SPECIALISTS IN EMPIRICAL ECONOMIC RESEARCH

GWS DISCUSSION PAPER 2023/03

Economic costs of climate change and effects beyond GDP

A model-based analysis of climate change impacts in Germany

Saskia Reuschel

Britta Stöver

Impressum

AUTHORS

Saskia Reuschel

Tel: +49 (541) 40933-283, E-Mail: reuschel@gws-os.com

Dr. Britta Stöver

Tel: +49 (541) 40933-250, E-Mail: stoever@gws-os.com

TITLE

Economic costs of climate change and effects beyond GDP: A model-based analysis of climate change impacts in Germany

PUBLICATION DATE

DISCLAIMER

Opinions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the GWS mbH.

FUNDING

The results at hand have been prepared in the course of a research project for the Federal Ministry for Economic Affairs and Climate Action.

PUBLISHER OF THE GWS DISCUSSION PAPER SERIES

Gesellschaft für Wirtschaftliche Strukturforschung mbH

Heinrichstr. 30

49080 Osnabrück

ISSN 1867-7290

TABLE OF CONTENTS

ABSTRACT

Climate change impacts are already noticeable today. Their future effects and costs is of increasing intrest and a growing number of research papers hence investigate climate change impacts and climate change adaptation. However, research focused mainly on the US economy and or on the agricultural sector. Other papers concentrated on the losses in GDP. Against this background, this paper examines the macro-economic costs of climate change in Germany taking also social dimensions such as SDG indicators into account. We used a model-based scenario-analysis that allowed us to identify the costs of climate change on sectoral level and on level of different household types. The impact of three intensities of climate change (low, medium, high) was assessed on GDP, on selected indictors of the UN sustainable development goals (SDGs) as well as on inequality using household income of different household types. The findings of this study indicate that the economic costs of climate change measured by the changes in GDP have the potential to be substantially high even under conservative assumptions. Strong effects on GDP are triggered in particular by those climate effects that lead to significant price increases such as yield losses in agriculture, damages to buildings and infrastructure and impariments in international trade. The results also indicate that it is worthwhile to assess socioeconomic effects beyond GDP: climate change would increase income inequality and deteriorate in particular national SDG indicators 2 (Zero Hunger) and 10 (Reduced Inequalities). The results illustrate the high need for action in climate mitigation and adaptation and highlight the importance of taking into account not only macroeconomic effects but also social dimensions.

Keywords: climate change, impact assessment, SDG, model-based scenario analysis, macro-econometric input output model

1 INTRODUCTION

Evidence is growing that the intensity and frequency of extreme weather events have already increased and will continue to increase in the future as global warming proceeds, which further increases the risk of climate change (IPCC 2021). With extreme events already occurring more frequently, there is growing interest in assessing economic costs of climate change and the effects of climate change adaptation both globally and at various administrative levels. This is reflected in a growing number of publications related to the impacts of climate change and (to a much lesser extent) adaptation to climate change. One branch of literature has an ex-post perspective focusing on statistical approaches using historical weather data to measure and explain the impact of climate change (a review is given by Kolstad and Moore 2020). Other papers focus on another facet of climate change: the economic impacts of natural disasters (a review provides Botzen et al. 2020). Another strand of papers uses economic models to show future effects of climate change on the economy. One prominent example are the analysis of Nordhaus (1994; 2013, 2014; 2017; 2019) that apply Integrated Assessment models (IAMs) to quantify the future social and economic costs of climate change. Other recent examples for model based assessment of climate change impacts are Dellink et al. (2017), Ngoma et al. (2021), and Vrontisi et al. (2022).

However, compared to the research field of climate change mitigation, the number of publications is still low leaving room for further research. Additionally, much of the empirical work focus on the United States and/or the agriculture sector, so that more research is needed going beyond these settings for a better and more complete understanding of the effects of climate change (Kolstad and Moore 2020).For Germany, which is one of the leading industrialized countries, there are, to our knowledge, only four studies from the last years that examine the effects of climate change on the German economy: Kemfert (2007), Lehr et al. (2016), Peter et al. (2021), and Philip et al. (2021). The focus of these analyses is on the losses in GDP and in economic activities. In addition, there exist a few assessments of climate risks and climate change costs at the European level which downscale the results to country or regional level (Ciscar 2009; Joint Research Centre 2020; COACCH 2019, 2021). However, climate change not only affects the economy and economic growth but also sustainable development. Fuso Nerini et al. (2019) show in a structured review process, that climate change and SDGs are strongly interlinked and that the achievement of especially SDG indicators representing material and physical well-being will be undermined by climate change. The SDGs mostly affected by climate change are 1 No Poverty, 2 Zero Hunger, 5 Gender Equality, 6 Clean Water, 8 Decent Work and Economic Growth, 13 Climate Action, 14 Life Below Water and 15 Life on Land (Fuso Nerini et al. 2019). Similar results are found by IPCC (2018) who concluded based on a literature review of scientific and grey literature, that climate change severely hinders achieving sustainability, reducing inequality, and eradicating poverty. Assessing the costs of climate change should therefore not solely focus on the losses in GDP but also on other parameters representing sustainable development.

In this paper we analysed future costs of climate change not only from an economic but also from a social and sustainable perspective taking Germany as example. We used the macro-econometric input-output model INFORGE / PANTA RHEI (PANTA RHEI hereafter) to calculate three different scenarios of climate change. The scenarios were compared to a reference where climate change did not proceed. We assessed the impact of three intensities of climate change (low, medium, high) on GDP, on selected indictors of the UN sustainable development goals (SDGs) as well as on inequality using household income of different household types.

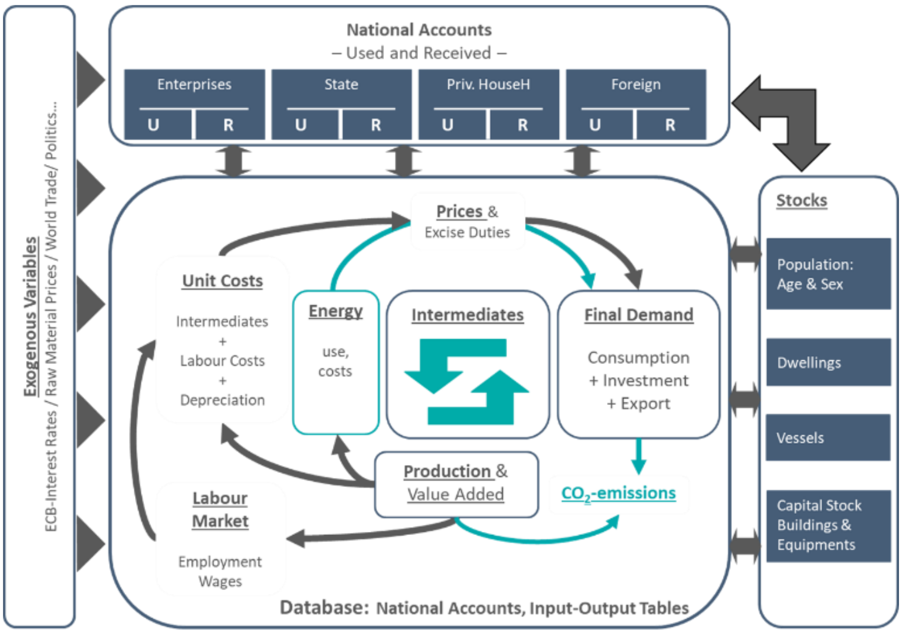
Our results show that losses in GDP due to climate change could be substantial. Additionally, the findings reveal that climate change in Germany would increase income inequality and lead to a deterioration of SDG 2 (Zero Hunger) and SDG 10 (Reduced Inequalities). Adaptation measures to ease the impact of climate change should therefore not only address the economic dimensions but also the social dimensions. The latter is challenging as the negative effects on sustainability and inequality mainly arise due to internationally induced price increases. The starting point for approaches to action therefore lies outside national spheres.

The remainder is organised as follows: Section 2 (Method) describes the model, the implemented scenarios, and the SDG indicators used in the analysis. Section 3 provides the results of the scenario analysis. Section 4 encompasses the discussion of the findings and outlines some limitations. Section 5 concludes.

2 METHOD

In this study, costs of climate change were estimated using a scenario-analysis based on the macro-econometric model PANTA RHEI. The model is designed for assessments of economic, energy, climate and environmental policies up to the year 2050. It follows the INFORUM philosophy (Almon 1991) of building bottom-up and fully integrated econometric input-output models. Like the CGE models it belongs to the group of input-output-based macroeconomic models, in which interactions, indirect effects and other interdependencies are mapped at a high sectoral level of detail (Stöver et al. 2022). Contrary to the very restrictive theoretical framework of CGEs, PANTA RHEI uses approaches from evolutionary economics explaining developments from the past via estimating equations and parameters and extrapolating them into the future (Lehr and Lutz 2020). As a result, prices in PANTA RHEI are determined on the basis of market imperfections triggered by incomplete competition, partially rigid prices and market dependencies as well as limited information of the economic agents through unit-cost-based mark-up pricing (Becker et al. 2022). No market side is favored, in that the production quantity is determined by both the supply and the demand side, i.e. companies set their prices based on their cost situation and the competing import prices, triggering a reaction in demand, which in turn determines the production quantity as a result of the level of the purchase decision. Technological change is represented in PANTA RHEI by the mode of production, labor productivity and capital intensity. Current technological developments that do not yet have a sufficient temporal foundation are integrated by setting assumptions. Figure 1 provides an overview of the model structure. For a more detailed technical description, see Becker et al. (2022).

Figure 1: Overview of the design and structure of the model INFORGE / PANTA RHEI



Source: Own illustration, adapted from Becker et al. (2022)

PANTA RHEI has been used for projections of labor demand, sectoral development and the overall economic development (Zika et al. 2022; Mönnig et al. 2021; Zika et al. 2021). Additionally, the model has been applied in many ways for scenario analysis: to calculate the macroeconomic effects of the Energiewende (Lutz et al. 2018), the socio-economic impact of the NECP (Lutz et al. 2021b), rebound effects of energy taxes (Lutz et al. 2021a; Ahmann et al. 2022), or the net employment effects of the transition to a green economy (Ulrich et al. 2022). The model has also been used to calculate the macroeconomic effects of climate change and adaptation to climate change (Lehr et al. 2016; Lehr et al. 2020).

For the scenario analysis at hand, we assumed three different intensities of climate change, that is low, medium, and high, and compared them to the reference. In the reference we assumed that climate change did not continue to proceed. Consequently, empirically observable changes in past behaviour due to climate change were still part of the projections. For the climate change scenarios, we modelled climate change as continuous effects. This means that extreme weather events were smoothed and continuously distributed over time, because we did not have exact knowledge of time and place of occurring future extreme weather events. With this approach we also wanted to prevent the impression of exact predictions. However, we assumed that the number and intensity of extreme weather events will increase over time, so that climate change will not develop linearly but slightly exponentially.

The biophysical impacts of climate change were translated into economic impacts at the sectoral level using impact chains. Not all biophysical impacts and their corresponding economic impacts could be considered. Rather, only those impacts could be mapped that could be monetarised and represented in an economic model. Thus, impacts not considered were for example loss of biodiversity, deterioration of quality of life, or loss of cultural assets. The scenario results therefore represented only a lower limit. The selection of climate change impacts used in the scenario was based on the national Climate Impact and Risk Assessment study for Germany (UBA 2021). The selection criteria were urgency, relevance, degree of certainty and the possibility of deriving economic values. The selected impacts were monetarised and represented the direct climate change costs at the sectoral level. In the macroeconomic model these direct costs triggered further indirect and induced effects, which altogether represented the total macroeconomic effects. The entry points for the translated economic impacts into the macroeconomic model were: changes in the production cost structure, changes in productivity, changes in final demand, changes in investment, changes in public expenditure, and changes in (import) prices. Table 1 gives an overview of the selected climate impacts, their entry points in the model and references for the direct impact values.[1]

[1] An extensive description of the scenario methodology and assumptions are given in Flaute et al. 2022. Details are also available upon request from the authors.

Table 1: Considered climate impacts and their entry points to the macroeconomic model PANTA RHEI

Field / Sector	Climate impact	Entry points PANTA RHEI	Sources of the scenario assumptions
Agriculture	Yield losses in agriculture	Higher import prices for intermediate products for agricultural sector, higher domestic producer prices for agricultural sector, higher import prices for food products (food industry), higher agricultural land leases and prices	Schlenker and Roberts (2009), Lesk et al. (2016), Brasseur et al. (2017), Mäkinen et al. (2018), Ren et al. (2018) Tigchelaar et al. (2018), Wang et al. (2018), Li et al. (2019), Beillouin et al. (2020), Knittel et al. (2020)
Forestry	Timber yield in forestry	Higher import prices for forestry industry, higher domestic producer prices for forestry industry, higher import prices for wood products, higher forestry land leases and prices	Augustynczik et al. (2017), Brasseur et al. (2017), Tei et al. (2017), Alegria et al. (2020)
Buildings and infrastructure	Damages to buildings and infrastructure due to heavy rain and river flooding and damages to or destruction of coastal settlements and infrastructure on the coast	Higher saving rate of private households (less private consumption), higher accruals in housing sector, more insurance payments and higher insurance costs, more accruals in economic activities (other than housing sector)	GDV and DWD (2019), Bubeck et al. (2020), Fritsch et al. (2021), GDV (2021), Voß et al. (2021), GDV (2022), Trenczek et al. (2022a), Trenczek et al. (2022b)
Trade	Impairment of the supply of raw materials and intermediate products (international); selection	Higher import prices (industry-specific)	Peter et al. (2019), Knittel et al. (2020), Peter et al. (2020), Wolf et al. (2021)
Transport	Impairment of goods traffic via inland waterways (low water)	Changes in the production cost structure (sector-specific)	Hänsel et al. (2020); Nilson et al. (2020)
Health	Effects on the healthcare system	Changes in public expenditure	Karlsson and Ziebarth (2018); Pfeifer et al. (2020)

Source: Own elaboration.

PANTA RHEI allows us to compute indicators from the UN SDGs. The SDG indicator we can compute from the model results are shown in Table 2. They cover aspects of SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), SDG 7

(Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 10 (Reduced Inequalities).

Table 2: Description of SDG - Indicators

SDG		Description of Indicator
1	No Poverty	Change in poverty-oriented public social expenditure in percent
2	Zero Hunger	Change in food prices compared to prices overall in percentage points
3	Good Health and Well-Being	Change in the proportion of the population with high expenditure on health in percentage points
7a	Affordable and Clean Energy	Change in the share of renewable energies in total final energy consumption in percentage points
7b	Affordable and Clean Energy	Change in energy intensity measured as primary energy to GDP in percent
8a	Decent Work and Economic Growth	Change in annual growth rate of real GDP per capita in percentage points
8b	Decent Work and Economic Growth	Change in annual growth rate of real GDP per person employed in percentage points
9	Industry, Innovation and Infrastructure	Change in manufacturing value added to GDP and per capita in percentage points
10	Reduced Inequalities	Change in labour income as a share of GDP in percentage points

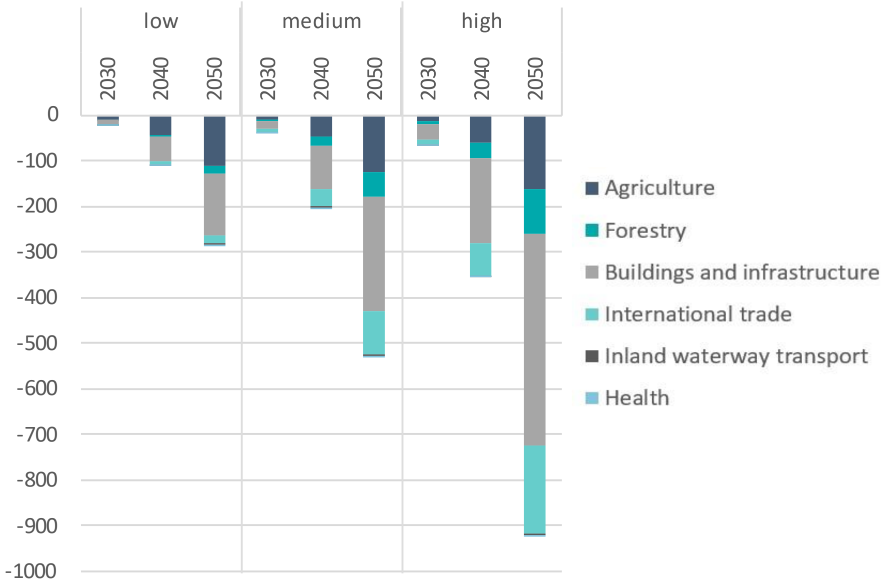
Source: Own elaboration based on https://sdg-indikatoren.de/

3 RESULTS

The costs of climate change were represented as losses in GDP, in deterioration of SDG goals, and in aggravation in inequality.

Figure 2 shows the cumulative changes in real GDP from 2022 to 2050 across the climate impacts under consideration (see Table 1) for the years 2030, 2040 and 2050 for each of the three different climate change scenarios. For the low climate change scenario, the cumulative economic costs added up to 280 billion euros, for the medium climate change scenario to 530 billion euros, and for the high climate change scenario to 910 billion euros. The costs were not distributed evenly over the individual years but increased over time. For the year 2050, this meant a loss in GDP of 0.6% to 1,8%. This is comparable with results from Philip et al. (2021), who calculated cumulative GDP losses of 730 billion euros by 2070. In 2070, the negative effect on GDP amounts to around 70 billion euros or 1.2 percent. The results are also in line with Kemfert (2007), who calculated climate costs for Germany of almost 800 billion euros by 2050, which would correspond to annual growth losses of 0.5 percentage points.

Figure 2: Changes in real GDP, cumulated for 2022 to 2050, in billion Euro



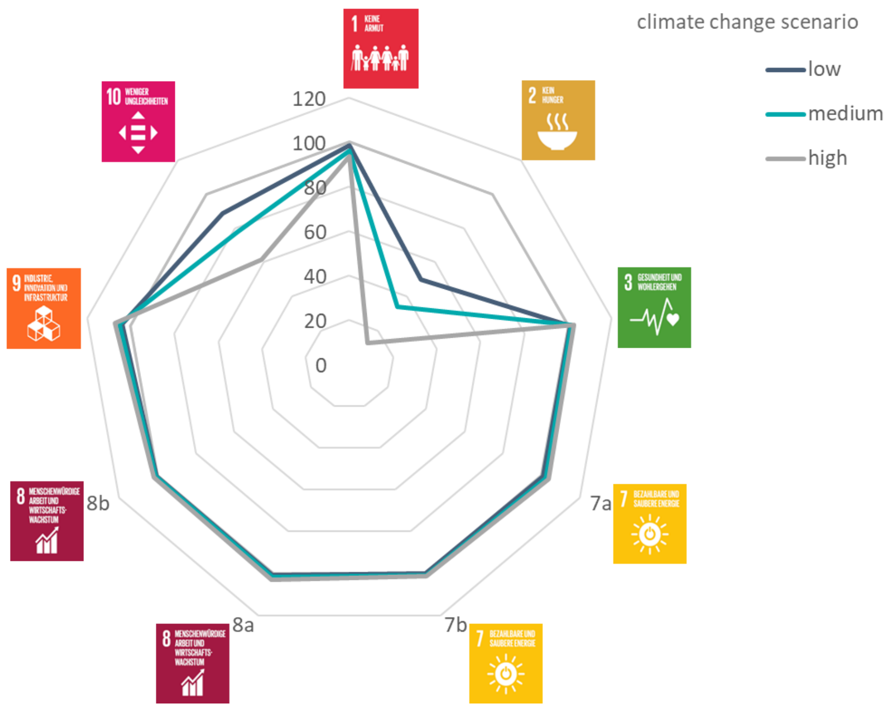
Source: Own calculations based on PANTA RHEI

Climate impacts in the areas of buildings and infrastructure, international trade and agriculture generated particularly high effects on GDP. This was mainly due to the national and international price increases in these sectors, which led to further price reactions via indirect and induced effects and thus developed a high overall impact. In field of agriculture, the assumed price increases associated with global yield losses had clear negative impacts on national economic development. The effects resulted primarily from the decline in exports and private consumption expenditures. Increasing prices raised production costs in the sectors that use agricultural products as intermediate goods and higher food prices and lower employment reduced private consumption expenditures. The effects in the buildings and infrastructure sector resulted from indirect consequences arising from the provisions of insurance companies, reserves in the housing sector, increased saving rates of private households, and increasing reserves of companies for expected damage of climate change. Additionally, the climate change-related impairments and restrictions in international trade and the associated increases in world market prices have substantial negative effects on the national economic development. The effects affect mainly exports and imports, so that the effects within the GDP components are significantly higher. The results are in line with Peter et al. (2021), who assessed the transnational impacts of global climate change for Germany and report losses in GDP in the range of 0.01% to 0.35%. On the other hand, there are climate impacts that did not lead to high macroeconomic costs at first sight, but to high structural changes, which changed the importance of economic sectors and employment needs. This was the case, for example, with the impairment of inland waterway transport due to low water. The affected companies reacted to the disrupted supply connections and changed their supply structure. The more frequent and prolonged inland waterway transport is disrupted, the more likely it is that the changed supply structures will become established.

Having a look at the GDP components in the macroeconomic assessment it can be seen that domestic and foreign demand contribute to the negative effects on GDP, in particular. Both household final consumption expenditure due to stockpiling and increased saving as well as lower export activities have clearly negative deviations from the scenario without climate change. The effect on imports associated with this decline in demand in turn has a dampening effect on GDP and the decline in production causes negative effects on gross fixed capital formation. There were also negative effects on employment investigated. In 2050 employment declined between 0.3% and 0.7% depending on the underlying climate change scenario. In absolute terms this corresponds with a decline in employment of around 320,000 people. This is roughly comparable with the results from Philip et al. (2021), who identified a decline in employment of 470,000 people in 2070.

The costs of climate change also affect the different dimensions of sustainability, so in addition to the analysis of GDP, the consideration of further indicators provide a more comprehensive picture. In particular, the analysis of sustainable development in the context of climate change is of increasing interest (Fuso Nerini et al. 2019). We meet these requirements and try to make the costs of climate change visible also on the socially sustainable level based on selected SDG indicators. Additionally, the effects on inequality will be examined in more detail. Figure 3 shows the deviation in the development of the respective SDG indicators (see Table 2) under the three different climate change scenarios compared to the baseline without additional climate change. The comparison is made between the year 2050 and 2021. The baseline specifies an index value of 100, i.e. values above 100 indicate an improvement in the achievement of the SDGs, below that a deterioration.

Figure 3: Impact of climate change on the achievement of selected SDGs



Source: Own calculations based on PANTA RHEI

A considerable deterioration can be observed for goal 2 “Zero Hunger” and goal 10 “Reduced Inequalities”. In particular because of rising world market prices due to the loss of agricultural yields, food prices rise more sharply than prices overall, leading to a deterioration in the indicator for SDG 2. SDG 10 is represented by the change in the share of labor income in GDP in percentage points. This deterioration results, among other things, from the decline in employment in all climate scenarios.

Table 3 shows the effects on inequality using household income of different household types. In a first step the deviation from average income for three different household types (employed, unemployed, and pensioners) was calculated. In a second step the change in inequality was calculated measured by the percentage deviation from each climate change scenario to the reference scenario.

Table 3: Deviation from average income for different household types in the reference scenario (in %) in 2050 and the percentage deviation from average for the three climate change scenarios

		(self)employed	unemployed	pensioners
Deviation from average income in the reference scenario (in %)		16%	-57%	-15%
Change in inequality (deviation from average) in %				
Climate change scenario	Low	1.6%	0.2%	0.6%
	Medium	2.6%	0.3%	0.8%
	High	4.2%	0.3%	0.7%

Source: Own calculations based on PANTA RHEI

In 2050, in the reference scenario the disposable income of a (self-)employed household is 16% above average, while the disposable income of households in which the main income earner is unemployed or retired is 57% and 15% below the average, respectively. Climate change will further exacerbate this inequality by increasing the difference from the average disposable income for all household types in each climate change scenario. Thus, working households can further increase their positive distance from the average income, while unemployed and retired households move further away from the average income. This is driven by two effects. First, there is a change in the structure of households. Due to the adverse effects of climate change on the economy there are less households in which the main income earner is employed or retired, but more unemployed households and also more self-employed households. Second, the differences in income change between the self-employed and employed households. Due to the more advantageous sector composition in the climate change scenarios, the income of the self-employed is higher than in the reference, while the compensation of employees is lower. Thus, income inequality increases with accelerating climate change.

Fuso Nerini et al. (2019) find that climate change impacts intensify the already existing challenges of sustainable development across the broad range of dimensions addressed by the SDGs. The underlying references for SDG 2 specifically address global impacts on food security and malnutrition. Due to their greater impact, effects on low-income countries are predominantly considered there. For the national targets of high-income countries, it is also recommended to draw on indicators on food security in developing countries as well as on the sustainability of German agriculture and globally sustainable consumption (Holzapfel and Brüntrup 2017). However, Raj et al. (2022) show that food insecurity is also decreasing with climate change in the US and involves poorer households. The underlying references for SDG 10 are also predominantly related to climate justice or climate change impacts on less developed countries (Fuso Nerini et al. 2019), which makes comparison with our results difficult.

4 DISCUSSION

Our results show that the economic costs of climate change may well be very high. At the same time, the results only represent a lower bound as several climate impacts cannot (yet) be sufficiently quantified. The fact that only monetizable impacts of climate change can be taken into account in the model means that costs arising from a loss of biodiversity or quality of life, for example, are neglected. It is therefore very likely that the actual costs will be even higher. Furthermore, the scenario analysis is based on several kinds of uncertainties. First, there are uncertainties regarding the development of climate change and the intensity and frequency of extreme weather events. Second, it remains uncertain where and when climate change-induced extreme weather events occur. However, the specific occurrence is decisive for the extent of the damages. While heat-related events tend to occur over lager areas, heavy precipitation events are usually highly localized.

Third, depending on the climate impact, there are more or less pronounced uncertainties regarding the concrete impacts of climate change on systems and groups, as well as regarding the interactions between climate impacts and the respective responses to them. Fourth, the development of the economy is uncertain, but structural changes in the economy can significantly affect the magnitude of the results. Fifth, uncertainties regarding the quantification of climate impacts remain. Even if there are qualitative descriptions of climate impact chains and interrelations, the quantification in economic terms is associated with assumptions.

Regarding the social dimensions of climate change impacts, the assessment beyond GDP reveals relevant aspects. However, these are initial estimates that should be interpreted with a degree of caution. The analysis carried out here only considered climate impacts and SDG indicators that could be implemented in the model. The findings should therefore be seen as initial assessment and not as a fully comprehensive evaluation. While the indicators for SDG 2 and SDG 10 show a clear deterioration, the other indicators hardly change. Especially for SDG 1 (No Poverty) and SDG 3 (Good Health and Well-Being) it seems questionable that climate change will have no or almost no effects. SDG 1 is represented by the change in poverty-oriented public social expenditure in percent. There is a slight increase in government expenditures in comparison of each climate scenario to the baseline scenario, which means a slight deterioration of the indicator, but compared to the increase of food prices it is much lower. This indicates that households may have to bear the increased costs of living themselves. Thus, there could be an increase in poverty, which cannot be adequately reflected by the indicator used in the model. SDG 3 is represented by the change in the proportion of the population with high expenditure on health in percentage points. That climate change seems to have almost no impact on good health and wellbeing has two reasons: first the climate impact considered and its implementation in the scenario and second the SDG indicator used for representing SDG 3. The considered climate impact includes the increase in heat-related hospital admissions. It is assumed that this leads to an increase in health-oriented government expenditures. There are various other climate change-related impacts on the health system, such as the spread of previously non-prevalent pathogens, that could not yet be included in the analysis but might affect the proportion of the population with high expenditure on health. Additionally, expenditures of private households for health encompasses mainly private insurance payments. Expenditure on statutory health insurance is not included in the consumption expenditure but is deducted from gross income. The higher government payments for heat-related hospital stays are hence not adequately reflected in the indicator.

Finally, the model PANTA RHEI, which is applied in this analysis, is a national model that is well suited for the analysis of national costs of climate change, for instance due to its high level of sectoral detail. However, due to the national focus of the model, global effects via trade and global value chains might not be sufficiently considered. Rather, the effects of climate change on international trade and global labor productivity were included in the model using assumptions regarding import prices. More precisely, the global effects of climate change were represented by sector-specific changes in import prices and affected the production cost structure of industries. For a more in-depth analysis, it would be appropriate here to extend the modeling approach by combining the national model with a global trade model.

5 CONCLUSION

The results show the magnitude of economic costs of climate change and effects beyond GDP under different climate change developments. Depending on the underlying climate change scenario (low, medium and high), the expected costs of climate change sum up to 280, 530 and 910 billion euros for the period from 2022 to 2050, measured in terms of cumulative changes in real GDP. While there are climate impacts such as yield losses in agriculture, damages to buildings and infrastructure and impairment in international trade that lead to high economic costs, there are also other climate impacts such as impairment of goods via inland waterways lead to structural changes in production and the labor market. These values each represent a lower limit, because non-monetarily assessable impacts could not have been assessed by the model-based scenario analysis.

Because climate change not only affects the economy and economic growth but also sustainable development, further indicators have been analyzed. Nine SDG-indicators as well as income inequality were used to reflect further socioeconomic dimensions of climate change impacts. Two of the SDGs (SDG 2 – Zero Hunger and SDG 10 – Reduced Inequalities) were strongly negatively affected. Also, the additional inequality assessment using household income of different household types shows an increase in income inequality. Thus, also from the perspective of social sustainability, the costs of climate change should be assessed critically even in high income countries.

Especially in recent times, it has become clear that crises should not be viewed singularly, as they might overlap and thus possibly amplify each other. This analysis has shown that significant prices changes can result from climate change “alone”. Supply chain disruptions during the Covid-19 pandemic or war-induced reductions of crops supplies from Ukraine already triggered significant price increases and structural changes in the recent past although some of these have been compensated by government programs and subsidies. In the following, it would be necessary to investigate more precisely to what extent crises are amplified and to what extent resilience can also be built up against multiple crises.

With regard to the need for further research, the question of the robustness of the scenario assumptions arises. For some climate change impacts small changes in the assumptions cause quite high changes in effects. In this study, the data of the different climate change impacts were generated model-exogenously based on literature studies. In the future, a linkage with, for example, agricultural models could be aimed at. Furthermore, future research is also needed on the integrated assessment of climate development and socio-economic development. For this purpose, different socioeconomic scenarios based on the Shared Socioeconomic Pathways (SSPs) could also be quantified for the national level and combined with the climate scenarios in the scenario analysis. In addition, socio-economic as well as climatic tipping points could be included in the analysis.

However, even if there is still a need for further improvement in the modeling of climate change impacts and especially in the modeling of climate change adaptation, the results already available show the urgent need for action.

REFERENCES

Ahmann, L., Banning, M. & Lutz, C. (2022): Modeling rebound effects and counteracting policies for German industries. Ecological Economics 197, p. 107432. DOI: 10.1016/j.ecolecon.2022.107432.

Alegria, C., Roque, N., Albuquerque, T., Gerassis, S., Fernandez, P. & Ribeiro, M. M. (2020): Species Ecological Envelopes under Climate Change Scenarios – A Case Study for the Main Two Wood-Production Forest Species in Portugal. Forests 11 (8), p. 880. DOI: 10.3390/f11080880.

Almon, C. (1991): The Inforum Approach to Interindustry Modeling. Economic Systems Research 3 (1), pp. 1–8. DOI: 10.1080/09535319100000001.

Augustynczik, A. L. D., Hartig, F., Minunno, F., Kahle, H.-P., Diaconu, D., Hanewinkel, M. & Yousefpour, R. (2017): Productivity of Fagus sylvatica under climate change – A Bayesian analysis of risk and uncertainty using the model 3-PG. Forest Ecology and Management 401, pp. 192–206. DOI: 10.1016/j.foreco.2017.06.061.

Becker, L., Bernardt, F., Bieritz, L., Mönnig, A., Parton, F., Ulrich, P. & Wolter, M. I. (2022): INFORGE in a Pocket. GWS-Kurzmitteilung 2022/02. https://www.gws-os.com/de/publikationen/gws-kurzmitteilungen/detail/inforge-in-a-pocket.

Beillouin, D., Schauberger, B., Bastos, A., Ciais, P. & Makowski, D. (2020): Impact of extreme weather conditions on European crop production in 2018. Philosophical transactions of the Royal Society of London 375 (1810). DOI: 10.1098/rstb.2019.0510.

Botzen, W. J. W., Martinius, M. L., Bröde, P., Folkerts, M. A., Ignjacevic, P., Estrada, F., Harmsen, C. N. & Daanen, H. A. M. (2020): Economic valuation of climate change–induced mortality: age dependent cold and heat mortality in the Netherlands. Climatic Change 162 (2), pp. 545–562. DOI: 10.1007/s10584-020-02797-0.

Brasseur, G. P., Jacob, D. & Schuck-Zöller, S. (Hg.) (2017): Klimawandel in Deutschland – Entwicklung, Folgen, Risiken und Perspektiven. Springer, Berlin, Heidelberg.

Bubeck, P., Kienzler, S., Dillenardt, L., Mohor, G. S., Thieken, A. H., Sauer, A., Neubert, M., Blazejczak, J. & Edler, D. (2020): Bewertung klimawandelgebundener Risiken: Schadenspotenziale und ökonomische Wirkung von Klimawandel und Anpassungsmaßnahmen – Abschlussbericht zum Vorhaben „Behördenkooperation Klimawandel und -anpassung", Teil 1. Hg. v. Umweltbundesamt. Climate Change 29/2020, Dessau-Roßlau.

Ciscar, J.-C. (2009): Climate change impacts in Europe – Final report of the PESETA research project. Publications Office of the European Union. JRC55391, Luxembourg (Luxembourg).

COACCH (2019): The Economic Cost of Climate Change in Europe – Synthesis Report on Interim Results. Hg. v. Paul Watkiss, Jenny Troeltzsch, katriona mcglade und Michelle Watkiss. Policy brief by the COACCH project. https://www.coacch.eu/wp-content/uploads/2019/11/COACCH-Sector-Impact-Economic-Cost-Results-22-Nov-2019-Web.pdf, last access 17.05.2022.

COACCH (2021): The Economic Cost of Climate Change in Europe: Report on The Macro-Economic Cost of Climate Change in Europe. Policy brief by the COACCH project.

Dellink, R., Chateau, J., Lanzi, E. & Magné, B. (2017): Long-term economic growth projections in the Shared Socioeconomic Pathways. Global environmental change : human and policy dimensions 42, pp. 200–214. DOI: 10.1016/j.gloenvcha.2015.06.004.

Flaute, M., Reuschel, S. & Stöver, B. (2022): Volkswirtschaftliche Folgekosten durch Klimawandel: Szenarioanalyse bis 2050 – Studie im Rahmen des Projektes Kosten durch Klimawandelfolgen in Deutschland. GWS Research Report 2022/02, Osnabrück.

Fritsch, U., Zebisch, M., Voß, M., Linsenmeier, M., Kahlenborn, W., Porst, L., Hölscher, L., Wolff, A., Hardner, U., Schwartz, K., Wolf, M., Schmuck, A., Schönthaler, K., Nilson, E., Fischer, H. & Fleischer, C. (2021): Klimawirkungs- und Risikoanalyse 2021 für Deutschland – Teilbericht 3: Risiken und Anpassung im Cluster Wasser. Hg. v. Umweltbundesamt. Climate Change 22.

Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H. & Milligan, B. (2019): Connecting climate action with other Sustainable Development Goals. Nature Sustainability 2 (8), pp. 674–680. DOI: 10.1038/s41893-019-0334-y.

GDV (2021): Naturgefahrenreport 2021 – Die Schaden-Chronik der deutschen Versicherer. Gesamtverband der Deutschen Versicherungswirtschaft e. V., Berlin.

GDV (2022): Ein Jahr nach der schadenreichsten Naturkatastrophe in Deutschland: Versicherer ziehen Bilanz zur Schadenregulierung. https://www.gdv.de/gdv/medien/medieninformationen/ein-jahr-nach-der-schadenreichsten-naturkatastrophe-in-deutschland-versicherer-ziehen-bilanz-zur-schadenregulierung-85458, last access 29.09.2022.

GDV & DWD (2019): Forschungsprojekt Starkregen – Summary. Hg. v. Gesamtverband der Deutschen Versicherungswirtschaft e.V. und Deutscher Wetterdienst, Berlin.

Hänsel, S., Nilson, E., Patzwahl, R., Forbriger, M., Klose, M. & Krieger, B. (2020): Einflüsse naturgefahrenbeding-ter Streckensperrungen auf überregionale Verkehrsströme – Verkehrsträgerübergreifende Stresstestszenarien für die Region 'Mittelrhein'. Schlussbericht des Schwerpunktthemas Fokusgebiete Binnen (SP-109) im Themenfeld 1 des BMVI-Expertennetzwerks – Schlussbericht des Schwerpunktthemas Fokusgebiete Binnen (SP-109) im Themenfeld 1 des BMVI-Expertennetzwerks. DOI: 10.5675/EXPNHS2020.2020.10.

Holzapfel, S. & Brüntrup, M. (2017): SDG 2 (Zero Hunger) in the context of the German Sustainable Development Strategy: are we leaving the starving behind? Briefing Papers. German Development Institute / Deutsches Institut für Entwicklungspolitik (DIE). 13/2017. https://ideas.repec.org/p/zbw/diebps/132017.html.

IPCC (2018): Global Warming of 1.5°C – An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. With the collaboration of Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani. Cambridge University Press, Cambridge, UK and New York, NY, US.

IPCC (2021): Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Unter Mitarbeit von Valérie Masson-Delmotte, Panmao

Zhai, Anna Pirani, Sarah Connors, C. Péan, Sophie Berger et al. Climate Change, Cambridge, UK, New York, NY, pp. 3–32.

Joint Research Centre (2020): Climate change impacts and adaptation in Europe: JRC PESETA IV final report. Hg. v. L. Feyen, J.C: Ciscar, S. Gosling, D. Ibarreta und A. Soria. Publications Office of the European Union, Luxembourg. DOI: 10.2760/171121.

Karlsson, M. & Ziebarth, N. R. (2018): Population health effects and health-related costs of extreme temperatures: Comprehensive evidence from Germany. Journal of Environmental Economics and Management 91, pp. 93–117. DOI: 10.1016/j.jeem.2018.06.004.

Kemfert, C. (2007): Klimawandel kostet die deutsche Volkswirtschaft Milliarden. Hg. v. DIW. Wochenbericht 11/2007, Berlin.

Knittel, N., Jury, M. W., Bednar-Friedl, B., Bachner, G. & Steiner, A. K. (2020): A global analysis of heat-related labour productivity losses under climate change—implications for Germany's foreign trade. Climatic Change 160 (2), pp. 251–269. DOI: 10.1007/s10584-020-02661-1.

Kolstad, C. D. & Moore, F. C. (2020): Estimating the Economic Impacts of Climate Change Using Weather Observations. Review of Environmental Economics and Policy 14 (1), pp. 1–24. DOI: 10.1093/reep/rez024.

Lehr, U., Flaute, M., Ahmann, L., Nieters, A., Hirschfeld, J., Welling, M., Wolff, C., Gall, A., Kersting, J., Mahlbacher, M. & Möllendorff, C. von (2020): Vertiefte ökonomische Analyse einzelner Politikinstrumente und Maßnahmen zur Anpassung an den Klimawandel. Abschlussbericht. Hg. v. Umweltbundesamt. Climate Change 43/2020, Dessau-Roßlau. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020_11_27_cc_43_2020_politikinstrumente-klimaanpassung.pdf, last access 26.05.2022.

Lehr, U. & Lutz, C. (2020): Macro-econometric and structural models. In: Soytaş, U. & Sarı, R. (Hg.): Routledge handbook of energy economics. Routledge International Handbooks. Routledge, London, New York, pp. 473–481.

Lehr, U., Nieters, A. & Drosdowski, T. (2016): Extreme Weather Events and the German Economy – The Potential for Climate Change Adaptation. In: Leal Filho, W., Musa, H., Cavan, G., O'Hare, P. & Seixas, J. (Hg.): Climate Change Adaptation, Resilience and Hazards. Climate Change Management. Springer International Publishing, Cham, pp. 125–141.

Lesk, C., Rowhani, P. & Ramankutty, N. (2016): Influence of extreme weather disasters on global crop production. Nature 529 (7584), pp. 84–87. DOI: 10.1038/nature16467.

Li, Y., Guan, K., Schnitkey, G. D., DeLucia, E. & Peng, B. (2019): Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. Global Change Biology 25 (7), pp. 2325–2337. DOI: 10.1111/gcb.14628.

Lutz, C., Banning, M., Ahmann, L. & Flaute, M. (2021a): Energy efficiency and rebound effects in German industry – evidence from macroeconometric modeling. Economic Systems Research 34 (3), pp. 1–20. DOI: 10.1080/09535314.2021.1937953.

Lutz, C., Becker, L. & Kemmler, A. (2021b): Socioeconomic Effects of Ambitious Climate Mitigation Policies in Germany. Sustainability 13 (11), p. 6247. DOI: 10.3390/su13116247.

Lutz, C., Flaute, M., Lehr, U., Kemmler, A., auf der Maur, A., Ziegenhagen, I., Wünsch, M., Koziel, S., Piégsa, A. & Straßburg, S. (2018): Gesamtwirtschaftliche Effekte der Energiewende. GWS Research Report 2018/04.

Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K. C., Nendel, C., Gobin, A., Olesen, J. E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takáč, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G. & Kahiluoto, H. (2018): Sensitivity of European wheat to extreme weather. Field Crops Research 222, pp. 209–217. DOI: 10.1016/j.fcr.2017.11.008.

Mönnig, A., Lutz, C., Becker, L., Maier, T. & Zika, G. (2021): Arbeitsmarkteffekte eines klimaneutralen Langfristpfads bis 2030 – Zusammenfassung der Ergebnisse. Kurzstudie im Auftrag der Stiftung Klimaneutralität, Osnabrück.

Ngoma, H., Lupiya, P., Kabisa, M. & Hartley, F. (2021): Impacts of climate change on agriculture and household welfare in Zambia: an economy-wide analysis. Climatic Change 167 (3-4). DOI: 10.1007/s10584-021-03168-z.

Nilson, E., Astor, B., Fischer, H., Fleischer, C., Haunert, G., Helms, M., Hillebrand, G., Labadz, M., Mannfeld, M., Riedel, A., Schulz, D., Bergmann, L., Kikillus, A., Patzwahl, R., Rasquin, C., Schröder, M., Seiffert, R., Stachel, H., Wachler, B., Winkel, N., Höpp, S., Razafimaharo, C. & Rauthe, M. (2020): Beiträge zu einer verkehrsträgerübergreifenden Klimawirkungsanalyse: Wasserstraßenspezifische Wirkungszusammenhänge – Schlussbericht des Schwerpunktthemas Schiffbarkeit und Wasserbeschaffenheit (SP-106) im Themenfeld 1 des BMVI-Expertennetzwerks. DOI: 10.5675/EXPNNE2020.2020.07.

Nordhaus, W. (2013): Integrated Economic and Climate Modeling. In: Dixon, P. B. & Jorgenson, D. W. (Hg.): Handbook of Computable General Equilibrium Modeling, Volume 1A-1B, Bd. 1. Handbook of Computable General Equilibrium Modeling. Elsevier, Oxford, UK, Waltham, USA, pp. 1069–1131.

Nordhaus, W. (2014): Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. Journal of the Association of Environmental and Resource Economists 1 (1/2), pp. 273–312. DOI: 10.1086/676035.

Nordhaus, W. (2019): Climate Change: The Ultimate Challenge for Economics. The American Economic Review 109 (6), pp. 1991–2014. DOI: 10.1257/aer.109.6.1991.

Nordhaus, W. D. (1994): Expert Opinion on Climatic Change. American Scientist 82 (1), pp. 45–51. http://www.jstor.org/stable/29775100.

Nordhaus, W. D. (2017): Evolution of Assessments of the Economics of Global Warming: Changes in the DICE model, 1992 – 2017. National Bureau of Economic Research. Working Paper 23319, Cambridge. DOI: 10.3386/w23319.

Peter, M., Guyer, M. & Füssler, J. (2019): Folgen des globalen Klimawandels für Deutschland – Erster Teilbericht: Die Wirkungsketten in der Übersicht. Hg. v. Umweltbundesamt. Climate Change 20/2019, Dessau-Roßlau.

Peter, M., Guyer, M., Füssler, J., Bednar-Friedl, B., Knittel, N., Gabriel, B., Schwarze, R. & Unger, M. von (2020): Folgen des globalen Klimawandels für Deutschland – Abschlussbericht: Analysen und Politikempfehlungen. Hg. v. Umweltbundesamt. 15/2020.

Peter, M., Guyer, M., Füssler, J., Bednar-Friedl, B., Knittel, N., Wegener, B. G. & Schwarze, R. (2021): The transnational impacts of global climate change for Germany – Abridged version. Hg. v. Umweltbundesamt. Climate Change 03/2021.

Pfeifer, S., Rechid, D. & Bathiany, S. (2020): Klimaausblick Deutschland. Climate Service Center Germany (GERICS). https://gerics.de/productsandpublications/factsheets/index.php.de, last access 19.05.2022.

Philip, P., Ibrahim, C. & Hodges, C. (2021): Germany's turning point – Accelerating new growth on the path to net zero. Hg. v. Deloitte Global.

Raj, S., Roodbar, S., Brinkley, C. & Wolfe, D. W. (2022): Food Security and Climate Change: Differences in Impacts and Adaptation Strategies for Rural Communities in the Global South and North. Frontiers in Sustainable Food Systems 5. DOI: 10.3389/fsufs.2021.691191.

Ren, X., Weitzel, M., O'Neill, B. C., Lawrence, P., Meiyappan, P., Levis, S., Balistreri, E. J. & Dalton, M. (2018): Avoided economic impacts of climate change on agriculture: integrating a land surface model (CLM) with a global economic model (iPETS). Climatic Change 146 (3-4), pp. 517–531. DOI: 10.1007/s10584-016-1791-1.

Schlenker, W. & Roberts, M. J. (2009): Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proceedings of the National Academy of Sciences of the United States of America 106 (37), pp. 15594–15598. DOI: 10.1073/pnas.0906865106.

Stöver, B., Flaute, M. & Reuschel, S. (2022): Forschungsstand und Literatur zu den volkswirtschaftlichen Folgekosten des Klimawandels in Deutschland – Studie im Rahmen des Projektes Kosten durch Klimawandelfolgen in Deutschland. Forschungsstand. GWS Research Report 2022/01, Osnabrück.

Tei, S., Sugimoto, A., Yonenobu, H., Matsuura, Y., Osawa, A., Sato, H., Fujinuma, J. & Maximov, T. (2017): Tree-ring analysis and modeling approaches yield contrary response of circumboreal forest productivity to climate change. Global Change Biology 23 (12), pp. 5179–5188. DOI: 10.1111/gcb.13780.

Tigchelaar, M., Battisti, D. S., Naylor, R. L. & Ray, D. K. (2018): Future warming increases probability of globally synchronized maize production shocks. Proceedings of the National Academy of Sciences of the United States of America 115 (26), pp. 6644–6649. DOI: 10.1073/pnas.1718031115.

Trenczek, J., Lühr, O., Eiserbeck, L. & Leuschner, V. (2022a): Schäden der Sturzfluten und Überschwemmungen im Juli 2021 in Deutschland – Eine ex-post-Analyse. Projektbericht "Kosten durch Klimawandelfolgen". Hg. v. Bundesministeriums für Wirtschaft und Klimaschutz.

Trenczek, J., Lühr, O., Eiserbeck, L. & Sandhövel, M. (2022b): Übersicht vergangener Extremwetterschäden in Deutschland – Methodik und Erstellung einer Schadensübersicht. Projektbericht „Kosten durch Klimawandelfolgen" – AP 2.1. Hg. v. Bundesministeriums für Wirtschaft und Klimaschutz.

UBA (Hg.) (2021): Klimawirkungs- und Risikoanalyse 2021 für Deutschland – Kurzfassung. Climate Change 26/2021.

Ulrich, P., Bernardt, F., Parton, F., Sonnenburg, A. & Többen, J. (2022): Das neue LÄNDER-Modell – Beispielszenario zum Ausbau der Photovoltaik. Hg. v. Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS). GWS Discussion Paper 2022/02, Osnabrück. https://www.gws-os.com/de/publikationen/alle-publikationen/detail/das-neue-laender-modell.

Voß, M., Kahlenborn, W., Porst, L., Dorsch, L., Nilson, E., Rudolph, E. & Lohrengel, A.-F. (2021): Klimawirkungs- und Risikoanalyse 2021 für Deutschland – Teilbericht 4: Risiken und Anpassung im Cluster Infrastruktur. Hg. v. Umweltbundesamt. Climate Change 23/2021.

Vrontisi, Z., Charalampidis, I., Lehr, U., Meyer, M., Paroussos, L., Lutz, C., Lam-González, Y. E., Arabadzhyan, A., González, M. M. & León, C. J. (2022): Macroeconomic impacts of climate change on the Blue Economy sectors of southern European islands. Climatic Change 170 (3-4). DOI: 10.1007/s10584-022-03310-5.

Wang, J., Vanga, S. K., Saxena, R., Orsat, V. & Raghavan, V. (2018): Effect of Climate Change on the Yield of Cereal Crops: A Review. Climate 6 (2), p. 41. DOI: 10.3390/cli6020041.

Wolf, M., Ölmez, C., Schöntaler, K., Porst, L., Voß, M., Linsenmeier, M., Kahlenborn, W., Dorsch, L. & Dudda, L. (2021): Klimawirkungs- und Risikoanalyse für Deutschland 2021 – Teilbericht 5: Klimarisiken in den Clustern Wirtschaft und Gesundheit. Hg. v. Umweltbundesamt. Climate Change 24/2021, Dessau-Roßlau. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_5_cluster_wirtschaft_gesundheit_bf_211027_0.pdf.

Zika, G., Hummel, M., Schneemann, C., Studtrucker, M., Kalinowski, M., Maier, T., Krebs, B., Steeg, S., Bernardt, F., Krinitz, J., Mönnig, A., Parton, F., Ulrich, P. & Wolter, M. I. (2021): Die Auswirkungen der Klimaschutzmaßnahmen auf den Arbeitsmarkt und die Wirtschaft. Forschungsbericht 526/5.

Zika, G., Schneemann, C., Zenk, J., Kalinowski, M., Maier, T., Bernardt, F., Krinitz, J., Mönnig, A., Parton, F., Ulrich, P. & Wolter, M. I. (2022): Fachkräftemonitoring für das BMAS – Mittelfristprognose. Forschungsbericht 602.