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Comparison of macroeconomic developments in ten scenarios of energy system transformation in Germany: National and regional results

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Abstract

Background: Different strategies have been proposed for transforming the energy system in Germany. To evaluate their sustainability, it is necessary to analyze their macroeconomic and distributional effects. An approach to do this analysis in an integrated consistent framework is presented here.

Methods: Comparing ten energy transition scenarios with emission reduction targets by 2050 of 80% or 95%, respectively, allows evaluating a broad range of energy system transformation strategies with respect to the future technology and energy carrier mix. For this purpose, an energy system model and a macroeconometric model are combined, thus re-modeling the unified scenarios. An important extension of the model was concerned with the integration of synthetic fuels into the energy-economy model. One focus besides the overall macroeconomic assessment is the regional analysis. For this purpose, own assumptions on the regional distribution of the expansion of renewable energies were developed.

Results: The effects on gross domestic product (GDP) and employment are similar on average from 2030 to 2050 across the scenarios, with most of the more ambitious scenarios showing slightly higher values for the socioeconomic variables. Employment in the construction sector shows the largest effects in most scenarios, while in the energy sector employment is lower in scenarios with high energy imports. At the regional level, the differences between scenarios are larger than at the national level. There is no clear or stable regional pattern of relative loss and profit from the very ambitious transformation, as not only renewable energy expansion varies, and hydrogen strategies enter the scene approaching 2050.

Conclusions: From the relatively small differences between the scenarios, it can be concluded that, from a macroeconomic perspective, it is not decisive for the overall economy which (supply side) strategy is chosen for the transformation of the energy system. More effort needs to be put into improving assumptions and modeling approaches related to strategies for achieving the final 20% CO₂ reduction, for example the increasing use of hydrogen.

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Keywords: Energy scenario, Macroeconomic modeling, Energy system modeling, Impact assessment, Regional impacts, Social indicators, Sustainability, Renewable energy, Hydrogen strategies

Background

Many studies describe development paths for achieving large reductions in greenhouse gas emissions in the short to medium term, and climate neutrality in the long term. At a global level, Gielen et al. [1] give a recent overview. The findings are that energy transition scenarios converge in the main strategies but diverge in some of the details. The role of renewable energy under the different scenarios and the need for electrification seem to be mainly agreed upon across international scenarios, while the role of bioenergy, carbon capture and storage (CCS) and carbon capture and utilization (CCU) is debated [2].

For Germany, the picture is similar, with a focus on different technologies and different implementation speed, depending on the level of ambition of the respective scenario [3]. Even scenarios achieving the targets in 2050 do so under different technology pathways, speeds, and energy mixes [4, 5].

While sustainability analysis needs to go beyond the mere megawatt and cost debate and increasingly focuses on coupling of models [6, 7], the socio-economic dimension is featuring highly, also in the just transition debate. Next to the macroeconomic indicators such as GDP and employment, structural change and distribution aspects increasingly enter the public debate [see, e.g., 8, 9]. Social aspects need to be addressed to make the energy transition just and inclusive and increase acceptance in the population.

Along the economic dimension, single scenario analyses comparing more ambitious scenarios to less ambitious business-as-usual (BAU) cases or a counterfactual scenario often show positive effects for gross domestic product (GDP) and employment in Germany [10–12]. Similar to the present analysis, Hartwig et al. [13] couple a bottom-up energy model with a macroeconomic model to estimate the effects of an ambitious energy policy on GDP and employment. In contrast, however, this study does not compare various energy systems with different energy mixes, but rather a stronger enforcement of efficiency development with a baseline scenario. Here, as well, the macroeconomic effects are positive. At the EU level, transformation scenarios are also assessed in terms of their socioeconomic consequences by soft linking energy system models with macroeconomic models [14, 15]. In the study by Fragkos et al. [14], there are some small negative effects on GDP, while employment is slightly higher than in the

reference development. Vrontisi et al. [15] point out that the direction of economic effects varies depending on the political conditions: thus, negative economic effects arise for the EU member states when asymmetric ambitions of climate policies exist. In contrast, economic benefits in the EU can be achieved if there are globally coordinated efforts to achieve the Paris climate goals. An integrated assessment of EU-wide energy transition pathways provides a combined evaluation of environmental and economic aspects. In this way, Nieto et al. [16] analyze a large number of scenarios concluding that only a post-growth scenario can achieve emissions reduction targets without negative impacts on employment.

These scenario comparisons are undertaken with different models and under different framework assumptions, making the comparison difficult. To create a more comprehensive picture, however, a consistent comparison of the economic outcomes in a consistent framework is much needed. It will also contribute to the wider picture of measuring the full sustainable footprint of different pathways of the energy transition to enhance public acceptance. Moreover, it answers the question if the socioeconomic benefits of an ambitious energy transition pathway differ largely, or if the decision for the energy transition can be made rather independently of socioeconomic indicators, as long as ambitious targets are set and reached. If the modeling framework can solve and produce results annually, socioeconomic results along the pathway, such as effects of earlier or later investment in certain technologies can be included in the analysis.

To contribute to this discussion on economic and distributional effects of energy transition and sustainability assessment, we compare ten different already published energy transition scenarios, all assuming a reduction of CO₂ emissions by at least 80% relative to 1990 in 2050. The methodological challenge is to harmonize assumptions across these different works in the literature, to enable this comparison across scenarios and provide meaningful differences. The joint assumption is that the energy transition as such has been decided [17, 18], and the sustainability analysis helps comparing the different pathways to attain the targets. Therefore, the technology mix in the future energy system is the crucial distinguishing feature in each scenario. There are scenarios with a focus on synthetic fuels or with a particularly large amount of renewable

electricity and storage. The expansion of renewable energy (RE) and the importance of synthetic fuels varies, as does the role of energy imports.

Socioeconomic outcomes differ along with different investment pathways, different price regimes and other differences in drivers. To compare these outcomes, we apply the macroeconomic simulation model PANTA RHEI, which is the environmentally extended version of the simulation and forecasting model INFORGE [19]. Besides the comprehensive economic core, the energy sector, and emissions as well as transport and housing are modeled in detail. This paper thus presents the simulation results of the German economy under ten energy transition scenarios. The output of this analysis are realizations of a set of economic indicators for the ten scenarios to assess macroeconomic effects on the national and regional scale. These results were used in further sustainability assessments of energy transitions [20]. According to a comprehensive review of the methods, measures and issues of the sustainability assessment of energy production compiled by Turkson et al. [21], economic indicators feature less often in these assessments. The results presented in the following try to address the gap. In addition, Turkson et al. [21] stress the importance to address different levels of geographic scale in the analysis. Besides drawing a more comprehensive picture, a regional analysis helps to share insights into the regional outcomes of the energy transitions, and hence increase acceptance on this level.

Regional actors need to be involved in developing solutions for transformation, which in turn requires a sound understanding of issues of regional distribution and impacts [22, 23]. Social and distributional aspect are often blurred if the analysis stops at the national level. Several studies assess regional effects of an energy system transformation in Germany. Sievers et al. [10] compare an energy transition scenario with a reference development until 2030. They conclude that the eastern federal states and generally coastal states would have the highest positive deviations in relative terms. Changes in the electricity market are the main reason for the regional differences. Ulrich et al. [24] use the scenarios for the German energy transition developed in Lutz et al. [11] for a model-based regional analysis until 2040. Here, as well, many German states in the north and east show particularly high positive deviations. No systematic comparison between different ambitious transformation paths until 2050 has yet been undertaken. In studies on the impacts of an energy transition, regional distribution aspects at the subnational level too often are ignored and not addressed. To bridge this gap, a modeling framework was developed here, which allows evaluating of long-term economic effects for 13 regions. We particularly

address which regional effects and regional differences can be expected for selected transformation strategies. The results contribute to the debate on just transition policies and provide valuable quantitative input for decision makers and regional stakeholders alike.

The paper starts in the methodological section with a description of the energy system, the macroeconomic modeling and how the models interact. In addition, the method of regionalization is outlined. The results are presented in the subsequent section: after showing the results of the energy system modeling and the macroeconomic effects, the paper turns to the regional dimension of impacts of an energy transition. At the end, based on the obtained findings, the conclusions are drawn.

Methods

To answer the questions outlined above, a combination of different models and data compilations has been employed (Fig. 1). The energy system model translates scenarios from the literature to a comparable data set, by harmonizing across assumptions of GDP, labor force, population, the level of energy efficiency and other indicators enabling a *ceteris paribus* comparison where only the characteristic elements of each scenario drive results. These harmonized energy system scenarios feed the macroeconomic assessment with the model PANTA RHEI. To perform regional analyses, key variables of the harmonized scenarios need to be regionalized using selected indicators. These regionalized scenarios enable the subnational analysis of value creation and jobs in a regional model coupled with the national macroeconomic model.

Techno-economic energy system modeling

Macro-economic impacts of national transformation strategies are based on scenario results from the harmonized re-modeling of different published transition scenarios for Germany [11, 25–32]. The scenarios describe the transformation of the entire energy system (electricity, heat, transport) in Germany up to 2050. Details on the selection process can be found in Naegler et al. [6], Additional file 1: Table S1 lists the underlying original studies. Scenarios I–V describe moderately ambitious strategies to reduce direct energy-related CO₂ emissions by 80% until 2050, whereas the highly ambitious scenarios VI to X reach an emission reduction of at least 95%. Sector-specific defossilization strategies were identified from the original studies, i.e., market shares of climate-friendly technologies in the end-use and conversion sectors. Subsequently, these supply side strategies were set as boundary conditions for a harmonized remodeling of the scenarios: drivers such as development path for the economy (exports), population, the development of useful energy demand and transport services, etc., were

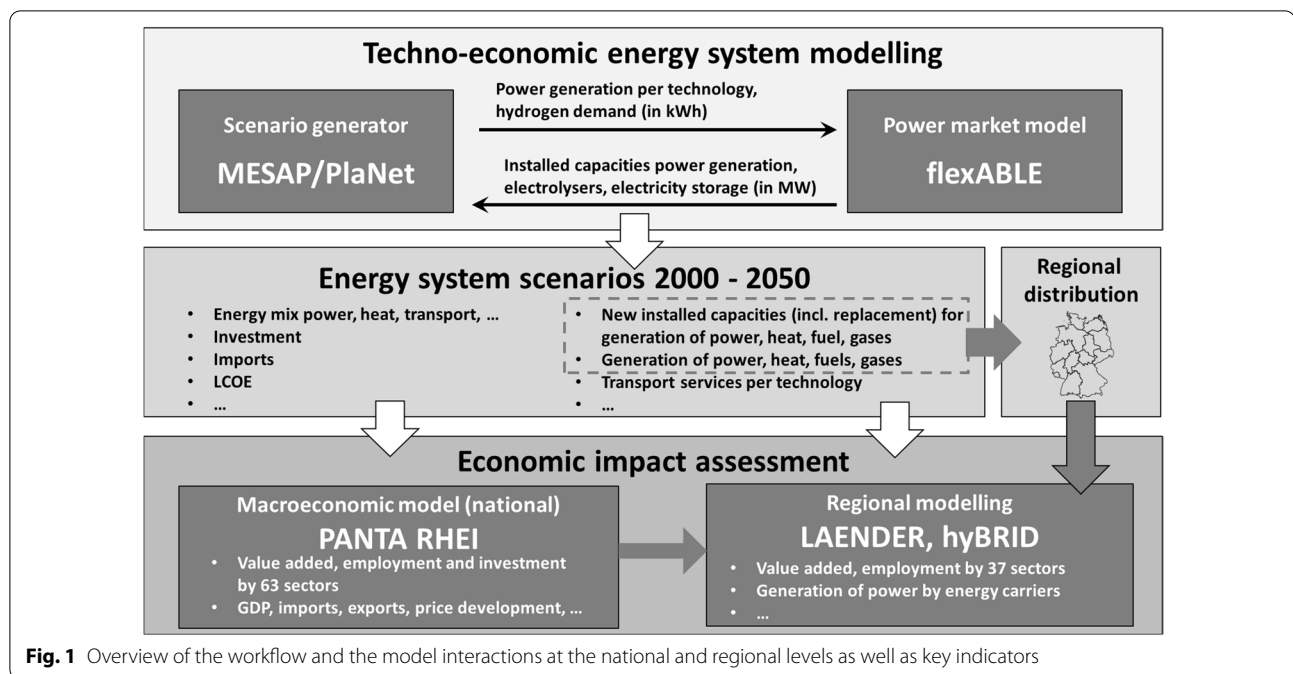


Fig. 1 Overview of the workflow and the model interactions at the national and regional levels as well as key indicators

held identical in all remodeled scenarios. In this way, the essence of the technical strategies of the original studies can be preserved. At the same time, the different studies are made comparable, as different boundary conditions (e.g., population and GDP development) are harmonized and biases between the scenarios due to different boundary conditions are avoided.

The energy system model (accounting framework) MESAP [33, 34] and the electricity market simulation model flexABLE [35] were used for the re-modelling. MESAP is an accounting framework for the German energy and transport system, mainly used for developing of backcasting scenarios until 2050 in annual to 5-yearly time steps. In MESAP, the variables that centrally determine the development of the energy system (such as energy intensities and market shares of different energy and transport technologies) can be specified exogenously. Therefore, MESAP is very well suited for a harmonized re-modelling of existing scenarios. MESAP includes a wide variety of technologies, in particular for the generation of power, heat, and fuels from renewable sources. In addition to complete energy balances, MESAP also calculates installed capacities for energy conversion technologies, as well as investments, system costs, etc. A more detailed description of MESAP can be found in the Additional file 1 (Sect. 2.1 and Additional file 1: Fig. S1).

FlexABLE is an agent-based electricity market simulation model. The model follows a bottom-up approach and includes main types of generation assets such as thermal power plants, variable renewable

generators, and storage units. These assets, represented by agents, can participate in both an energy exchange market and a control reserve market. In addition, eligible power plants capable of heat co-generation, such as coal and gas power plants, can participate in a regional district heating market. The model calculates market results and the corresponding plant dispatch in a 15 min time resolution.

Here in this approach, MESAP is used to calculate complete annual energy balances for Germany for the conversion and end-use sectors. flexABLE then takes MESAP results and verifies or calculates capacity factors and installed capacities of flexible power generators, energy storages units, and electrolyzers. In the next step, MESAP integrates the flexABLE results and calculates annual gross new and decommissioned capacities for all relevant system technologies (including cars and trucks).

Finally, results for economic indicators such as the annual investments in new technologies, capital, operating and maintenance costs resulting from new installations and existing plants, levelized costs of electricity, import quotas, and total system costs, are determined and exported to the macroeconomic model (see section 'PANTA RHEI'). They define the economic dimension of the energy system transformation and are exogenous inputs to PANTA RHEI. Note that for the transport sector, only fuel costs, but no capital costs are considered. More details on scenario re-modelling and model coupling between energy system models and the macro-economic model can be found in Naegler et al. [6].

Energy system modeling results were used as boundary conditions for the macroeconomic calculations with PANTA RHEI. In addition to energy variables, economic scenario results such as investments in the expansion of renewable energy technologies are decisive for macroeconomic assessment. These inputs from MESAP are exogenously fed into PANTA RHEI, placing the energy system part in a macroeconomic context.

Regional distribution

The regional distribution of environmental, social and economic impacts of an energy scenario is relevant for a sustainability assessment, because larger regional inequalities are usually not preferred, and a good regional balance of effects is associated with a just transition [23, 36]. Although political questions of equity and balancing of interests are related to just transition, these assumptions are not integrated and discussed in the remodeled scenarios. Therefore, three different distribution keys for the expansion of renewable energies were used to elaborate different aspects and criteria of allocation. The regional level modelled are the German federal states. Distribution keys and evaluation were based on 13 regions, as the three city states Berlin, Hamburg and Bremen were merged with respective territorial states Brandenburg, Schleswig–Holstein and Lower Saxony.

For new capacities in wind onshore and solar photovoltaic (PV), which will see the largest expansion in all considered scenarios, three different regionalization approaches are considered for both capacity and investments from 2020 onwards, to allow for a sensitivity analysis. The different approaches are selected to represent technical criteria, current planning strategy and social criteria separately. Investments are solely based on capacity expansion, which leads to a slight inaccuracy, neglecting repowering. The three selected distribution criteria are:

- Distribution according to the technical potentials for respective technologies
- Distribution according to the National Grid Development Plan for power
- Distribution according to social criteria to include the aspect of promoting structurally weak regions

For renewable power sources that face a small expansion in all scenarios, such as biomass, hydro and geothermal energy, the expansion was allocated according to the current distribution as considered in the model, based on data from the national renewable energy agency in Germany [37]. To harmonize the developing paths from the base year onto 2050, some adjustments and further assumptions were applied. The capacity of PV and wind

for each year up to 2050 and in each of the federal states results from the respective existing capacity and the new installation. Thus, the model applies the current distribution of capacities based on AEE [37] up to 2019, consistent with the other renewables. New wind offshore installations are allocated to the three coastal regions Niedersachsen–Bremen (59%), Schleswig–Holstein–Hamburg (24%) and Mecklenburg–Vorpommern (16%), based on a social criteria distribution, described below.

The distribution according to the technical potential considers the availability of solar and onshore wind sources. The total technical potentials are taken from a comprehensive potential study for the German federal states [38]. We calculate shares of the national potential of installable capacity for each region (Table 1). Federal states with a high share of the potential record an equally high share of new installations per year. This target distribution in 2050 gradually evolves from the current distribution of existing capacity.

The distribution of PV and wind onshore according to the National Grid Development Plan for power (GRDP) was adapted from the German transmission system operators [39]. The regional distribution assumptions in the GRDP were generally prepared in three steps, which are the mapping of existing plants, analysis of technical and yield potential, and modelling of the new installations. The new installations of PV and wind onshore plants were calculated from the difference between the total installation in the target years (in the study year 2030 and 2035) and the existing installation (for PV in 2017, for wind onshore in 2016). According to the study, the shares of each technology per state hardly change over the years despite growing capacities. For this reason, it is

Table 1 Distribution of PV and wind potentials in Germany based on AEE [37]

Capacity potential	Wind onshore (%)	PV (%)
Baden–Württemberg	11	10
Bavaria	20	8
Brandenburg and Berlin	7	13
Hesse	7	6
Mecklenburg–Vorpommern	6	13
Lower Saxony and Bremen	14	14
North Rhine–Westphalia	10	15
Rhineland–Palatinate	6	6
Saarland	1	1
Saxony	5	4
Saxony–Anhalt	4	4
Schleswig–Holstein and Hamburg	6	5
Thuringia	4	3

assumed that the shares of new installations per state in 2035 remain the same until 2050.

The distribution according to social criteria is the result of a combination of six indicators. The number of unemployed is the primary distribution criterion and it is multiplied by a factor resulting from the combination of normalized individual indicators (see Table 2): labor productivity (producing industries), subsidies paid from the structural funds, employment in lignite coal mining, the share of the construction sector in the region and the gross employment from renewable energy expansion. The latter distinguishes existing employment in the wind and PV sectors, to generate specific distributions. The social distribution should reflect concentration of existing energy-related jobs (both conventional and RE) and favor structurally weak regions. Each indicator has a weight to reflect the content importance and generate a realistic but more contrasting regional distribution compared to the other allocation schemes.

Figure 2 shows the distribution of new installed capacities according to the three distribution keys. The shares of new installations for onshore wind energy differ more from distribution of the population than those for PV. It becomes obvious that the GRDP distribution in general is very similar to that according to natural potentials. For wind energy, the GRDP sees much more expansion share in Lower Saxony and less in Schleswig–Holstein. The distribution according to social criteria is a more contrasting assumption. Note that fossil-fuel power plant decommissioning was not performed using region-specific assumptions. The deconstruction is proportional to the region-specific inventory in the base year.

PANTA RHEI

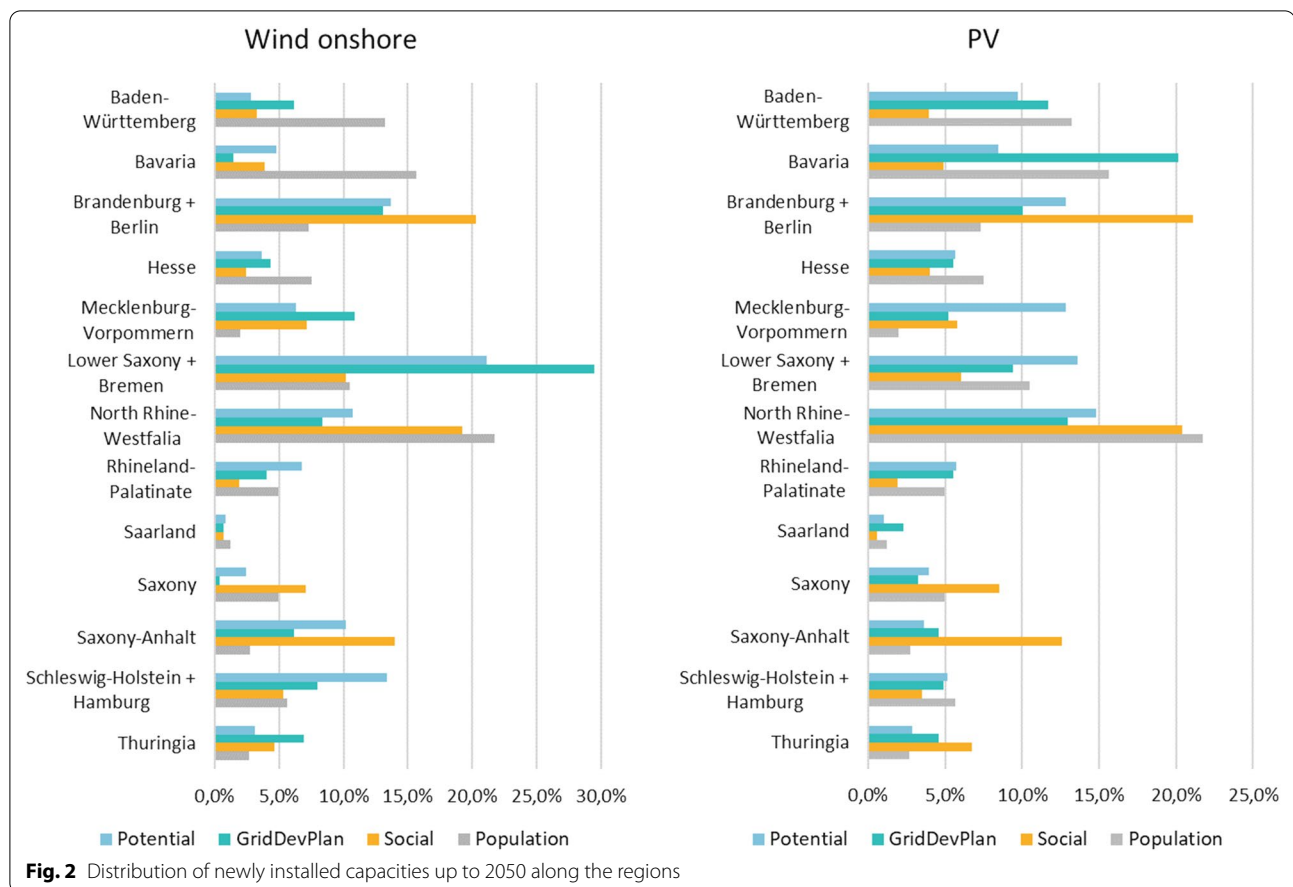
In line with the United Nations Agenda 21, the economic dimension is an important element for a comprehensive sustainability assessment [40]. Indicators proposed there, such as employment–population ratio,

investment share in GDP, or expenditure on research and development, emphasize that securing jobs, maintaining the investment capability of companies and the government, and the long-term stability of the economy characterize a sustainable development from the economic perspective. Thus, economic indicators are also part of the sustainability assessment of energy systems, as included in the analyses of, for example, Afgan et al. [41] and Rösch et al. [42]. To determine the macroeconomic effects of the energy transition, the simulation model needs to reflect the responses of the economy to changes in the energy system. The energy system is strongly embedded in almost all areas of the economy, which means that the energy transition impacts the economy at many points. In this context, the different effects cannot be calculated separately, but the feedback and second round effects as well as interactions must be included in a consistent framework of the entire economy with all its actors [43].

The analysis is based on results from the macro-economic input–output model PANTA RHEI, which covers not only the German energy sector, but the overall economy with all its linkages. The long-term simulation model allows analyses to be carried out up to 2050, calculated annually. The latter is utterly relevant to compare different pathways towards the targets of the energy transition. Annual outcomes influence the acceptance and cannot be mapped with other modeling approaches, such as CGEs. PANTA RHEI was most recently used to estimate the socio-economic effects of the German Climate Change Act and alternative target paths [12] and to model rebound effects in the energy consumption of industries [44]. The model's philosophy and properties as well as its applications are summarized in Lehr, Lutz [45]. A short overview of the model can be found in the Additional file 1: (Sect. 3.2 and Additional file 1: Fig. S2) as well as on <https://www.gws-os.com/en/energy-and-climate/models/detail/panta-rhei>.

Table 2 Indicators combined for the distribution by social criteria, specific weights and data sources

Indicator	Weight	Source
Number of unemployed	Primary key	Federal Employment Agency
Labor productivity	0.25	National accounts of the federal states
Subsidies paid from the structural funds	0.2	Federal Institute for Research on Building, Urban Affairs and Spatial development (2018): Indikatoren und Karten zur Raum- und Stadtentwicklung (INKAR)
Employees in lignite coal mining	0.15	Federal Ministry for Economic Affairs and Energy (2018): Der Bergbau in der Bundesrepublik Deutschland—Bergwirtschaft und Statistik 2016
Share of construction sector in region	0.2	National accounts of the federal states
Gross employment from renewable energy expansion 2016 (Wind energy or PV)	0.2	Ulrich and Lehr (2018): Erneuerbar beschäftigt in den Bundesländern



The macroeconomic core of the energy-economy model PANTA RHEI comprises national accounts and input–output tables [46], leading to disaggregation to at least 63 sectors or commodity groups. Econometric estimation of behavioral equations determines the model's parameters. The model is solved annually in an iterative process and does not emphasize either the supply or demand side [19]. The comprehensive economic core is complemented by energy and environment modules. The energy module contains energy balances [47], satellite balances for renewable energy [48], and energy prices [e.g., 49], as well as energy-specific behavioral equations. New energy sources such as power-to-X technologies are not yet explicitly contained in the statistics, but highly relevant for future scenarios. Therefore, the data structures must be extended for modeling future developments. A proposal for integrating these energy sources into energy balances can be found in Lehr et al. [50].

The energy module shows a multidimensional linkage with the economic core through trade, investment, and prices. To reflect the particular structure of renewable energy and energy efficiency investment, which is crucial for any energy transition, technology-specific investment

converters are used. These cost structures are based on surveys, and they use the economic sector classification NACE [51] applied throughout the model [52, 53].

Regional modeling

The macroeconomic effects determined by comparing scenarios might show only minor deviations for aggregated indicators. At the regional level, however, the effects can be significantly larger, as the conventional energy sector, investment goods production and renewable energy potentials are concentrated [54, 55]. The LÄNDER model is used to analyze and project structural changes at the level of the 16 federal states of Germany [see 56]. It is directly linked to the national model PANTA RHEI and uses the sectoral results for value added and employment determined there at the regional level. The model enables the analysis of different simulation scenarios at the federal state level. In the modeling, the regional labor markets (number of employed persons and employees), gross value added and indicators of wage and salary development are modelled at the level of 37 economic sectors. In addition, the effects of a selection of intermediate inputs are represented at the regional level.

In the version used to analyze the energy system transformations, further links between the regional economic and energy systems were established [24].

The comprehensive model thus enables the analysis of regional effects of different transformation paths and considers the entire economy of the federal states with their specific structures. However, such an analysis requires explicit assumptions on the design of the transformation in the regional context. The default configuration for the comparison of developments between the ten scenarios is the distribution along the natural potentials. For the scenarios I and VI, distributional effects were examined using the alternative regional distribution keys, namely, ‘GRDP’ and ‘social indicators’.

A large share of the value added created from the investment in the expansion of renewable energies is generated by the production of the systems in Germany. Depending on the technology, a substantial share of the direct and indirect demand effects is also attributable to on-site installation. Thus, the demand associated with the investment is significantly redistributed spatially compared to a proportional allocation. Based on the findings in Ulrich, Lehr [57, 58] and the model used there, we analyze the effects of this redistribution in a sensitivity analysis. The used model—here referred to as hyBRID—is an input–output model with an integrated spatial reallocation algorithm [see 59, 60]. The model allocates direct demand by detailed data on RE expansion and productions sites as well as indirect effects by a regional representation of input–output tables. In addition to techno-economic data sets, detailed information on the production locations of the RE sector as well as specific

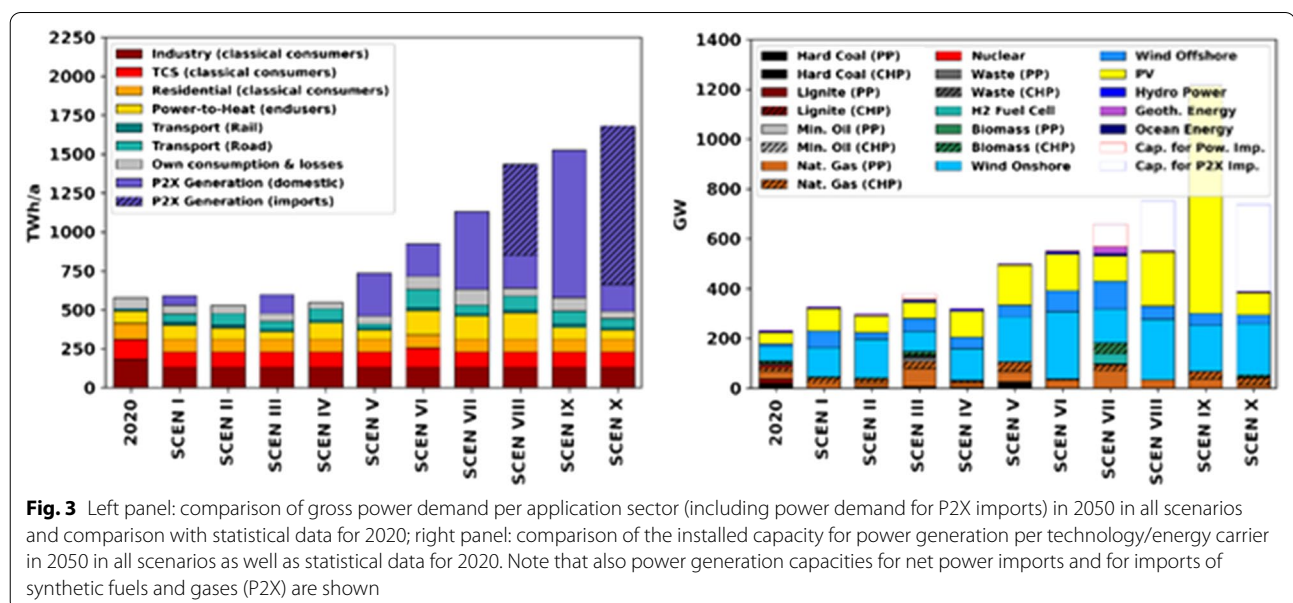
structures of the 16 federal states are stored as essential bases of the model. In this model framework, scenario VI was compared with scenario I and deviations were implemented in the composite model PANTA RHEI-LÄNDER. The results—the redistribution by additional regional demand from investment—is integrated in the synthesis of regional impacts into the section with the regional results. It reflects the potential additional effect from the specific structure of the German RE manufacturing market in the present.

Results

Outline of the energy system transformations

In the following section, we summarize some central results from the scenario modeling. A detailed documentation of the results can be found on <https://zenodo.org/record/5993177> (Zenodo), and <https://zenodo.org/record/5992432>.

Figure 3 (left panel) shows the gross power demand in 2050 in the different scenarios, differentiated by application. It can be seen that the gross power demand in the moderately ambitious scenarios I–V (between 528 and 598 TWh in 2050) is similar to today’s power demand (577 TWh in 2020), although new applications—in particular road transport and power-to-heat, but also synthetic fuels and gases (P2X)—contribute increasingly to the demand. The highly ambitious scenarios SCEN VI–IX are characterized by a significantly higher gross power demand (between 924 TWh in SCEN VI and almost 1700 TWh in SCEN X), mainly due to a higher demand for synthetic fuels and gases (P2X), along with a higher degree of direct electrification of road transport and



heat. In SCEN VIII and SCEN X, a significant share of synthetic fuels and/or gases are assumed to be imported for Germany, increasing the power demand abroad significantly.

Figure 3 (right panel) shows the resulting capacities for power generation, which broadly follow the power demand. PV, wind onshore and wind offshore provide the bulk of power generation, but the scenarios differ significantly with respect to the share of these technologies in total installed power generation capacity. Estimates for the installed capacity of PV range between 64 and 913 GW, for wind onshore between 81 and 267 GW, and wind offshore between 26 and 114 GW. The import of electricity and P2X requires significant installed capacities abroad in some scenarios (particularly pronounced in SCEN VIII and SCEN X).

It is noticeable that the range of possible solutions for the energy system is significantly higher in the case of the very ambitious scenarios SCEN VI–SCEN X than in the case of SCEN I–SCEN V which achieve only 80% CO₂ reductions. The wider spread of results for the 95% scenarios illustrates the higher uncertainty as to how the final 15–20% CO₂ emission reductions can be achieved. An 80% reduction in GHG emissions is largely achievable

with technologies that are very advanced today. However, the path to (near) net zero emissions requires the use of new energy carriers (such as H₂ or synthetic liquid fuels) and new technologies (such as H₂ for steel production) in many areas, especially in industrial processes and the transportation sector. Furthermore, the advanced electrification of heat and transport requires much higher efforts for the system integration of all technologies. In addition, the import of synthetic energy carriers plays an increasingly important role. For all these options, however, there are still great uncertainties regarding costs, potentials, acceptance, and other constraints, so that the ideas about the role these technologies will play in the future diverge considerably in the very ambitious scenarios.

Figure 4 summarizes the energy system model output which either has been used as an input for the macroeconomic modeling or for the assessment of macroeconomic model results below. Panel (a) shows the development of gross energy imports (fossil fuels, P2X, electricity, ...), which decreases in all scenarios from today's level of ca. 10,000 PJ/a to values between 1350 PJ and more than 4500 PJ. Panel (b) shows the decrease in direct energy related CO₂ emissions by 80% (SCEN I–V) and by 95%

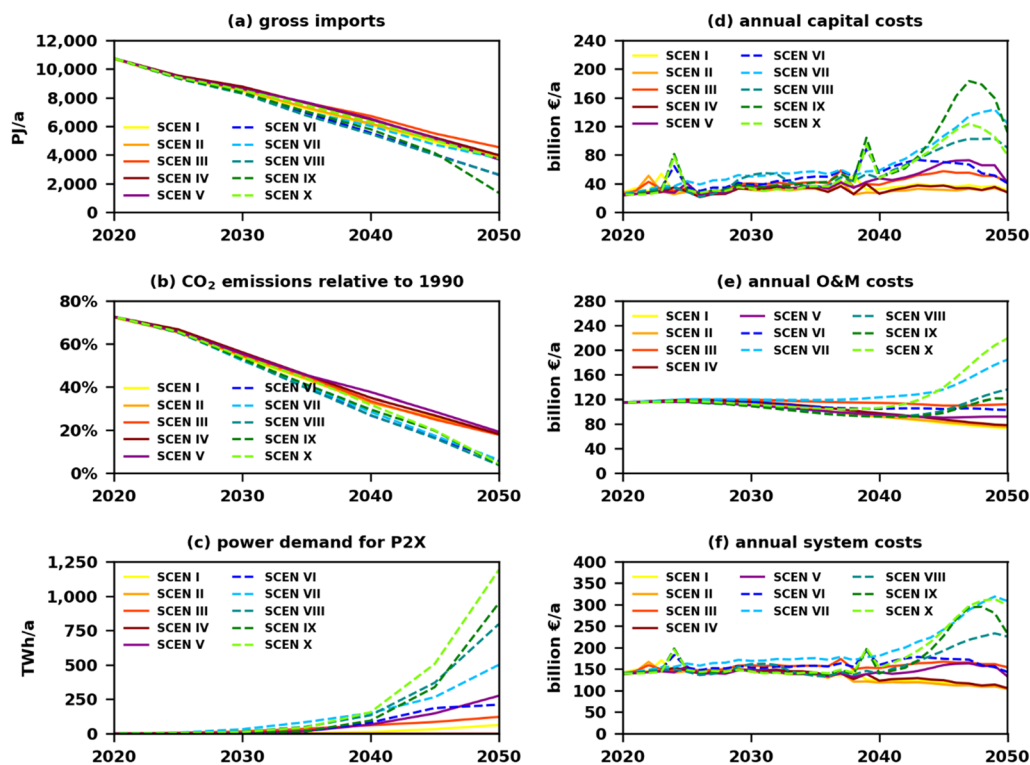


Fig. 4 Comparison of results for all ten scenarios: (a) gross imports of energy carriers (in PJ/a); (b) CO₂ emissions relative to 1990; (c) power demand for P2X generation (including power demand for P2X imports); (d) annual capital costs (annuities); (e) annual O&M costs; (f) total system costs (= capital costs + O&M costs)

(SCEN VI–X) relative to 1990. In panel (c), we see the increase in power demand for P2X generation (domestic and abroad) in all scenarios (compare with Fig. 3). Panel (d) shows the annual capital costs (annuities) resulting from the investments necessary to achieve the different transformation paths. Panel (e) in Fig. 4 shows the annual operation and maintenance (O&M) costs, and panel (f) the total system costs, i.e., the sum of capital and O&M costs. Here it can be seen that the different transformation strategies and CO₂ emission reduction targets result not only in different power demand and technology portfolios, as can be seen in Figs. 3 and 4, but also in significantly different system costs. The highly ambitious scenarios SCEN VI–X tend to show significantly higher system costs over most of the transformation paths than the moderately ambitious scenarios SCEN I–V, reflecting higher investment due to a faster and deeper transformation, but also higher O&M costs than the moderately ambitious scenarios. A detailed documentation of the scenario results can be found in the supplementary material hosted on ZENODO.

Results from the national macroeconomic analysis

GDP, investment, imports, consumer prices and employment have been selected as indicators for evaluating macroeconomic results of the model. As we evaluate economy-wide net-effects, indicators only representing the energy sector or new technologies were not included. GDP, despite being criticized as being too broad and unilateral [61], still serves as the indicator of choice for economic development and growth. Investment indicates future returns and wealth; it also shows how much effort is needed to initiate and drive the energy transition. Investment drives production, be it domestically

or imported. When produced domestically, additional production drives value added and leads to more value and employment in the respective sectors. Employment provides livelihoods and contributes to people's wellbeing. Additional income feeds back to the economy as additional consumption, thus increasing the multiplier effects. In an open economy, additional activities also spur imports, thus lowering the overall result. Over time, investment will be recovered by higher costs. In addition, substitution of domestically produced energy by imports affects prices. Policies to drive the energy transition, such as carbon pricing, put additional pressure on prices. The ten scenarios compared contain different levels and pathways for the above, leading to different outcomes of the economic simulation model runs.

The simulation results for a selection of key indicators are shown in Fig. 5. When comparing the ten scenarios, the first observation is that the macroeconomic variables are very close to each other on average from 2030 to 2050. Most of the more ambitious scenarios VI to X show higher levels of GDP and employment at the end of the projection period than the scenarios aiming at an 80% GHG reduction compared to 1990 (I to V). Investment is generally higher in the more ambitious scenarios, resulting in more positive economic effects. Scenarios VII and IX, for example, assume a high expansion of offshore wind and photovoltaics, respectively, which tend to be more employment-intensive than onshore wind. However, the development of GDP also depends on the development of price levels, operating and maintenance costs, and imports along the path. For example, the comparatively low employment in the very ambitious scenario X is the result of an investment level comparable to that of an 80% scenario and high energy imports. In

Scenario	GDP	Investment, Construction	Investment, Equipment	Imports	Consumer Price Index	Employment
	price-adjusted, Bn Euro				2015 = 100	1 000
	Average of the years 2030 to 2050					
Scen I	3752	275	545	2729	147.9	43880
Scen II	3749	273	542	2724	147.8	43870
Scen III	3756	276	549	2730	148.0	43888
Scen IV	3749	275	542	2724	147.4	43890
Scen V	3757	280	556	2740	147.7	43936
Scen VI	3775	285	558	2736	147.8	43983
Scen VII	3788	292	571	2753	148.3	44009
Scen VIII	3762	281	553	2735	148.0	43946
Scen IX	3784	295	576	2762	147.6	44048
Scen X	3744	276	546	2734	147.8	43875

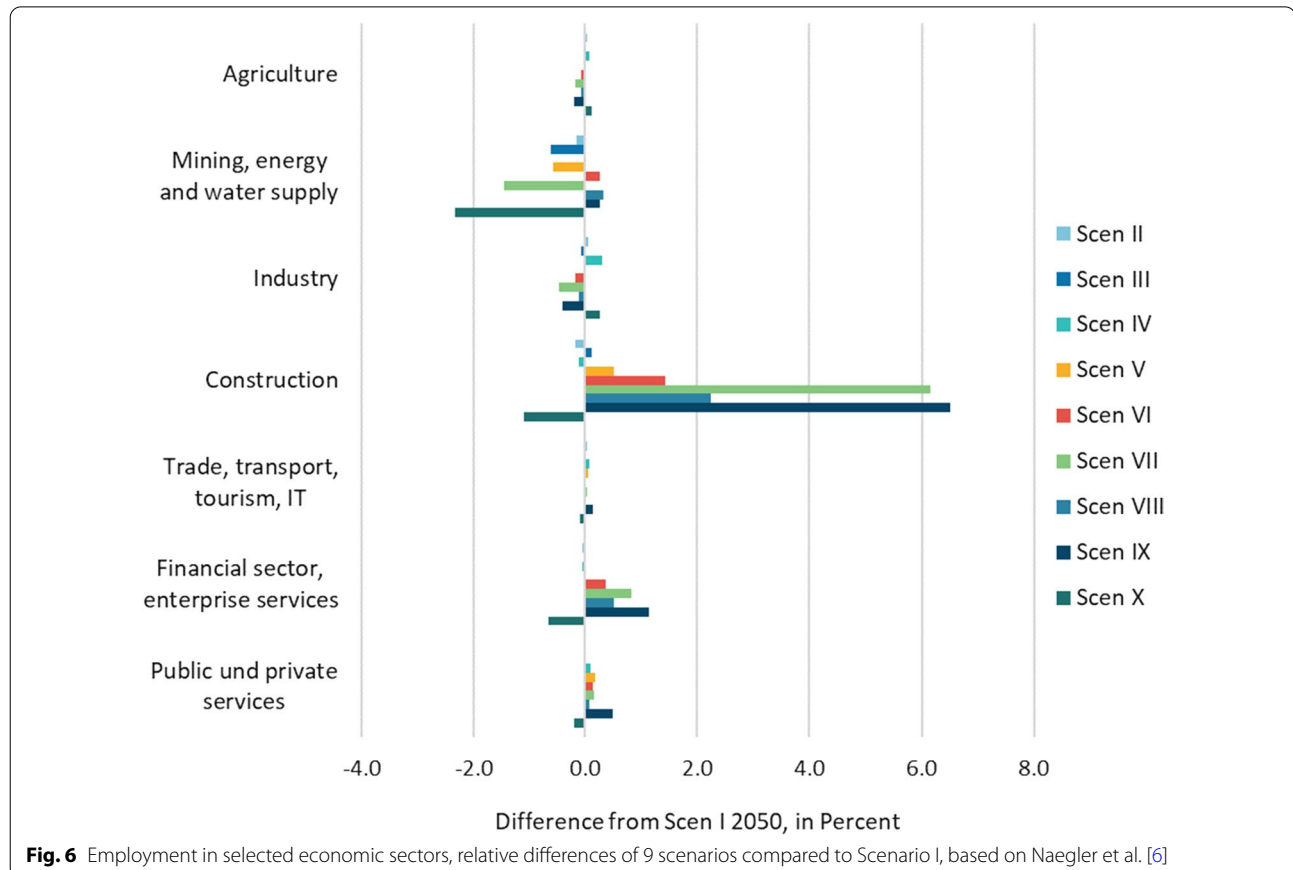
Fig. 5 Simulation results of the macroeconomic model PANTA RHEI for selected economic indicators, averages for the period 2030–2050. See also Naegler et al. [6] for further indicators

scenario seven, macroeconomic imports and the price level develop dynamically. However, domestic demand impulses dominate, and less energy is imported. Overall, the small differences between the alternative pathways can be considered plausible. All scenarios represent a transformation, with investments in new technologies and an energy mix that is fundamentally different from that of the past. In scenario VII, GDP is around 1 percent higher than in Scenario I. A comparison with scenario without substantial low carbon policies would show significantly larger differences in the long term. For example in Lutz et al. [11] deviations rise to 3.5 percent in Germany up to 2050. An analysis by Lutz et al. [12] finds deviations of a similar magnitude to those shown in our analysis, since different low carbon scenarios are also compared there. It should also be remembered that final energy consumption is roughly the same in all scenarios, so that no scenario can set itself apart with import savings, for example. More ambitious scenarios have rather high overall imports. Scenario VII reaches the highest economy-wide price level by 2050, Scenario IV the lowest. Scenarios with high transformation-related demand through investment on average arrive at a slightly higher price level. Constellations in which high prices meet

rather low employment are problematic. Therefore, Scenario VIII does not have much more favorable characteristics than the less ambitious Scenario V.

Of particular importance is how the individual economic sectors develop, and which economic sectors benefit from the transformation, and which may be disadvantaged by 2050. This analysis is carried out based on employment in 2050. We analyze differences between scenarios to better illustrate these effects. To better highlight the differences, we selected one of the 80% scenarios (Scenario I) as a reference and compare the simulation results of the other nine scenarios to this reference scenario. Relative differences in percentage provide the scenario's relative impact when all other factors are held equal (*ceteris paribus* assumption). Relative differences allow us to see whether the impact on a particular sector of the economy is large or small compared to developments in Scenario I.

The scenarios have different effects on employment in the respective sectors. Figure 6 shows the relative differences in employment in seven sectors (groups of ISIC-rev4 sections). Construction shows the largest positive effects, especially in four out of five very ambitious scenarios. Investment leads to higher demand, which is most

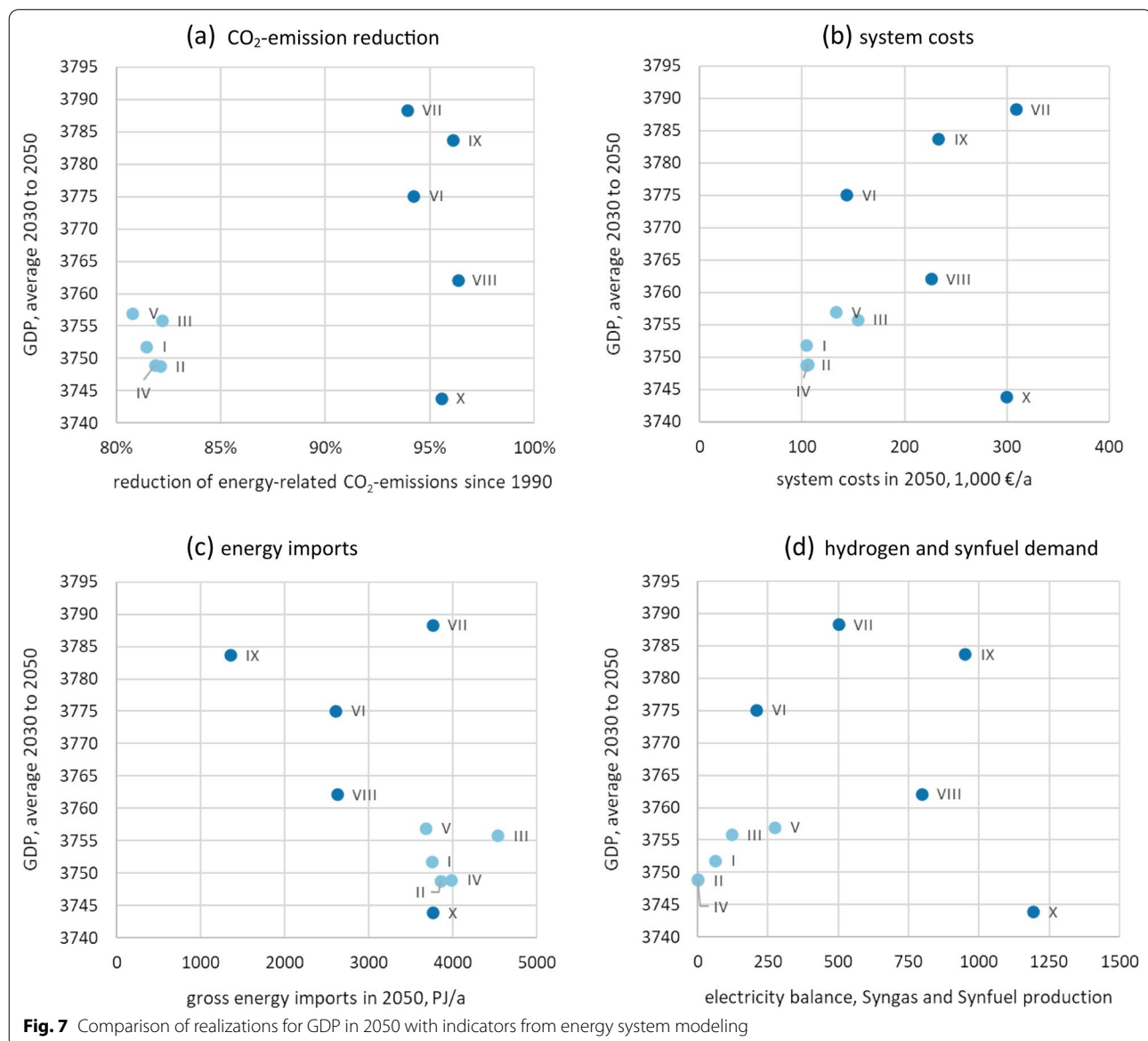


evident in construction, but also in business services. In the energy sector and industry, the effects are different but also small. As a rule, this sector in terms of employment cannot sustainably benefit from the additional investment in the very ambitious scenarios. Higher prices reduce the demand effect due to stronger labor productivity increases. Scenario X, as a special case, has lower employment compared to the reference scenario, as it relies mainly on hydrogen imports, with little investment in domestic infrastructure or technology. In particular, scenarios with high energy imports (see below) lead to reduced employment in the energy sector.

Note that total employment will decline in all scenarios by 2050 due to demographic change. The number of

people in the labor force will decrease accordingly. In addition, the *ceteris paribus* assumption includes the general structural shift toward services in all scenarios.

In Fig. 7, four energy system indicators are correlated with GDP. Graph (a) clearly shows the cluster of ambitious and very ambitious scenarios regarding the CO₂ reduction until 2050. Furthermore, four of the five scenarios with more than 90% energy-related CO₂ reduction show a higher GDP than all less ambitious scenarios. Graph (b) illustrates that most of the ambitious scenarios have significantly higher system costs. Overall, the realizations of GDP at the end of the projection period increase with the system costs. Scenario X is the least advantageous here, with lowest GDP and one of the



highest system costs. Scenario VI attains a high GDP with rather low system costs. In contrast to total economic imports (of all goods), gross energy imports in physical units show a different relationship with economic output. The ambitious scenarios save large amounts of fossil fuel imports. Therefore, low gross imports are accompanied by high GDP realizations [Graph (c) in Fig. 7]. However, scenario VII has very high energy imports and still achieves the highest GDP, as investment is particularly high. Technologies for the use of hydrogen and synthetic fuels are needed to varying degrees. For the Scenarios VIII, IX and X, the demand for hydrogen and synthetic fuels reaches amounts of 1300 PJ and more by 2050. In nearly all very ambitious scenarios, these new energy carriers play a substantial role, which does not have a negative impact on the economic outlook. It should be mentioned, however, that due to a lack of data, it had to be assumed that the prices of synthetic fuels do not differ fundamentally in level and development from comparable conventional energy sources. A striking finding is that a reduction of greenhouse gas emissions by another 15%, since 1990 compared to the 80% scenarios significantly changes the macroeconomic developments. The less ambitious scenarios hardly differ one from another, while the 95% scenarios show a wider range of developments until 2050. This corresponds to the higher diversity of the energy systems among the more ambitious scenarios as shown in the energy system results above.

Regional results

The regions show different levels of GDP and employment across the scenarios by 2050. In fact, a deviation analysis from a reference (here scenario I) shows that regional GDP can be lower, although a higher GDP is achieved for Germany as a whole. For example, not all German states can benefit from a very ambitious scenario in a regional comparison. Attributes were selected for clustering to summarize the results for ten scenarios and 13 regions. One attribute is the standard deviation of the regional share across the scenarios. Furthermore, the largest and smallest regional shares were identified for each federal state to assign them to the group of ambitious and very ambitious scenarios. The shares in employment in 2045 were evaluated, since the differences in this year are comparatively high. The differences are high, because both the national level of investment and the respective differences between the scenarios are high in that period. In general, at the end of the projection period, structural developments as long-term macroeconomic adjustments to the transformation paths are more likely to occur.

Figure 8 shows how the regional distribution of employment is affected throughout the transformation

scenarios. For example, the regional share of Lower Saxony–Bremen within Germany varies across the scenarios in 2045 between 9.08 and 9.18 percent. If the average share across the very ambitious scenarios (VI to X) is higher than the average of the average across scenario I to V, they are declared to have relatively high advantage from a zero-carbon transformation. These regions for 2045 are located in nearly every part of the country. They only do not occur in the southwest. The pattern changes slightly between 2040 and 2050, as northern federal states are increasingly unlikely to belong to the group of regions for which a very ambitious transformation path is particularly advantageous. The sensitivity to changes in the technology mix is defined by the standard deviation of regional shares across scenarios. If the value is above the highest tercile, the sensitivity is considered high. In 2045, the uncertainty is highest in Lower Saxony–Bremen and North Rhine–Westphalia, but also in Hesse, Baden–Württemberg, Saxony and Brandenburg–Berlin, and the economic development proves to be very dependent on the transformation strategy in detail. The results show that familiar patterns of positive effects dissipate, when long-term transformation strategies are compared. All scenarios assume a substantial expansion of RE-facilities, so that other changes in the energy system and in the whole economy have a higher impact, especially the evolving hydrogen strategies from 2040 and later. None of the scenarios leaves individual regions behind in terms of development. However, there are individual scenarios that are highly polarizing, such as Scenario VII, Scenario V and Scenario IX.

The structural characteristics in the major regions, those of the energy industry but also across all sectors, are decisive for the regional effects. Regions specialized in a certain technology due to technical potential are sensitive to the technology mix. An important factor is the focus of RE use in the scenarios. Scenarios 6 and 7 focus on the expansion of wind energy. Here, those federal states achieve the highest shares that have a focus on wind energy—today and according to the distribution keys for the future expansion (the north). Scenario IX in contrast achieves the highest PV expansion and favors of regions, such as Baden–Württemberg and Saxony. Higher sensitivity also can result from a higher focus on fossil power generation and no RE focus in the past. As for Hesse, this is more clearly a question of ambitiousness of the transformation. The results for North Rhine–Westphalia and Saxony, which also fall into the “fossil” group, show that power generation structures are overlapped by effects of overall economic structures and dynamics. A major structural effect is that in the east-German regions, construction has a high weight on regional employment. In scenarios with high investment, the construction



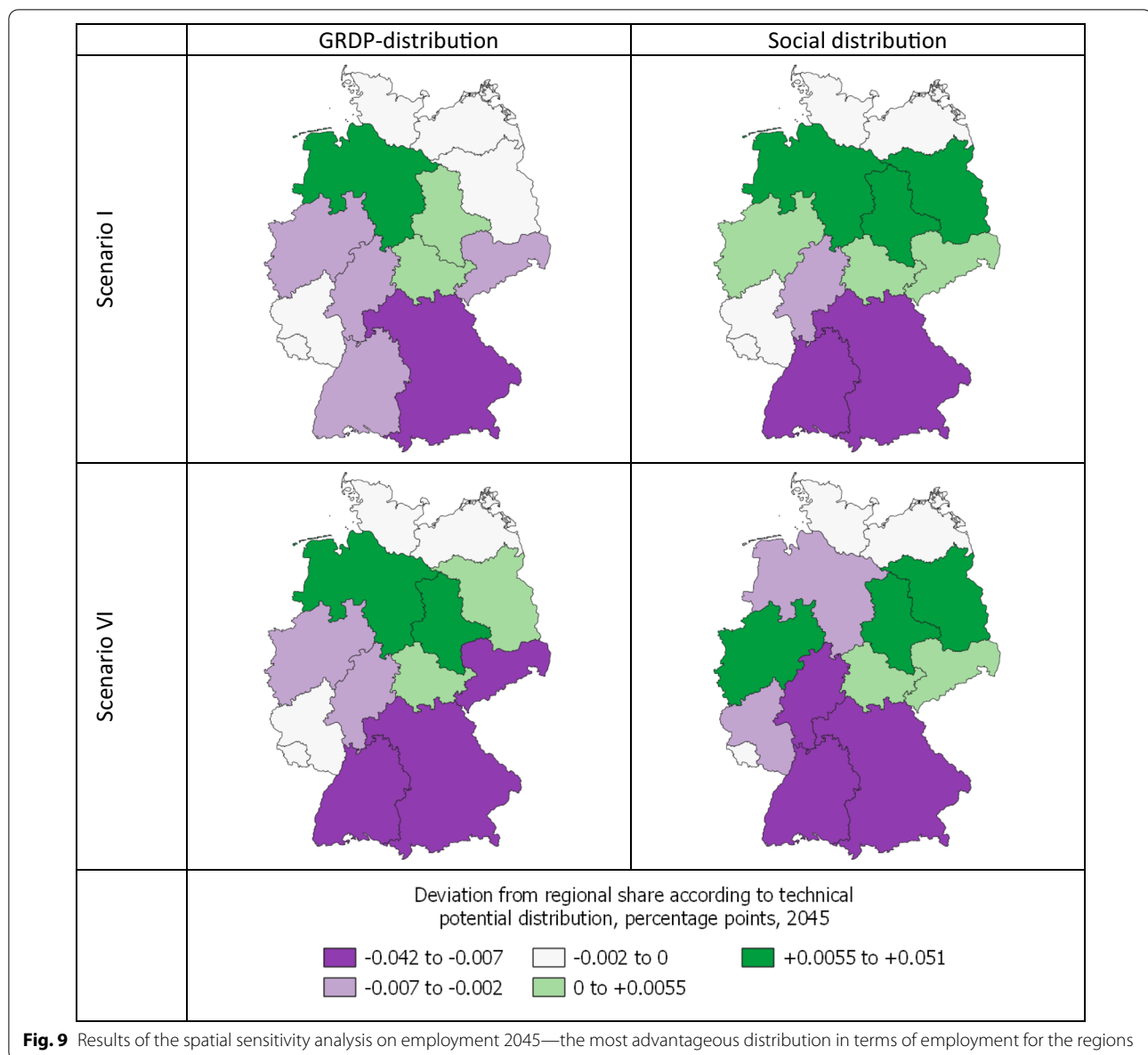
Fig. 8 Clustering of regional effects on employment for 13 major regions in 2045

sector benefits particularly strongly, which is less noticeable in regions with a disproportional low weight of this sector.

Focusing on Scenario I and VI, the analyses were enhanced. The results are summarized in Fig. 9. First, the effects of the alternative regional distribution keys for the expansion of renewable energies were examined as sensitivities. The alternative, regional distribution keys—‘Grid Development Plan’ (GRDP) and ‘Social indicators’—for the expansion of renewable energies reinforce the already described gradient from southwest to northeast. The assumption for the GRDP favors most of the eastern German states (except Mecklenburg–Vorpommern), but also Lower Saxony–Bremen. Compared to distribution by potential, the distribution key with social indicators

places greater emphasis on eastern German regions, especially Saxony–Anhalt and Brandenburg. There are hardly any differences for North Rhine–Westphalia, although this federal state benefits slightly from a distribution according to social criteria in comparison. The entire south and southwest have an advantage in a distribution by RE potentials. The spatial deviation pattern is almost the same in scenario I and scenario VI.

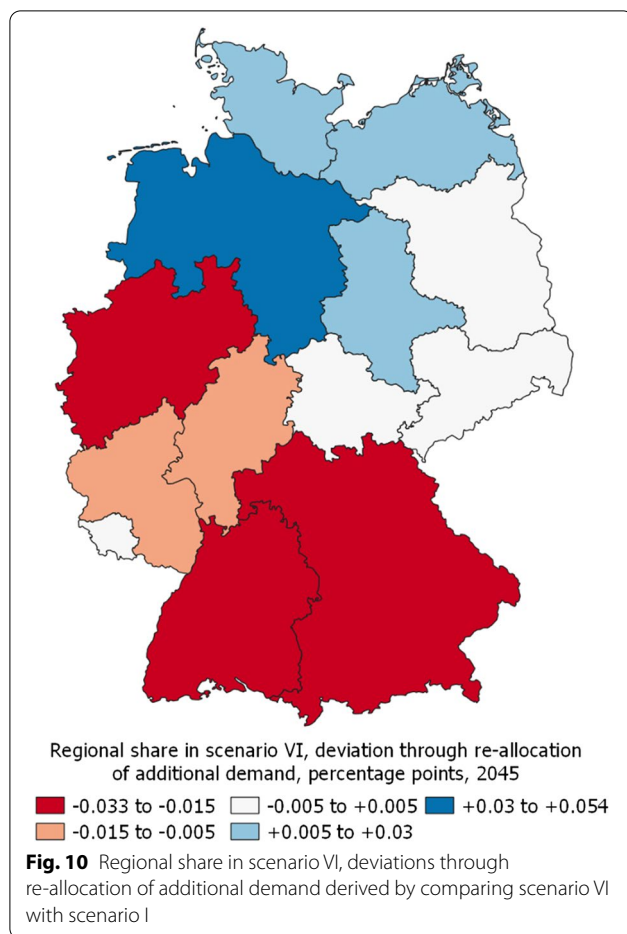
The second modeling extension was the analysis of the impact of regional additional demand triggered by investment. The allocation of additional demand from RE investment in scenario VI compared to scenario I, both with resource potential distribution, was estimated by processing the regional input–output model and by refeeding results into the macroeconomic projection.



As can be seen from Fig. 10, the demand is redistributed to the north and parts of east-Germany. This is due to the spatial focus of expansion in these regions. In addition, however, it is also noticeable that the manufacturers of wind turbines and PV modules are located in these regions. Parts of this pattern can also be found in the studies on the jobs of renewable energy expansion, for which the same model was used [57]. From these studies, it was also deduced that in principle all regions benefit from the expansion, regardless of the location of the plants. However, the relative importance for the overall economy is particularly high in the regions marked with the green buttons in Fig. 9.

Discussion

At the national level, the comparison of different, long-term target scenarios, exhibits patterns which are often found in macroeconomic analysis of the energy transition to date. Investments are decisive and dominant, prices and imports less so. Differences among the more ambitious scenario towards 95% CO₂ reduction are higher than among the 80%-scenarios. In summary, the pathways of GDP and employment are not differing largely. Furthermore, an ambitious approach up to 2050 tends to have a positive effect on the variables, overall, results are in line with similar studies for Germany.



The modeling approach takes several relevant aspects of a sustainability analysis of the outcomes of energy transitions further; however, some important aspects of the transformation have had to be sacrificed for the sake of harmonized scenarios. In particular, the scenarios do not differ with regard to energy efficiency or system costs in transportation. Although different policies are assumed in some of the scenarios compared, and they are modeled explicitly, in the above analysis no explicit modeling of policies to achieve the targets is included. The analysis focuses on the investments, saving and the respective prices taken from the various studies, independent of the policy behind them, i.e., if prices are a result of carbon taxes or other market dynamics in the respective study. Even though mechanisms and structures of an increasing use of hydrogen and synthetic fuels are implemented in the model, only weak assumption could be made about prices (relation development) of these fuels. From an overall national macroeconomic perspective, there will be no regret no matter which transformation path is taken, and

due to the harmonization, differences between GDP-development among the very ambitious scenarios are underestimated.

When comparing regional developments across the ten scenarios, the differences are low, but still larger than at the national level. The north/east-to-southwest divide often identified in energy transition impact assessment changes to a more complex pattern when only transformation scenarios are compared. Regions have different structures and preconditions that are reflected as regionally differentiated effects in the context of transformation paths. However, it is not only structures but also industry-specific dynamics and development contexts that determine the region-specific developments. The regional impact patterns of effects slightly differ from previous studies with time horizon 2030, as scenarios represent all high but different renewable energy expansion strategies. The important issue of regional implications of expanded production and use of hydrogen could not be addressed with regional specific assumptions, as there is only sparse data.

Conclusions

This paper compares socio-economic outcomes under different energy transition scenarios. The indicators reported and selected are GDP, investment, imports, consumer prices and employment, all as net relative differences. This is one of the main contributions of this research to the sustainability discussion. Net relative differences at different points in time and different geographical scale enhance the understanding of socio-economic outcomes of different energy transition pathways in a coherent and consistent way. For this analysis, ten existing scenarios were selected, harmonized, and remodeled in an energy system model. Two basic targets of CO₂ reduction (80% and 95%) group the ten scenarios, which represent very different strategies with respect to the future technology and energy carrier mix.

The comparison employs a macroeconomic simulation model framework along with regional modeling approaches, addressing regional distribution effects and thus the social sustainability dimension in new detail. Another aspect is the almost complete substitution of fossil fuels in the energy system—a regime that has not yet been extensively analyzed in studies up to 2030 or 2040. The majority of the 95% scenarios assume high importance of synthetic fuels, and some see increasing energy imports. The process of import substitution through the expansion of RE is partly phased out approaching 2050. This is reflected in the trade balances under different scenarios.

The claim of the deeply disaggregated and empirically based model is to map the future on current behavior

and trends by econometric analyses. However, disruptive transitions cannot be foreseen based on past behavior. To meet this claim, we combine data driven empirical modeling and energy system backcasting accompanied by intensive technical discussions on specific scenarios to simulate new technological pathways.

Assessing regional impacts needs a debate on the future regional distribution of new energy production capacities and thus investment. Regional concepts fitted to national objectives and scenarios need to be developed, to improve coordination between regional and national policies, and to address implications more precisely in impact analysis.

The combination of the energy system model with the national and regional economic models leads to a more comprehensive picture of growth employment and distribution effects. The good news in terms of decision making and policy recommendations is that the differences in the socioeconomic indicators at the national level between the scenarios are not very large, but all scenarios performed much better than a less ambitious scenario. In particular in the light of the current debate on the price effects of climate change mitigation and renewable energy, the results of the above analysis showed the benefits of aiming high in terms of CO₂ reduction. In terms of future research, data on regional value added and inter-regional trade could strengthen the results and make them even more applicable and useful for a full sustainability analysis. Particularly, data on the regional distribution of P2X technology are needed, because of their importance in the more ambitious scenarios. A sensitivity analysis varying these localizations could be a valuable contribution compared to existing impact assessments scenarios.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13705-022-00361-5>.

Additional file 1: Table S1. Overview of all scenario studies taken into account during the scenario selection process. **Figure S1.** Schematic overview of the structure and workflow of MESAP. For details see main text. **Figure S2.** Overview of the PANTA RHEI model.

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Author contributions

Conception, P.U., L.B., U.L.; acquisition, T.N., U.L., analysis, P.U., L.B., U.L., S.S., C.S. interpretation of data, P.U., T.N., U.L.; writing original draft, P.U., L.B., S.S., C.S.; writing—review and editing, U.L., A.W. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets generated and/or analyzed during the current study are available on <https://www.innosysprojekt.de>, accessed on 12 August 2021. The documentation of the underlying scenarios as well as the data itself can be found on Zenodo (<https://zenodo.org/record/5992432> and <https://zenodo.org/record/5993177>).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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