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Analysis

Macroeconomic impact of the German energy transition and its distribution by sectors and regions

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ABSTRACT

Macroeconomic impacts such as changes in economic structures and employment are very important when evaluating the energy transition in societal terms. We employ a macroeconomic model that accounts for regional, economic and sectoral features. The model results show how the overall positive net impacts of the energy transition in Germany – energy efficiency and renewable energies - on economic growth and employment up to 2030 are distributed across sectors and regions. The biggest relative increases in value added occur in construction, real estate and electricity generation; the biggest decrease is in mining of lignite. Significant effects mainly result from changes in the heat and transport sectors, while the transition in the electricity sector entails smaller impacts. The latter are, however, relevant to the regional distribution: The model results suggest that especially northern and eastern German federal states will benefit economically from the energy transition because they offer attractive locations for investments. At the same time, these states are less affected by decreasing conventional energy generation. Moreover, the impact of rising electricity prices is less negative here than in the other federal states because of their lower electricity intensity in production. In summary, the energy transition represents an opportunity for these regions to strengthen their economies.

1. Introduction

Germany has set itself the goal of significantly reducing its greenhouse gas emissions compared to 1990 levels: −40% by 2020, −55% by 2030 and −80% to −95% by 2050. Achieving these targets requires significant changes in the energy production sector as well as in all energy-consuming sectors over time. These fundamental and comprehensive changes are referred to as the “energy transition”. Specific strategies and targets for different sectors and individual areas supplement this overarching goal. Renewable energies play an essential role in the German energy transition and should increase their share in final energy consumption to 30% by 2030 and to 60% by 2050. This requires far-reaching transformations in electricity, heat and transportation, not only with respect to generation and consumption, but also with respect to distribution, storage and sector coupling. Energy efficiency represents another important pillar of the energy transition. Specifically, the targets are to reduce the primary energy required by 20% until 2020 and by 50% until 2050 compared to 2008 levels.

Macroeconomic impacts of the energy transition include but are not limited to economic growth and employment (see Wei et al., 2010 and Cameron and van der Zwaan, 2015 for a good overview in this respect). They are triggered by investments in renewable energy sources (RES) and energy efficiency (EE) measures, altered demand of the electricity generation sector for intermediate and primary inputs including labour, reduced fossil fuel imports, altered electricity prices and reduced energy demand. Next to its impact on the economy as a whole, the energy transition also entails significant structural changes with impacts on the sectoral and regional distribution of value added. Given Germany's federal system comprising of sixteen states with quite different economic structures, the regional distribution of macroeconomic net impacts is of particular relevance in this context but has not received much (scientific) attention yet. While some western German states with a traditionally strong mining sector and energy-intensive industries are facing substantial and costly structural changes most likely accom-

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panied by (short-term) negative employment effects, some states in the north and north-east (based on suitable natural conditions) will likely benefit from the economic pull-effect of renewable energy. Finally, the situation is ambivalent for highly competitive and knowledge-intensive southern states which might benefit from increasing investments in renewable energy technologies but need to overcome a strong dependency on nuclear energy (which might require the import of renewable energy form the northern part). Given this, this study analyses how the energy transition affects regional and sectoral value added and employment. In so doing, the presented model does not only account for the net impacts based on declining fossil/nuclear energy and increasing RES but explicitly includes also net impacts related to improvements in energy efficiency. Though distributional impacts might be less pronounced in this case, they still affect regional (and therefore federal) industries with different intensities.

In the following, we model the future macroeconomic impacts of RES and EE deployment, taking place in the electricity, heat and transport sectors up to 2030 and depict these impacts differentiated by industries and regions. The aim is to determine the net impacts for regions and industries by considering all positive and negative effects as comprehensively as possible.

2. Background

Economic impact assessments of energy policy can be roughly divided into analyses of gross and net effects (cf. Lutz et al., 2012; Breitschopf et al., 2013 for a comparative presentation). Analyses of gross effects are limited to the quantification of positive impacts, for example employment in production and operation of renewable energy technologies. Analyses of net effects always compare a situation with and without strong efficiency and renewable deployment, and thus depict negative impacts such as loss of employment with respect to conventional power generation. In addition, most macroeconomic models account for positive and/or negative indirect effects, such as increasing investments and exports, higher energy prices or crowding out effects.

Dehnen et al. (2015) provide a concise summary of the main results of a large number of analyses exploring gross and net effects of the energy transition in Germany. They show that even though most studies differ with respect to modelling approach, assumptions and scenarios, the results are similar in scale and the majority of studies predict positive net effects. Certainly the modelling approach has an impact on the assessments, as has been shown by a comparison of impact assessments of EU energy policy. The comparison of the modelling approaches is based on the same scenarios and showed slightly negative results for economic growth when applying a CGE model, and slightly positive results when applying a post Keynesian macro econometric model (European Commission, 2016). The results converged after adjusting the assumptions on availability of capital (crowding-out effect) in both models. A comparison of the system dynamic model ASTRA and the macro econometric model PANTA RHEI showed positive impacts of increased investments for both models. However, in the long run the positive impact on factor productivity is weighted more strongly in ASTRA, whereas in PANTA RHEI dampening effects due to increased capital costs are of higher importance (Lehr et al., 2011). In contrast, a model comparison of the econometric, neo-Keynesian model NEMESIS with ASTRA (Duscha et al., 2016) reports larger positive impacts by NEMEIS than ASTRA, because positive effects from investments on GDP were delayed in the ASTRA model.

While many studies focus on the increase of renewable and the loss of fossil/nuclear energy, some also include energy efficiency in the building sector and industry (e.g. Ringel et al., 2016). However, in most of the cases, the focus of the analysis is on the European or national level (see e.g. Fankhaeser et al., 2008; Frondel et al., 2010; Hillebrand et al., 2006; Lehr et al., 2012; European Commission, 2016), and not the regional level.

Some studies do focus on regional impacts. These are either based on value chains, regional input-output tables or hybrid approaches. However, most of these models focus on gross rather than net impacts and only some account for indirect effects (Ulrich et al., 2012; Heinbach et al., 2014; Raupach-Sumiya et al., 2015; Kosfeld and Gückelhorn, 2012; Bröcker et al., 2014). Only one study determines the net effects of renewable energy expansion ex-post for the year 2011 for all federal states by applying a multi-regional input-output quantity and price model (Többen, 2017).

To the best of our knowledge, however, there is no ex-ante analysis that determines the net impacts of the energy transition (i.e. including energy efficiency) and depicts them for all German federal states.

In this context, the present study analyses the net impacts of the energy transition – of renewables and energy efficiency – for Germany at the level of federal states. We include GHG emission savings, EE and RES targets and account for impacts in the heat, electricity and transportation sectors. Results are depicted in terms of value added and employment for 2030.

3. Methodology

In order to identify the economic consequences of the energy transition, we apply an economic impact assessment model that links economic activities arising from the physical consumption and supply of energy (differentiated by electricity, heat and transport) with a macro-economic model of the German economy and regional economic structures of the federal states. A reference and an energy transition scenario describe the socio economic and political framework conditions. By comparing the results of the two scenarios, the net effect on regional value added can be determined. An illustration of the modelling approach is given in Fig. 1.

In contrast to a fully integrated assessment modelling approach, the models are not hard linked but are based on the same scenario framework. This means that the energy models are used iteratively to balance the supply and demand sides, but do not have a feed-back link (for details see Pfluger et al., 2017b). There is a one-way soft link between the energy models and the economic impact assessment model. Feeding-back impacts on sectoral production to the energy demand models would allow accounting for indirect rebound effects. However, such a hard link between energy and macroeconomic models is the exception in impact assessment studies. E.g. Lutz et al. (2018), European Commission (2016) and Duscha et al. (2016) do not portray feedbacks from the macroeconomic model to the energy models and consider the potentially resulting indirect rebound effects as negligible.

The models differ with respect to their assumptions. Energy models do for example take into account supply side constraints such as limited availability of biomass or areas for renewable energy, whereas no supply side constraints are implemented in the economic model. Moreover, the energy models differ in their modelling focus. Consumption is simulated based on the employed targets and policies, while the electricity model optimizes the generation mix of electricity based on given policies providing the lowest electricity prices under the assumption of profit maximization of electricity suppliers.

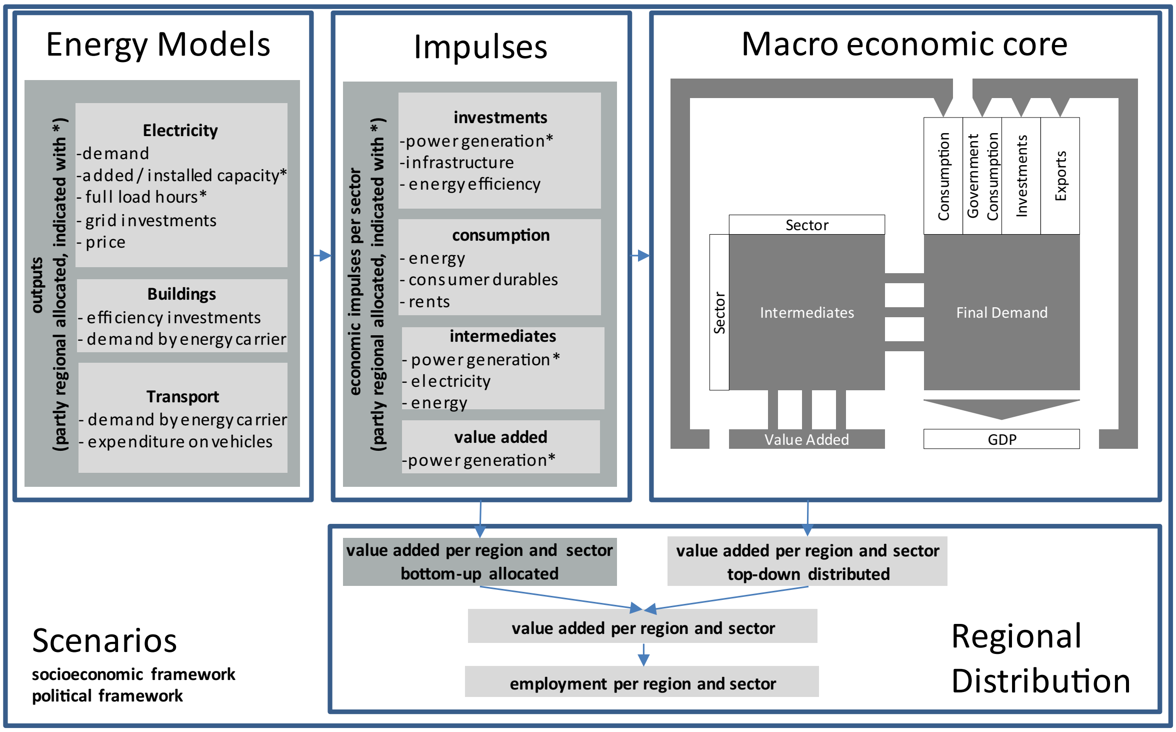

Fig. 1. Schematic representation of the modelling approach.

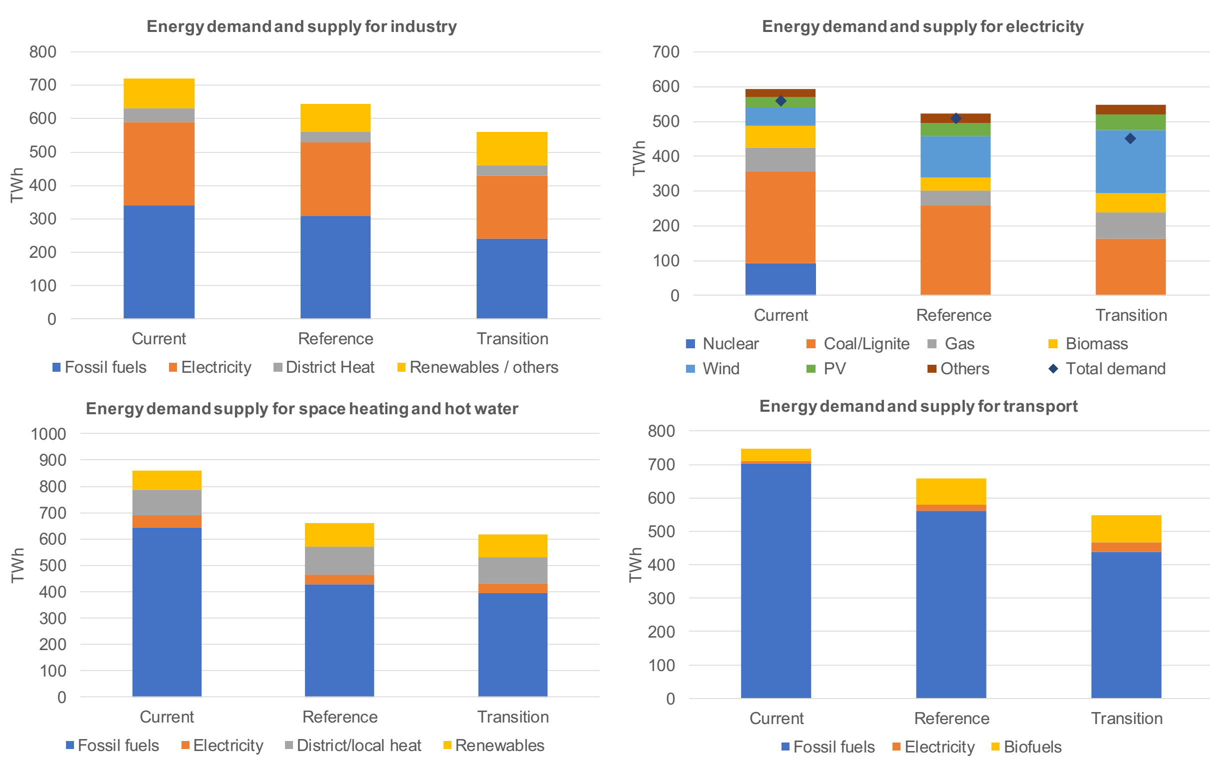

Fig. 2. Energy demand and supply for electricity, heat in buildings, transport and industry by energy carriers in the reference and transition scenario (in TWh). Source: based on Pfluger et al. (2017c).

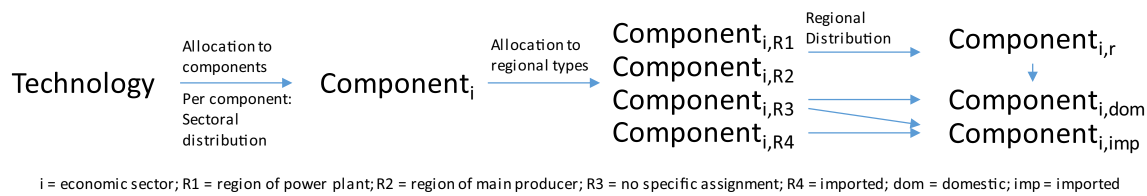

Fig. 3. Decomposition of investment impulse into components.

3.1. Scenarios

The reference scenario and the energy transition scenario (time horizon 2010 to 2030) form the socioeconomic and political framework of the modelling. They basically follow two scenarios, that were developed for the" German Federal Ministry for Economic Affairs and Energy" based on an integrated approach with various energy models (for details see Pfluger et al., 2017a, 2017b, 2017c). In the energy transition scenario, political instruments remain unchanged or are even tightened so that goals for renewable energies, energy efficiency and greenhouse gas mitigation are reached. In the reference scenario, stricter targets are not applied and existing policy support expires at the end of 2010, while standards which were set before this date remain valid.

As illustrated by Fig. 2, the energy supply of fossil sources decreases and that of renewable sources increases. In a growing economy, the decreasing energy demand further reflects increasing energy efficiency. These trends are similar for both scenarios but more pronounced for the energy transition scenario. Notably, electricity production is higher in the transition compared to the reference scenario and it clearly exceeds demand in this case (implying import of electricity in the reference scenario, export in the transition scenario due to more RES installations).

3.2. Modelling approach

3.2.1. Economic impulses

The energy transition triggers substantial changes in the physical energy flows and economic activities within the electricity, heat and transport sector. Among others, this includes the build-up of capacity for renewable energy and power grids, reduced capacities of fossil and nuclear energy, impacts on energy prices, increased expenditures in energy efficient technology or new household consumption patterns (see light grey columns in the left part of Table Annex 2 and box "Energy Models" in Fig. 1). These outputs of the energy models translate into sector- and region-specific changes of wages and profits as well as demand for intermediate products, investments and consumption goods (see light grey columns on the right of Table Annex 2 and box "Impulses" in Fig. 1):

- Intermediate deliveries: Positive direct effects occur in the industries that provide the operation and maintenance of technologies applied for the energy transition whereas negative direct effects occur in industries that provide the operation and maintenance of conventional energy technologies including fuel suppliers.
- Investments: direct positive effects occur in the industries supplying capital goods for the energy transition. That is, in industries manufacturing renewable energy, energy efficiency and infrastructure technologies, in each case for electricity, heat and transport. On the other hand, direct negative effects arise in the industries that supply capital goods for conventional energy technologies.
- Consumption: direct effects occur in industries supplying consumer durables for the energy transition, such as energy efficient appliances or electric vehicles. Household spending for energy, in each case for electricity, heat and transport, takes into account changes in demand caused by efficiency improvements as well as changes in prices. Additional investments in energy efficient buildings increase household spending for rents.

Economic impulses are annualized and differentiated for 72 economic sectors i.e. industries of the German input output table. The dark grey column in the centre of Table Annex 2 explains how outputs of the energy models are transformed to economic impulses in the desired form.

Regionally assigned economic impulses. Parts of the impulses are not only differentiated by economic sectors but in addition directly allocated to a region (outer right column of Table Annex 2). We explain the procedure using the example of investments in energy generation technologies. The model differentiates between ten technologies: Nuclear, coal, lignite, gas, photovoltaics (roof-top and large-scale), wind onshore, wind offshore, water and biomass. The specific investments differ in terms of size (Euros per newly installed capacity), sectoral structure and regional assignment. Therefore, the model contains investment vectors for each technology.

The first step is to break down the energy generation technologies into individual components (first arrow in Fig. 3).[1] In addition, the investment for each component can be allocated to one or more economic sectors i.[2] For example a photovoltaic system is broken down into various components: the modules, inverter, cable, connectors and mounting systems, as well as various services such as planning, wholesale, grid connection and installation. The component "inverters" is assigned to the economic sector electrical equipment, installation is assigned to the construction sector etc.

For the individual components, the second step (second arrow in Fig. 3) specifies whether they will be distributed regionally or not, and the third step (third arrow in Fig. 3) applies the distribution. In detail, the impulse can be assigned either directly or indirectly. Direct assignments could be based on the location of energy production (R1)[3] or the regional distribution of the main manufacturers of the component (R2).[4] Indirect assignments are applied if direct regional allocation is not possible (R3)[5] or the component is imported (R4).

[1] Hirschl et al. (2010) offer a database for this purpose, which we have adapted using further sources (e.g. EEG experience reports) and expert knowledge.

[2] This is carried out using an update of the techno-economic database by Rütter Soceco AG (Duscha et al., 2016).

[3] In the case of direct assignment the regional distribution is given as input from EnerTile (impulse 1 in Table Annex 2).

[4] The regional distribution of the main manufacturers is only given for photovoltaics and wind (onshore and offshore) as these form the main part of the aggregated investment impulse. It is based on literature research (industry magazines, market information by Germany Trade and Invest, EEG experience reports) and expert knowledge. For the other technologies, it is assumed that the distribution of the main manufacturers is the same as the regional distribution of production of an average good in the corresponding economic sector.

[5] Indirect assignment of the components: the fractions given in the input-output table are used for the allocation to the corresponding domestic or foreign production.

Coming back to the example of photovoltaics, installation is assigned to the location of energy production, resulting in a positive demand for construction in the regions with an expansion of photovoltaics. Inverters are partly imported but mainly increase demand for electrical equipment in the regions of the main manufacturers. Solar cells, wafers and modules are mainly imported and only a small fraction is assigned to the region of the main manufacturers. Metal products are not assigned to a specific region: domestic production is derived by applying fractions of the input output table. Additional information on the regional allocation of investments in energy generation technologies and further economic impulses is provided in the supplementary material 2.

3.2.2. Macroeconomic core

ISI-Macro (see Fig. 1 for a simplified illustration) can be described as a partially closed quantity input-output model implemented in System Dynamics. It complies with macroeconomic accounting conventions and establishes supply relationships (input matrix) between 72 economic sectors (input-output accounting 2012, in large part consistent with the classification of economic activities in 2008). Sectoral gross value added is determined in the input-output module. Consumption depends on household income, i.e. wages, capital income and government transfers, and thus on sectoral value added. This corresponds to a partially closed quantity model with the additional feature that the closure of the model is delayed to the next time step, thus resulting in a dynamic development. Government consumption is also linked to aggregated value added and exports are exogenous. Investments depend on aggregated value added. In contrast to neo classical models and in line with post Keynesian models, there is no budget constraint for investments. As no supply side constraints are implemented, prices are not endogenously modelled but assumed to be implicit.

A formal description of ISI-Macro including a discussion of underlying assumptions is given in the supplementary material 1 of this paper. It also describes the integration of economic impulses, which can be summarized as follows:

Consumption and investment impulses derived in the energy module alter the sectoral structure and (in the case of investment) also the level of final demand. This leads to indirect effects due to the vertical links of the economy, i.e. to changed demand for intermediates. Without bottom-up impulses, the sectoral structure of consumption and investment remains unchanged over time.

Changes in intermediate demand for energy as well as changes in in the intermediate demand of the electricity production sector compared to the baseline are depicted as impulses to the matrix of secondary inputs. To be precise, the impulses are given as absolute changes to the intermediate delivery matrix for each time step for the sectors which are subject to an altered input structure. If for example a sector demands less coal due to efficiency improvements, this would be portrayed as a direct change to the intermediate delivery matrix. The resulting decrease in demand for all upstream industries of coal is however not pictured by the impulse. Thus, to secure that input equals output a balancing mechanism is applied (see supplementary material for details). As we do not apply a price model we assume that altered cost structures result in altered value added. In the example above, the sector demanding less coal experiences an increase in value added. The technical coefficient matrix is calculated from the matrix of secondary inputs and sectoral output at each time step and thus reflects structural changes. Without bottom-up impulses, the technical coefficient matrix remains unchanged.

Direct and indirect effects bring about value added changes in the individual economic sectors. The described closure of the model leads to induced effects.

3.2.3. Regional distribution

The regional distribution (see Fig. 1 for an illustration) differentiates between 38 regions[6] and 37 economic subsections, which is an aggregation of the 72 economic sectors of the macro economic core.

Two approaches are applied to account for regional features and regional impacts:

1. Some of the impulses derived in the energy module are attributed directly to individual regions and economic sectors. Factors from the input-output table are used to derive the corresponding regional value added from regionally assigned sectoral output (left part of regional distribution in Fig. 1). We implicitly assume that all value added components (wages, profits, taxes) occur in one region.
2. The regional value added of impulses that cannot be allocated directly to regions is derived from national value added by means of a distribution key that is based on economic data by government district and economic sector (right part of regional distribution in Fig. 1). In addition, we also use this key for allocating indirect and induced effects.

The distribution key is a composite indicator which draws on a regionally highly resolved time series of sectoral employment (special evaluation of the Labour Force Survey[7]) and value-added (data from the Federal Statistical Office and the statistical offices of the federal states). Temporal dynamics derive from the development of regional and sectoral labour productivity and on forecasts for the regional distribution of labour force (Destatis, 2015; Schlömer et al., 2015).

These two approaches take into account differences among the individual regions in terms of economic power and structure as well as their dynamic development and can therefore be defined as a combined bottom-up & top-down approach: Regionally assigned impulses are directly transformed into regional effects; while supra-regional (national) impulses are translated into supra-regional impacts, which in turn are converted into regional impacts. A formal description of this regional extension to ISI-Macro is given in the supplementary material 2 of this paper.

4. Results and discussion

The model assesses regional and sectoral impacts, but the focus of our analysis is the regional distribution of impacts. For better interpretation, aggregated effects and their structural composition are presented first.

4.1. Aggregated and sectoral impacts

In line with other modelling results, the overall aggregated impacts on GDP and employment are positive: The energy transition scenario features a slightly higher cumulated gross domestic product of 0.8% in 2020 and 1.6% in 2030 compared to the reference scenario. Total employment is also higher by about 0.7% in 2020 and 1.1% in 2030. In 2030, the transition in the electricity sector contributes 20% to the relative change in GDP, heat and transport sector 40% each. The relative change in employment is more equally distributed across sectors (31% electricity, 37% heat and 32% transport).

The main drivers behind this economic growth are additional investments that are primarily due to measures in buildings and to a lesser extent due to additional investments in power generation

[6] The regional granularity extends to administrative districts (NUTS 2 level), but an exact spatial allocation of all power generation technologies is not possible. Therefore, the results are presented at NUTS1 level.

[7] The European Union's Labour Force Survey is integrated into the Microcensus, the official representative statistics on the population and the labour market in Germany, collected by the Federal Statistical Office/State Offices.

technologies, transport infrastructure and efficiency improvements in the electricity and transport sectors. The overall investment stimulus is enhanced by multiplicator and accelerator effects. The applied modelling approach implies no crowding out of other investments. Subsequently, additional investment in energy generation technologies, infrastructure or efficiency in the energy scenario compared to the reference leads to economic growth.[8]

Next to the investment impulse, the substitution of imported fossil fuels with domestic renewable energy production also has a positive impact on the economy, although the imports of renewable energy technologies reduce this impact. In the case of PV about 30% of the investments are assigned to imports (mainly wafer, solar cells and modules) with fixed import shares per component.[9] The positive impact on domestic production might therefore be overestimated as in the past an increase in import shares was observed. In contrast to other studies (Duscha et al., 2016; Lehr et al., 2012), exports of renewable or energy efficiency technology are the same in both scenarios. There are arguments that under the energy transition these are higher compared to the reference situation, and thus might drive economic growth even further than depicted above.

It is commonly argued (Breitschopf et al., 2013; Cox et al., 2014; Duscha et al., 2016; Lehr et al., 2012; Lutz et al., 2012), that increases in electricity prices or heating expenditures have a dampening effect on the non-energy consumption of households and on value added of industries. We differentiate between electricity prices for households and service sectors, non-energy intensive and energy-intensive industry. Electricity prices are indeed higher in the energy transition scenario, but final energy demand is lower due to increased efficiency. Energy expenditures of households are thus actually lower in the transition scenario (although expenditures for rents and consumer durables increase). The same effect can be observed for service sectors which have to spend slightly less on electricity (measured as a proportion of their output). Industrial sectors on the other hand face slightly higher expenditures for electricity as their decrease in energy consumption does not outweigh increasing electricity prices. This results in lower value added (both measured as a proportion of their output). We do not include impacts on international competitiveness in our analysis as these effects are small, as a recent study shows (Grave et al., 2015).[10]

Fig. 4 illustrates the relative change of the gross value added by sector and industry under the energy transition as well as the overall absolute change of the value added.

The transition of the energy system induces changes in the electricity industry (sector group D). The main drivers of the growth in value added are increasing investments in electricity generation technologies and thus high depreciation and surplus. Higher investments in the electricity system also explain the significant increase in value added in construction (F) and in the financial sector (K). Due to the decreased demand for fossil energy sources, especially coal, there are large negative effects for mining and quarrying (B), while additional demand for biomass increases the value added of the agricultural sector (A).

With respect to the heat sector, increased energy efficiency measures in buildings result in the growth of value added in construction (F). The largest absolute change in value added occurs in real estate (L). This can be explained by the fact that German law allows 11% of additional building investments that increase energy efficiency to be passed on to the tenants via rents, which (at least partly) reflects the higher value of the property. So we assume that the actual (for tenants) and hypothetical (for homeowners) rents increase accordingly.[11] As the energy savings achieved by investments in energy efficiency cannot offset these higher rents, the corresponding reduction of household spending leads to slight negative impacts in some industries. However, the value added of the public sector (O-Q) increases slightly compared to the reference situation due to higher economic growth and thus government spending.

The system transition in the transport sector requires additional investments in infrastructure such as the rail network or charging infrastructure for electric vehicles. Expenditures for vehicles also exceed those in the reference scenario due to energy efficiency measures and electric powertrains, which are more costly. The largest relative change in value added therefore occurs in construction (F) and manufacturing (C). Mining (B) serves as an important input industry for construction and thus benefits, too. Higher household expenditures for vehicles are almost offset by lower energy expenditures for mobility, so that the impact on household budgets is neutral. The positive investment impulse acts as a stimulus for the economy as a whole so that all the industries shown in Fig. 4 experience a slight increase in value added compared to the reference scenario.

The dominant effects of the differentiated results (electricity, heat and transport) are still visible in the aggregated result. These include a strong relative decrease in mining and a strong relative increase in electricity generation (electricity), construction (mainly heat but also transport and to some extent electricity) and real estate services (heat). In absolute terms, the negative impacts on mining are small, while there are large positive impacts on real estate services.

The employment effects (Fig. 5) are spread across economic sectors in a similar pattern as displayed by the changes in value added, but with two differences: Higher rents increase the value added of real estate services (capital related components), but do not lead to additional employment. Value added in the electricity sector increases mainly because of increased capital input and income. This implies that the labour productivity of this sector increases slightly and the change in employment is lower than the change in value added. Similar to the value added changes, the absolute changes in employment are small and negative in mining, but large in relative terms. In contrast, the employment effects are significant and highly positive for construction.

4.2. Distribution of impacts across regions

In all the federal states, the gross value added in the energy transition scenario is higher than in the reference scenario. The regional differences are illustrated in Fig. 6. Abbreviations used and

[8] Accounting for the crowding out effect potentially reduces positive impacts or even leads to negative impacts on economic output in neoclassical models. In post-Keynesian models however, financial constraints dampen but do not reverse the growth effect as modelling exercises with the macro-econometric model E3ME (E3MLab, 2016) show (European Commission, 2016; Lewney et al., 2017; Pollitt and Mercure, 2018)

[9] The overall import share decreases to 20% in 2030, as the presumed decline in costs is more pronounced for components with a high import share.

[10] Input-output tables present always an average of many firms, and there will certainly be firms which are more affected, while others are less. Modelling this is however beyond the scope of the model. Electricity input coefficients of service sectors are up to 3% lower in the transition scenario. Electricity input coefficients of most industry sectors are up to 2% higher in the transition scenario. Only for three sectors (paper, chemicals and ferrous metals) the input coefficient of electricity is up to 8% higher in the energy efficient scenario. To calculate the electricity expenditures of these sectors, they are split into an energy intensive and non energy intensive part based on Grave et al., 2015 and the differentiated electricity prices are applied. Energy intensive industries continue to be exempted from special levies on electricity prices.

[11] The Federal Statistical Office includes both actual and hypothetical rents into national economic accounting. Hypothetical rents of homeowners are calculated based on actual rents of comparable housing (Statistical Office of the European Communities, 2013). To the best of our knowledge, there is no literature that analyses if the increase in rents can fully be achieved on all local housing markets. A reduction to 8% is planned but not in place yet. Thus, the impact should be interpreted as upper limit, especially for regions with housing markets that do not suffer from excess demand.

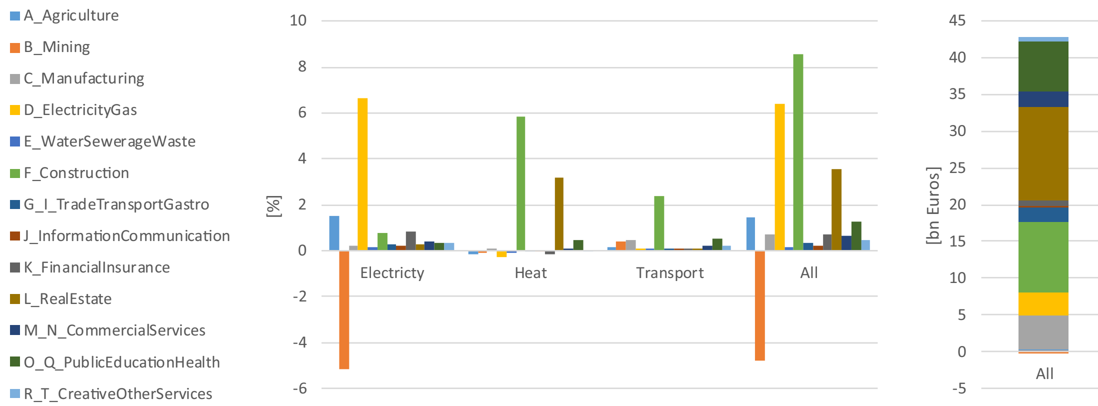

Fig. 4. Change in gross value added per sector group in the scenario compared to the reference scenario in 2030 as an overall impact and differentiated for electricity, heat and transport. The left part of the diagram shows the relative changes in percent; the right part shows absolute changes in billion euros.

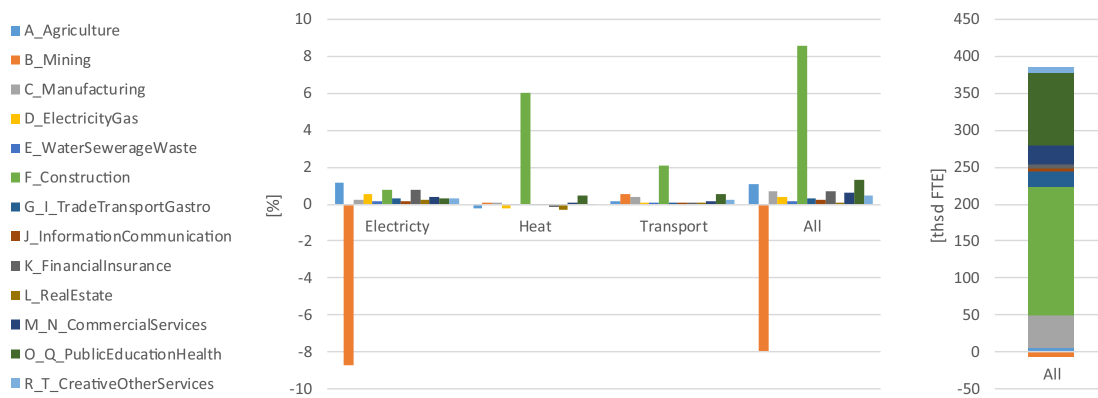

Fig. 5. Change in employment per sector group in the scenario compared to the reference scenario in 2030 as an overall impact and differentiated for electricity, heat and transport. The left part of the diagram shows the relative changes in percent; the right part shows the absolute changes in thousand full-time equivalents.

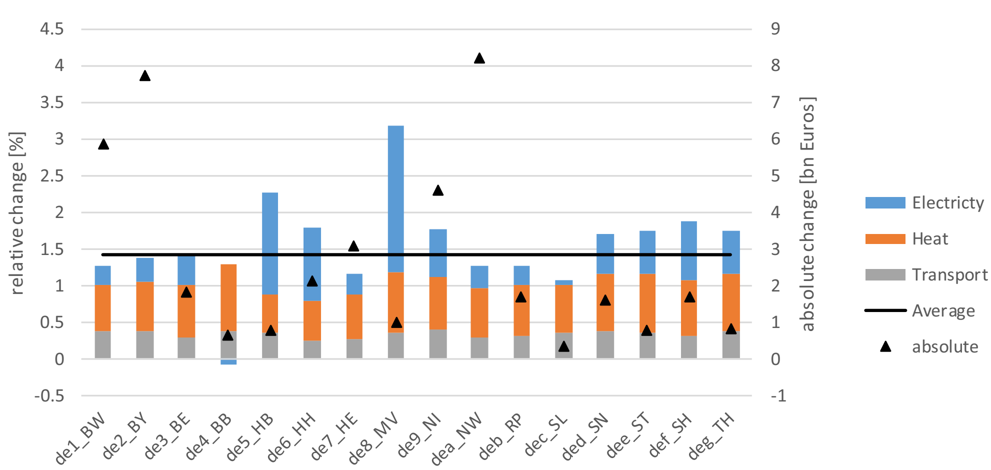

Fig. 6. Change of gross value added per region in the energy transition scenario compared to the reference scenario in 2030. The left axis shows the relative changes in percent differentiated for electricity, heat, transport, overall impact and the national average. The right axis shows the corresponding absolute values in billion euros.

geographical location of the federal states are given in Table Annex 1 and Fig. Annex 1 respectively. Fig. 6 shows strongly varying relative changes in gross value added under the energy transition, whereas changes in the heat and transport sector are more evenly distributed among the regions. In absolute terms, the changes correlate with the respective economic strength of the federal state.

Mecklenburg-Western Pomerania (MV) experiences the largest relative increase in value added in 2030, partly because the value added in the reference case is much lower here than in other federal states. Thus, even small changes are large in relative terms. However, the absolute change is also clearly positive and similar to other federal states. There is a significant expansion of renewable energy, especially offshore wind, in Mecklenburg-Western Pomerania between 2020 and 2030. This is associated with additional investments and increased value added from servicing and operating the installations. At the same time, Mecklenburg produces hardly any electricity from fossil energy sources that could be displaced, so that the net impact here is clearly positive. Mecklenburg-Western Pomerania is also less strongly affected by higher electricity prices. The relative changes in gross value added due to the energy transition in the heat and transport sector are similar to those in other federal states. A more detailed description of the impacts for MV is given in the supplementary material 2.

Electricity production from wind (both offshore and onshore) also expands in Lower Saxony (NI) and Schleswig-Holstein (SH) as well as in the coastal regions assigned to the city-states of Hamburg (HH) and Bremen (HB). This means that the five regions with the largest relative increase in value added (both for electricity alone and for the overall impact) are all characterized by additional wind energy and their geographic location, i.e. in the wind-rich northern part of Germany.

The eastern federal states of Saxony (SN), Saxony-Anhalt (ST) and Thuringia (TH) show relative changes of value added in 2030 that are above the average of 1.3%. Production from renewable energy (PV and wind) is higher in these regions compared to the reference scenario, and losses due to reduced electricity production from fossil fuels are of minor importance.

Negative effects on value added in 2030 are visible in Brandenburg (BB), but only when looking at the energy transition in the electricity system on its own. This is due to lower electricity production from lignite and the resulting decrease in the mining of lignite, which cannot be offset by the positive impact from the expansion of solar energy in this region. However, when taking into account the economic impulses of the energy transition in the heating and transport sectors as well, the overall net impact is still positive for Brandenburg.

Beside Brandenburg, there is also a negative absolute change in value added in the electricity production sector for Baden-Wuerttemberg (BW), Hessen (HE) and especially Saarland (SL). However, in these regions, the positive impacts of the energy transition in other economic sectors again compensate (SL) or even overcompensate (BW and HE) any negative impact.

In North Rhine-Westphalia (NW), electricity production from coal and lignite is lower than in the reference scenario, but PV and gas capacities increase. The lower value added in the mining sector is offset by positive effects in the electricity sector and other economic sectors. The absolute change in value added is largest in this federal state for both electricity only and the overall impact. A more detailed description of the described impacts for NW is given in the supplementary material 2.

Bavaria (BY) shows the second largest absolute change in value added and a relative change just below the average. The installed capacities of PV, wind and gas are higher than in the reference scenario but lower for coal. In Berlin (BE), the installed capacities of rooftop PV and gas are higher than in the reference scenario, but lower for coal and lignite. The net impact on all industries is positive for Berlin with the relative change in value added just reaching the average. In Rhineland-Palatinate (RP), the installed capacity for electricity production from wind and gas is higher but lower for PV than in the reference scenario.[12] A slight negative impact on the manufacturing sector is offset by positive impacts in other sectors.

The relative change in employment in the regions is illustrated in Fig. 7. The impact depends on where and in which sectors increases or decreases in value added take place, and how labour-intensive these sectors are in the respective region. For many regions, the employment effects are of a similar magnitude to the value added effects and the regional distribution pattern is similar as well. However, some aspects should be noted.

Energy efficiency measures in buildings increase rents and trigger an increase in the value added in real estate, but not in employment. Thus, in all regions, the relative change in employment is lower than the relative change in value added when looking at heat only. This effect is strongest in the city-states Berlin (BE) and Hamburg (HH).

With respect to transport, the relative change of employment is of a similar magnitude or higher than the relative change in value added. This is because a main part of the increase in value added occurs in the labour-intensive construction sector.

Looking only at the transition of the electricity system, the relative change of employment is smaller than the change of value added. This is especially the case for federal states where a high proportion of the increase in value added takes place in the electricity production sector, such as Hamburg (HH) and Bremen (HB). In Brandenburg (BB), negative effects occur in the less labour-intensive energy sector, and positive effects in labour-intensive construction. The negative effects dominate the value added, the positive effects employment.

Comparing the regional changes in value added with the current regional value added per capita clearly shows that (with the exception of Brandenburg) especially the less productive economies of the northern and eastern German federal states benefit, while the more productive western and southern federal states experience below average growth (Fig. 8). Under the given model and scenario assumptions, therefore, the energy transition could contribute to a convergence of economic strength and cohesion of German regions. Nevertheless, it should be noted that this effect is very small when viewed in the context of regional differences in 2030 according to the model results.

However, there are some shortcomings in the modelled impacts:

(1) Indirect and induced effects are to a large extent calculated nationally in the model and distributed via a top-down approach, affecting economically very active regions (value added) more strongly in absolute terms. The distributional effects would be more pronounced if regionally assigned economic impulses affect value added of the respective region not only via direct but also via indirect and induced effects. This includes for example income resulting from investments in wind energy in Mecklenburg-Western Pomerania which is again spent on products from Mecklenburg-Western Pomerania. Most likely the positive impact of the energy transition on regional cohesion would be strengthened.
(2) An increased value added in one region does not necessarily mean increased income in the same region because the distribution of profits depends, e.g. less on the location of the operating company and more on the hometown of the relevant shareholders. Regionally provided labour services do not necessarily increase demand because the earned income can be transferred to and spent in other regions.
(3) The regional effects build upon the regional disaggregation of renewable use in the electricity sector, manufactures and operating firms, while investments into energy efficiency are allocated through the top-down module. A further direct regionalisation of energy efficiency investments might alter the regional distributional effects.

5. Conclusions and policy implications

Macroeconomic impacts such as changes in economic growth and employment are very important when evaluating the energy transition in societal terms. We assess these impacts by employing a macroeconomic model that accounts for regional, economic and sectoral features. The model results show overall positive – albeit moderate - net impacts of the energy transition on economic growth and employment.

The major part of the positive impact can be explained by the energy transition in the heat and transport sectors: Energy efficiency measures in buildings and investment in transport infrastructure and vehicles raise the level of domestic demand, while energy efficiency and renewable energies reduce the imports of fossil fuels. In comparison to

[12] This modelling result of Enertile reflects that another regional distribution of installed PV capacities is optimal under the conditions of the energy transition scenario compared to the reference scenario. Total installed PV capacity is higher in the energy transition scenario.

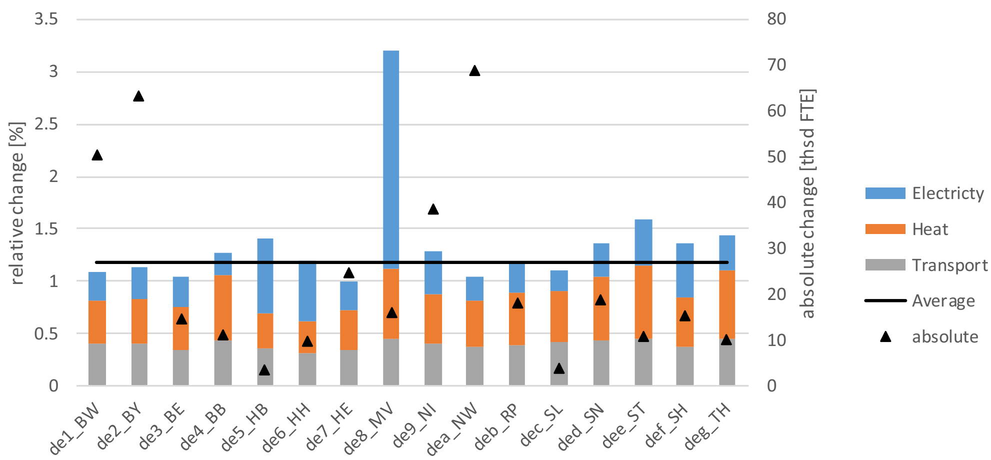

Fig. 7. Change of employment per region in the energy transition scenario compared to the reference scenario in 2030. The left axis shows the relative changes in percent differentiated for electricity, heat, transport, overall impact and the national average. The right axis shows the corresponding absolute values in thousand full-time equivalents.

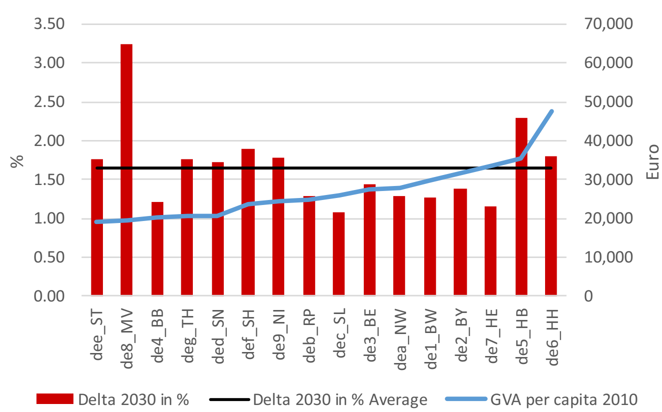

Fig. 8. Relative change of gross value added per region (red bars, left axis) and national average (black line, left axis) in the energy transition scenario compared to the reference scenario in 2030. Regions ranked by gross value added per capita in 2010 (blue line, right axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

this, the expansion of renewable power generation based on Pfluger et al. (2017c) has a weaker net impact. At the same time, structural changes have diverging regional and sectoral effects.

Regarding the impacts on industries, the biggest relative increases in value added occur in construction, real estate and electricity generation. The biggest decrease is in mining due to the reduced demand for fossil fuels. The distribution of changes in employment across industries follows the same pattern as for value added. However, the labour intensities in the sectors vary so that some sectors are less affected than others.

Regarding regional impacts, the model results suggest that especially northern and eastern German federal states will benefit economically from the energy transition in the future because they offer attractive locations for investments in renewable energy. At the same time, these states are less affected by decreasing conventional energy generation. Moreover, the impact of rising electricity prices is less negative here than in the other federal states because of their lower electricity intensity in production. In summary, the energy transition represents an opportunity for these regions.

However, the modelling approach does not account for regional value added multiplication effects. Instead, the indirect and induced impacts in a sector are calculated nationally and then distributed based on the relative economic strength of a region within this industry. Altering this aspect would result in a regional distribution of value added that is more dominated by direct effects. Especially for less productive regions with high direct effects, the positive impact would be more pronounced. On the other hand, the model does assume that a high share of the value added from producing, installing, operating and maintaining renewable energy technologies remains in the region where it is located. However, this would have to be supported by suitable incentives.

As stated above, the modelling results show clear distributional effects of the relative change in value added caused by impulses that can be attributed to the energy transition in the electricity system. This is in line with ex-post analyses (Többen, 2017) and is the result of including regional differences with respect to electricity consumption, electricity generation, as well as the distribution of economic activities for producing, installing, operating and maintaining the technologies. The database for the latter could be improved by conducting a survey instead of relying on scarce data, literature and expert knowledge.

The model could be improved by including the regional allocation of bottom-up impulses for the heat and transport sectors. With respect to energy efficiency measures in buildings, including regional differentiation of the building stock in bottom-up models would make it possible to allocate the investments required to meet policy targets. Ideally these would also address the open question on the actual increase of rents due to these efficiency measures based on local housing markets. Another open question is the location of the firms actually involved in the building measures and the transfer of income given the high share of migrant workers in the construction sector. Although there are some studies that argue there is a high local content of value added (Weiß et al., 2014), we have no knowledge of published data on this aspect. One should also note that, in contrast to the impact on the real estate sector, this is a temporary effect, i.e. lasts only during the period of construction.

The model results show the potential and risks of the energy transition for the regions and point to structural changes in labour demand. Regarding policy, there are several issues that deserve special consideration:

- Ensure sufficient qualified human resources: The modelling results display in which industries jobs will be created. To benefit from long-term effects of the energy transition, policy makers should spur, prompt or stimulate education and training in cooperation with the industry and education sector. The activities are manifold, ranging from providing infrastructure up to elaborating curricula for training programmes and certifications of programmes.
- Enable retraining: This is necessary in regions suffering from the decline in mining or manufacturing of conventional energy generation (technology), as this is a permanent change. People who have lost their jobs need training opportunities and special support to acquire new qualifications.
- Structural changes: But beyond this, seriously affected regions are challenged to identify new opportunities and provide targeted support/incentives for setting up new industries and services e.g. green industries, IT services, health services, etc. Networking, experience sharing at national or international level, participative discussion forums on new technologies or developments could provide impulses for new ideas or help identifying opportunities.
- Focus on education, health, creativity: The increase in value added through the energy transition entails higher tax revenues. Spending these additional revenues for better early childhood development, education, nutrition, creativity and health services can contribute to a higher living standard, improve qualifications and knowledge that eventually result in innovative products and services and finally in further economic growth. This potential positive effect of the energy transition is not included in the model.
- Planning certainty for industries in transition: Rising energy prices in one country provide incentives for efficient energy use of industries and consumers but at the same time distort the market and weaken the competitiveness of national industries (model result shows higher energy expenditures for some industries). A trade-off is needed to further stimulate investments in energy efficiency, induce structural changes and maintain competitiveness. Thus, a transparent, clearly communicated and finite scheme of exemptions for large industrial electricity consumers provides planning certainty, avoids negative impacts of a sudden abolishment of exemption schemes (Grave et al., 2015) and still stimulates transition in those industries.
- Facilitate new businesses: The model highlights the positive impact on regional value added of natural conditions and locations that favour wind power, in particular. Recalling Porter (1990), factor endowment, including natural conditions are just one factor driving economic growth; business structures and strategies and frameworks set by governments are other crucial drivers. Changing prices of energy carriers or resources in the course of the energy transition in combination with quickly advancing changes in information, communication, material and biotechnologies create new business opportunities for small companies as well. Regions able to benefit in the long term do not rely solely on their natural conditions, but also have a flexible and open administration and policies in place that support or create a favourable environment for businesses and economic activities, e.g. a highly qualified workforce, reliable (IT) infrastructure, effective and efficient administration and jurisdiction. They facilitate the development of start-ups and new business models. Taking into account potential new businesses, products or processes would further push economic growth.

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Appendix A. Annex

Table Annex 1
Germany's Federal States: Acronyms (Source: First part of abbreviation NUTS1-classification, second part of abbreviation ISO-3166-2 subcode) and regional distribution of population and GDP in 2010 and 2030 (reference scenario).
(Source: model results).

Acronym	State	Share in population 2010	Share in population 2030	Share in GDP 2010	Share in GDP 2030
de1_BW	Baden-Wuerttemberg	13.1%	13.8%	14.2%	15.4%
de2_BY	Bavaria	15.3%	16.2%	17.4%	18.7%
de3_BE	Berlin	4.2%	4.5%	4.1%	4.3%
de4_BB	Brandenburg	3.1%	2.9%	2.2%	1.8%
de5_HB	Bremen	0.8%	0.8%	1.0%	1.1%
de6_HH	Hamburg	2.2%	2.3%	3.7%	3.9%
de7_HE	Hesse	7.4%	7.6%	8.9%	8.9%
de8_MV	Mecklenburg-Western Pomerania	2.0%	1.8%	1.4%	1.1%
de9_NI	Lower Saxony	9.7%	9.7%	8.6%	8.7%
dea_NW	North Rhine-Westphalia	21.8%	21.6%	22.0%	21.5%
deb_RP	Rhineland-Palatinate	4.9%	5.0%	4.4%	4.4%
dec_SL	Saarland	1.3%	1.2%	1.2%	1.1%
ded_SN	Saxony	5.1%	4.6%	3.8%	3.2%
dee_ST	Saxony-Anhalt	2.9%	2.4%	2.0%	1.4%
def_SH	Schleswig-Holstein	3.5%	3.5%	2.9%	3.0%
deg_TH	Thuringia	2.8%	2.3%	2.0%	1.5%

Table Annex 2
Exogenous inputs from the energy sector models, their transformation and distribution as macroeconomic and regional impulses.

Output of energy sector models					Transformation and distribution	Impulse for macroeconomic core model in Euro (2010 – 2030)	Impulse for regional distribution module in Euro (2010–2030)
Model origin	Sector	Type of variable (impulse)	Unit	Time			
Enertile	Electricity	1. Added capacity per technology and region	kW	2012, 2020, 2030	**Per technology**: Investment components in Euro/kW **Per component**: • Sectoral distribution • Assignment to regional categories: region of power plant, region of main producer, no specific region, imports • Regional distribution per regional category	1. Domestic and imported investments in energy generation technology per economic sector (2012 – 2030)	1. Regionally assigned **investments** in energy generation technology per economic sector and region (2012–2030)
Enertile	Electricity	2. Installed capacity per technology and region	kW	2012, 2020, 2030	a) Operation and maintenance components in Euro/kW per technology and year: • Sectoral distribution per component of each technology • Distribution of each component to regional categories • Regional distribution of main producers b) Wages, profits, depreciation in Euro/kW per year	2. a) Domestic and imported **intermediates** for electricity generation (2012–2030) **b) Value added** of electricity generation: wages, profits, depreciation (2012–2030)	2. a) Regionally assigned intermediates for electricity generation per economic sector and region (2012–2030) b) **Value added** of electricity generation per region (2012–2030)
Enertile	Electricity	3. Differential investments in transformation and distribution grids	Euro	2020, 2030	Sectoral distribution	3. Additional **investments** per economic sector	
Forecast	Electricity	4. Electricity prices (energy-intensive and non-energy-intensive industries, services, households)	Euro/ kWh	2010–2030	Applying relative annual changes in electricity price and efficiency to intermediate matrix of input output table	4. Change in **intermediate** demand for electricity (energy-intensive and non-energy-intensive industries, services)	
Forecast	Electricity	5. Electricity consumption (industry, services, households)	TWh	2010, 2015, 2020, 2025, 2030		5. Electricity **consumption** (households)	
Forecast	Energy	6. Industry energy demand per energy carrier)	TWh	2010, 2020, 2030	Per energy carrier (oil, coal, gas, biomass): cost development and assignment to economic sector	6. Change in domestic and imported **intermediates**	
Forecast	Electricity	7. Differential expenditure in energy efficient technology (households)	Euro	2020, 2030	Sectoral distribution	7. Additional **consumption** of energy efficient technology per economic sector	
Forecast	Electricity/ heat	8. Differential expenditure in energy-efficient technology (services, industry)				8. Additional **investments** in energy-efficient technology per economic sector	
Invert	Heat	9. Differential investments in buildings and heating systems	Euro	2010–2030	11% of additional investments allocated to increased rents	9. a) Additional **investments** in specific construction sector b) Additional **consumption** in real estate sector	
Invert	Heat	10. Household expenditure by energy source for operating heating system	Euro	2010–2030	Sectoral distribution	10. Energy **consumption** for heating per economic sector	
ASTRA	Transport	11. Energy demand for fossil fuels, biofuels, electricity	TWh	2010–2030	Per energy carrier: cost development and assignment to economic sector Division into private and commercial transport	11. a) Fuel **consumption** (households) b) Domestic and imported **intermediates** for commercial transport	
ASTRA	Transport	12. Differential expenditure on vehicles (households)	Euro	2010–2030	Sectoral distribution	12. Additional **consumption** of vehicles	

(*continued on next page*)

Table Annex 2 (*continued*)

Output of energy sector models					Transformation and distribution	Impulse for macroeconomic core model in Euro (2010 – 2030)	Impulse for regional distribution module in Euro (2010–2030)
Model origin	Sector	Type of variable (impulse)	Unit	Time			
ASTRA	Transport	13. Differential expenditure on vehicles (services, industry) 14. Additional investment in infrastructure	Euro	2010–2030	Sectoral distribution	13. Additional **investments** in vehicles 14. Additional **investments** in infrastructure	

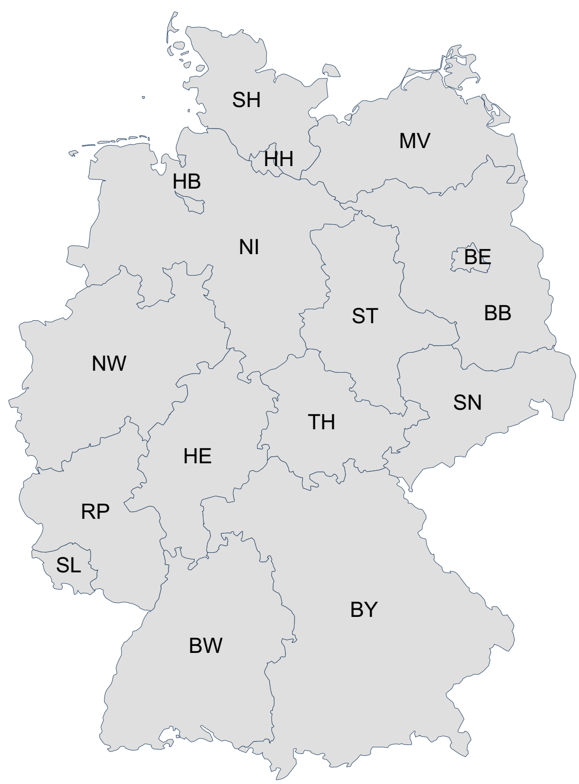

Fig. Annex 1. Germany's federal states.

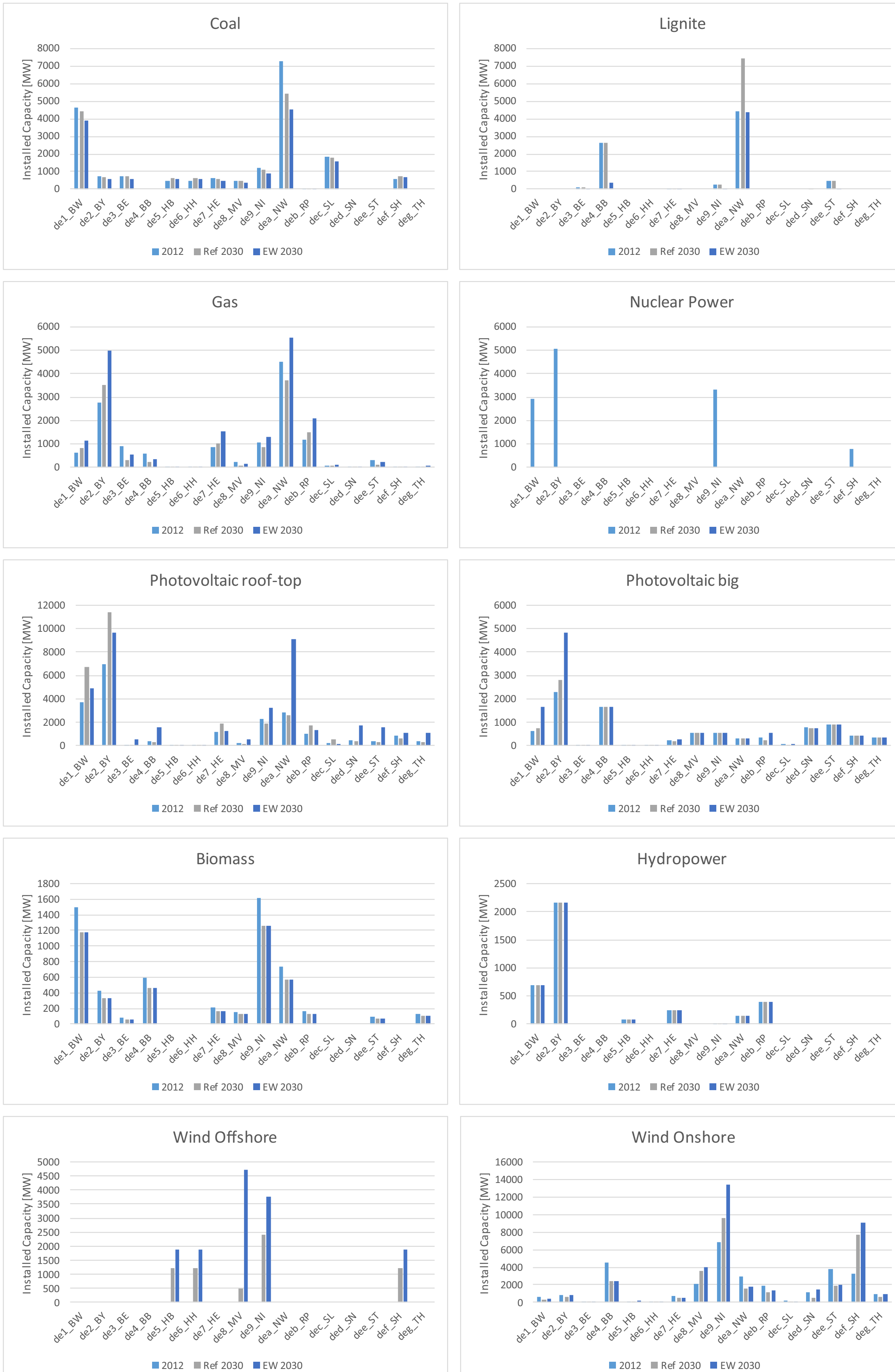
Coal
Lignite
Gas
Nuclear Power
Photovoltaic roof-top
Photovoltaic big
Biomass
Hydropower
Wind Offshore
Wind Onshore
Installed Capacity [MW]
de1_BW de2_BY de3_BE de4_BB de5_HB de6_HH de7_HE de8_MV de9_NI dea_NW deb_RP dec_SL ded_SN dee_ST def_SH deg_TH
2012
Ref 2030
EW 2030

Fig. Annex 2. Installed capacity in MW per technology and region for the years 2012 (dark blue bar), and 2030 (reference scenario green bar, energy transition scenario light blue bar).
Source: own calculations based on Pfluger et al., 2017c and Bundesnetzagentur, 2015.

Appendix B. Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.02.017.

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