2030 and 2045 in M. Euro, real values**




Due to the foreseen phase-out of coal-fired power generation in Germany, the adaptation of cooling systems is very unlikely. Thus, no additional modeling is performed for this climate impact.

## 3.3. Health

Older people are especially vulnerable to heat waves. According to the population projections underlying the three SSP scenarios and the assumption that mainly elderly people (over 65 years of age) are affected, heat-related hospital admissions will increase by 44% until 2030 and by 54% until 2045 compared to the period of 1999–2008. Although the dynamic scenario is characterized by a somewhat higher population development (see Table 1), the comparison of the three socioeconomic scenarios shows only slightly differences for the age group under consideration. This demographic effect therefore results in an increase in costs per additional hospital day in the future. Table 3 shows the costs per additional hot day in million Euro for 2030 and 2045 based on the projections of the average costs per hospital day and the respective population projections.

For assumed 20 hot days in 2030, this results in additional health expenditure of around 300 million euros and for assumed 30 hot days in 2045 of around 800 million euros. The magnitude of the effect is mainly determined by climate change and hardly differs between the socioeconomic scenarios.

The economic effects of increased health expenditure may seem paradoxical at first. It is conceivable that the growing demand for health services initially leads to higher GDP. But these funds are then no longer available elsewhere, so that not only adverse health effects but also adverse economic effects can occur. Non-monetary consequences such as death or loss of well-being show, particularly for health, that not only economic indicators need to be considered. The evaluation of other indicators, such as Sustainable Development Goals, could provide a more comprehensive picture. Adaptation measures to reduce heat stress fall primarily into the categories of raising awareness or investment in construction.

**Table 3**
**Costs per additional hot day in M. Euro for 2030 and 2045**

| | Trend | Stability | Dynamic |
|---|---|---|---|
| 2030 | 24.5 | | 24.9 |
| 2045 | 35.0 | | 36.8 |

## 4. Discussion and Conclusion

Quantifications of selected impacts of climate change and adaptation measures are linked to three different socioeconomic developments for Germany. The findings indicate that the economic costs of climate change impacts may vary significantly across alternative socioeconomic scenarios, if they assume different structures and levels of activity, such as in energy production and transport. Ambitious climate and energy targets result in lower adaptation costs and needs. Adaptation has positive macroeconomic effects through the reduction of damages and the additional investment in adaptation. The national socioeconomic scenarios depict a business-as-usual, a sustainable, and a dynamic development and differ regarding economic development, population structure, and energy and climate targets. Accordingly, the effects of climate change differ: The disruption of road transportation due to heavy precipitation leads to lower effects in the sustainable scenario than in the dynamic scenario, which includes higher freight transport and higher share of road transport. The expansion of renewable energy in the sustainable scenario also results in a lower risk of heat- and drought-related cooling water scarcity for thermal power plants compared to the dynamic scenario, which is largely based on conventional power generation. The age structure between the scenarios differs rather slightly, so that the effects of heat on the demand for healthcare services are only a bit greater in the dynamic scenario. In any case, there is a larger demographic effect in the future compared to current levels.

Combining the IC method and macroeconomic modeling provides quantitative values for the qualitative strands of the ICs. Besides the enhancement of the method through the integration of quantitative, qualitative, and dynamic aspects, the method is improved through the integration of socioeconomic scenarios. The model PANTA RHEI allows the identification of direct, indirect, and induced impacts, so that further effects, which were not yet discovered in the development of qualitative ICs, can be revealed. The quantification of climate change impacts and exemplary visualization of adaptation challenges shows a possible and plausible corridor of results for different socioeconomic developments to better understand and assess the impacts of different adaptation measures. This illustrates how assumptions about future socioeconomic development influence the magnitude of climate change impacts and the effectiveness of adaptation measures. It allows for assessing risks regarding impacts of climate change on infrastructure.

Three climate impacts were selected as illustrative examples, while the German climate impact and risk analysis list a total of 102 climate impacts [39]. Additional climate impacts should be examined in more depth in the future. Looking at the power sector, for example, there are various other climate risks. On the supply side, electricity generation from renewables, e.g., hydro power, is also affected, as is the capacity of the distribution and transmission grid, which could be harmed by storms or floods. Aall et al. [40] call for an expansion of the research agenda on energy transformation and climate risks in this direction. Moreover, transboundary climate risks have rarely been considered, despite the degree of global integration of societies and economies [41]. For Germany, initial approaches look at international trade, and the supply of raw materials and intermediate goods [42–45].

Further research is also needed on the integrated consideration of uncertainty, in terms of climate impacts and socioeconomic development. For this purpose, climate modeling and socioeconomic modeling should be more closely linked via ICs. Sensitivity analyses in both areas could then provide information on which uncertainties are particularly large and can particularly influence the effects of climate change as well as the impact of adaptation measures. Corresponding information can provide important conclusions for the design of adaptation measures at the national level. Another important step would be a stronger spatial disaggregation of socioeconomic effects because climate change and adaptation options vary greatly from region to region. However, research about this regionalization is still limited. At the same time, climate impact assessments should be more standardized. Therefore, the IC approach will be very useful.

## Funding Support

The authors gratefully acknowledge funding received for the work presented here under the UNCHAIN project. UNCHAIN is part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), DLR/BMBF (D), AEI (ES), and ANR (FR) with co-funding by the European Union (Grant No. 776608). The quantification of the scenarios was carried out within the framework of the project "Sozioökonomische Szenarien als Grundlage der Vulnerabilitätsanalysen für Deutschland" (FKZ 3716 48 1000) funded by the German Environment Agency (UBA).

## Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

## Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

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**How to Cite:** Flaute, M., Reuschel, S., & Lutz, C. (2024). Economic Impacts of Exemplary Climate Change and Adaptation Effects Under Different Socio-Economic Developments in Germany. *Green and Low-Carbon Economy*, *2*(3), 184–192. https://doi.org/10.47852/bonviewGLCE42021658