Energising EU Cohesion

Powering up lagging regions in the renewable energy transition

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Powering up lagging regions in the renewable energy transition

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Abstract

The European Green Deal mandates a substantial transformation of the energy sector, responsible for more than 80 % of total greenhouse gas emissions. This study investigates the economic implications of achieving climate neutrality in the European energy sector in light of the EU's core goal of economic cohesion, i.e. harmonious economic development across European regions. Employing a novel multi-regional input-output model, our analysis reveals how the renewable energy transition affects European regions. Under complete decarbonisation, changes in value added per capita range from -2,450 Euro to +1,570 Euro, and employment levels fluctuate between -2.1 % and +4.9 %. On average, most regions experience positive effects, characterised by an average increase in value added per capita of 10 Euro and a 0.3 % rise in employment in 2050. Overall, rural regions with substantial renewable energy potential derive the greatest benefits, while urban regions heavily reliant on carbon-intensive industries are more likely to experience adverse effects. This dynamic fosters economic cohesion by providing opportunities for lagging regions to catch up, yet also poses fresh challenges to achieving this goal. Therefore, cohesion policy must expand its scope to counter the adverse effects as well as leveraging opportunities created by the renewable energy transition in all European regions.

JEL-Codes: C67, O11, Q43

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Bertelsmann Stiftung – Europe’s Economy

As part of the *Europe's Economy* project, the Bertelsmann Stiftung investigates which economic, social and territorial imbalances are relevant for the European Union. The team analyses how the structural changes associated with the green and digital transition will affect Europe's economic base. Against this background, the project develops proposals on how to improve the EU's internal market and how the EU can make better use of its policies and resources to strengthen cohesion in Europe.

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Contents

1 Introduction

Decarbonising the European Union's (EU) economy by 2050 is the core mission of the European Green Deal (European Commission 2019, 2020; OECD 2023). Transforming the energy sector, which accounts for more than 80 % of CO_2 emissions (EEA 2023), will be critical for the process of decarbonising virtually all economic sectors across the continent. Specifically, this means increasing renewable energy production (European Commission 2019; OECD 2023) whilst at the same time reducing substantially the consumption of fossil fuels (European Commission 2019; IPCC 2023). Yet the policies to bring about the required energy transition that are currently in place will only halve current greenhouse gas emissions by 2050 (European Commission 2021). Put simply, there remains a huge gap between policy ambition and policy practice.

The renewable energy transition plays a pivotal role in closing this gap – whilst at the same time reshaping the structure of Europe's economy. It brings substantial positive changes by promising additional opportunities for economic development and job creation. At the same time, phasing out fossil fuel-based energy production threatens certain economic structures and makes employment in some sectors obsolete. How precisely regions are affected hinges on their respective energy systems and economic structures. In any case, the changes imposed by the energy transition will alter the landscape of economic prosperity in Europe as we know it today by introducing new imbalances and disparities in the EU en route to carbon neutrality. (European Commission 2022; Bertelsmann Stiftung 2022; Többen et al. 2023; Sasse and Trutnevyte 2023).

In this study, we assess the economic impact that a fully-fledged energy transition would have on Europe's regions, whilst at the same time considering the need for harmonious economic development across the EU. Using a new multi-regional input-output (MRIO) model, we quantify the potential effects on value added and employment created by phasing out fossil fuel-based energy and expanding renewable energy. This allows us to calculate the geographical distribution of these effects and analyse the impact upon regional convergence.

Our results show that the economic effects caused by the renewable energy transition vary greatly across European NUTS-2 regions. The change in value added per capita ranges from -2,450 Euro to +1,570 Euro and in employment between -2.1 % and +4.9 %. A majority of regions are positively affected showing – on average – a plus of 10 Euro per capita in value added and 0.3 % more employment by 2050. Overall, however, the results show that the positive and negative economic effects of the energy transition balance each other out across regions. If a climate-neutral energy system is achieved, our results suggest a negligible decrease in value added and employment by 2050 (-0.3 % for GDP and -0.1 % for employment). This aggregate result is in line with earlier findings of Vrontisi et al. (2020), Dejuán et al. (2022) and Su et al. (2022).

Further, our results show that regions leading the way in renewable energy expansion and rural regions with high technical potential for installations of renewable energy technologies should benefit from the energy transition. Regions with carbon-intensive industries and urban regions that have low technical potential are inevitably more challenged. We find that economically lagging – mostly rural – regions today are more likely to benefit from the energy transition than more advanced – mostly urban – regions.

Countering imbalances in economic development across EU regions is an explicit political aim of the EU, which seeks to prevent damaging territorial inequalities. Ensuring equal opportunities among all EU citizens to enjoy the benefits of economic prosperity is meant to hold Europe together at its core, a prerequisite for public backing of the Green Deal. From the perspective of this parallel EU objective of economic cohesion, then, our results are both good and bad news. More convergence between European regions supports the main goal of cohesion policy. However, this convergence means that today's economically more advanced regions will eventually have lower shares in EU wide value added and employment. Despite their overall high level of readiness for the green transition (Bertelsmann Stiftung 2022), urban regions face greater challenges in the switch to renewable energy than rural regions. This is because of their lower potential for renewable energy generation and their – at least in absolute terms – higher energy demand.

To counter negative effects on the EU’s aim of harmonious economic development, European cohesion policy must extend its reach to encompass the challenges faced by regions currently not on policymakers' agenda, let alone radar. Supporting these regions in their efforts is not only important for European cohesion but critical to guaranteeing support for the European Green Deal. Cohesion policy must therefore leverage synergies with energy policy and broaden its scope to make the renewable energy transition beneficial for all European regions.

The remainder of this study is organised as follows. In Section 2, we describe the necessary transformation for a decarbonised European energy sector. It is followed in Section 3 by an assessment of the regions’ different starting positions. In Section 4, we explain our MRIO-modelling approach. In Section 5, we present the results of our scenario analysis on how the green transition reshapes EU-wide cohesion. In Section 6, we summarise the results of the study and provide policy recommendations.

2 Transforming the European energy sector

More than 80 % of the EU's greenhouse gas emissions are created by the production and use of energy (EEA 2023). Given the relevance of energy for all other economic sectors, decarbonisation of the energy system is crucial to reach the EU's climate objectives in 2030 (55 % less greenhouse gas emission compared to 1990) and 2050 (climate neutrality) (European Commission 2019). This involves adjustments of multiple levers:

Phasing out fossil energy: Carbon neutrality and a decarbonised economy requires the phasing out of all fossil energy sources. This entails the substitution of fossil fuel-based electricity generation, space heating and private transportation and lower coal, refined petroleum and gas usage. EU and national restrictions on using coal for generating energy, the stipulations of the Industrial Emissions Directive (2010/75/EU) and uncertainty about near-future carbon pricing all support the fossil phase out (Alves Dias et al. 2018).

Expanding renewable energy production: Phasing out fossil fuel-based energy goes hand in hand with greater renewable energy production. There has been an EU-wide increase in the share of renewables in the energy mix (see Figure 1). To fully decarbonise the energy system more renewable energy needs to be combined with a lower total demand leading to higher energy efficiency (IEA 2023; Busch et al. 2023). That ineluctably means decoupling economic growth and energy consumption. The EU's decoupling ambitions (European Commission 2019) are supported by recent studies outlining that economic growth is possible without greater energy consumption (Pirlogea and Cicea 2012; Bianco et al. 2019; Topolewski 2021).

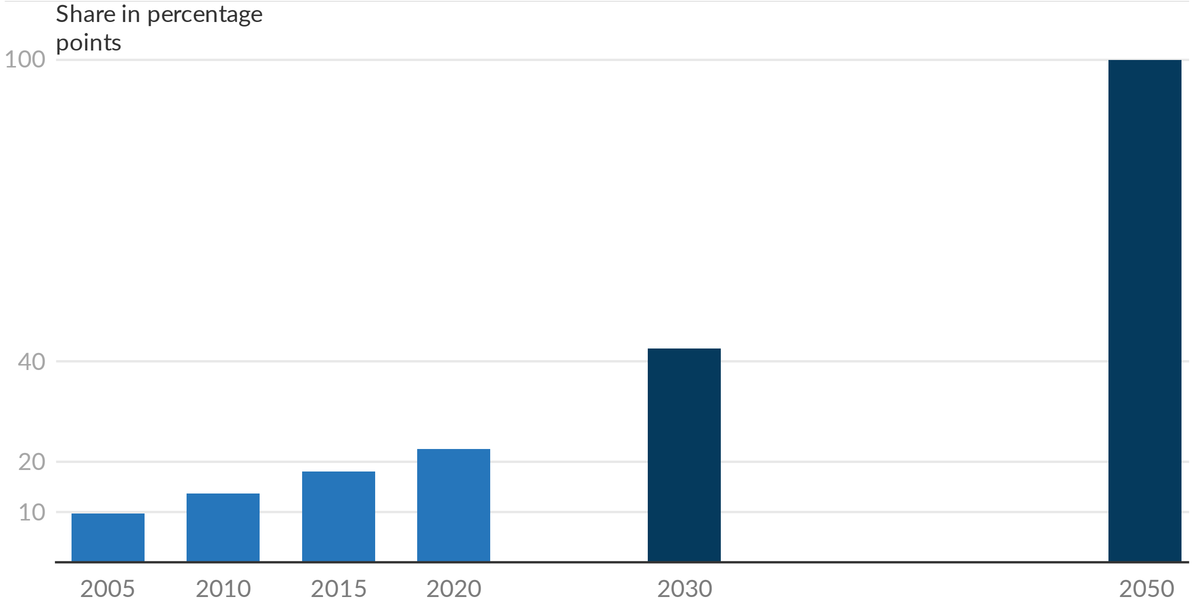
Investments in renewable energy technologies, storage and transmission capacities: The incorporation of more volatile renewable energy sources requires a fundamental structural change to the energy system. Given the uneven geographic distribution of fossil fuel and renewable energy sources, new infrastructure that links regions where energy can be produced cheaply with high demand centres is needed (IEA 2023).

Changes in energy prices: The investment costs required to build up the new renewable energy system including transmission grids and storage facilities will drive future electricity prices. At the same time, phasing out fossil fuel-based energy cuts out the costs of emitting carbon, which has a dampening effect on energy prices. Whether or not the net-effect of decarbonisation on energy prices is positive or negative is highly uncertain and depends, on the one hand, on the cost degression of renewable energy, transmission, and storage technologies and, on the other hand, on EU carbon pricing policy.

Overall, decarbonisation will bring macroeconomic effects in its wake: An increase in the demand for renewable energy technologies and changes in the energy system's costs via required investments will be passed on through the supply chains with wider knock-on effects on consumer prices, value added and employment.

European policymakers are keen to foster the transition to a renewable energy system. Thus, several policies are in place to accelerate this transition. By 2030, at least 42.5 % of the EU's total energy demand should be provided by clean energy technologies like wind and solar energy (European Commission 2023). By 2050 at the latest, almost 100 % of total energy demand must be met by renewable energy to meet climate neutrality. Figure 1 shows the development of renewable energy shares in gross final energy consumption since 2005. Starting at 10 %, that share consistently grew to 22.1 % in 2020 (European Commission 2021). However, to meet the targets set for 2030 and 2050, it now needs to grow more rapidly.

Figure 1: Renewable energy consumption more than doubled between 2005 and 2020 – but a further doubling by 2030 and quadrupling by 2050 is necessary



Notes: The figure shows the share of renewable energy in total energy consumption in Europe. Values for 2030 and 2050 are policy targets. Source: European Commission (2021).

The transformation to a carbon neutral economy and reaching the current climate goals for 2030 are estimated to require additional annual investment of about 260 billion Euro (European Commission 2019, 2020). However, in the long-run the costs of decarbonisation and a rapid transformation of the energy system will be lower than the damage caused by climate change (Gillingham 2019; Flaute et al. 2022).

To assess and project future developments in decarbonisation and greenhouse gas reduction targets, the EU uses model-based projections like the "EU Reference Scenario 2020" (European Commission (2021), hereafter *EU Reference Scenario* or *EU REF*). The EU Reference Scenario reflects policies and market trends and provides a possible future outlook on the development of the EU energy system, transport systems and greenhouse gas emissions, for the 27 EU member states individually and altogether. It outlines where the EU energy and climate policy stands today and where it likely stands in 2030 and 2050.

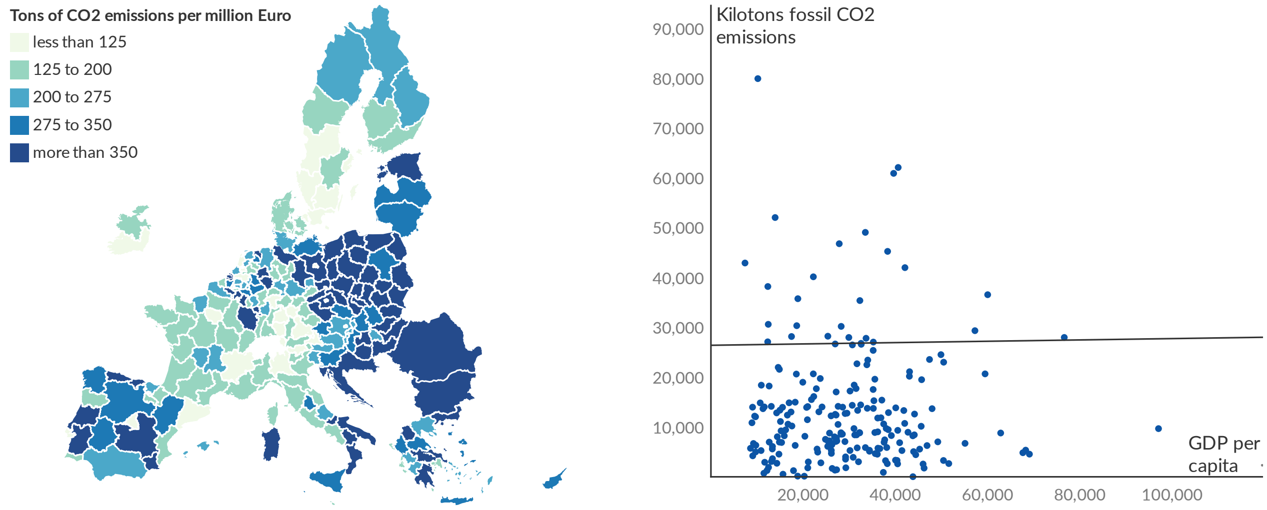
If no further actions are undertaken, climate neutrality in 2050 will not be achieved as greenhouse gas emissions will be reduced by just about 60 % (European Commission 2019, 2021; IPCC 2023). The main reason is that, according to the EU Reference Scenario, current policy programmes and technological developments are not sufficient to increase the renewable energy share to more than 40 % in the heating sector and more than 57 % in transport sector by 2050. Also, the share of renewable energy in the electricity sector will rise to 75 % only. To achieve climate neutrality, the share for each sector needs to be 100% or close by. Hence, current EU decarbonisation efforts fail to match the political ambitions set out in the Green Deal. To close this gap, these efforts need to be stepped up substantially. For the purposes of our study, we focus on what must be done to achieve a climate-neutral energy system in Europe and how this will impact upon economic cohesion.

3 Regions have different starting positions for the energy transition

European NUTS-2 regions present very diverse preconditions for the renewable energy transition. They differ in current energy mix, their economic structure, actual carbon intensity, level of decarbonisation already achieved as well as potential for expanding renewable energy production.

To achieve the goals of the European Green Deal, all regions need to decarbonise by 2050. Some have a longer way to go to climate neutrality than others. Figure 2 shows the carbon intensity – measured in fossil CO_2 emissions per unit of GDP – of European NUTS-2 regions. Carbon intensity is high in many regions in Central and Eastern Europe as well as parts of Southern Europe. The highest levels are observed in regions in Czechia, Poland and Greece. Here, energy systems require root-and-branch change. In contrast, many regions in France, Italy, Germany, and Scandinavia already enjoy low carbon intensity. In sum, European regions are in different positions regarding the decarbonisation of their energy systems (European Commission 2019, 2020). The scale of the required transformation depends on current energy and greenhouse gas intensity, sectoral specialisation, mobility patterns and housing stock.

Figure 2: Economically strongest regions in Europe with lowest CO_2 emissions



Notes: The left panel shows the fossil CO_2 emissions per unit of GDP for European NUTS-2 regions. The right panel shows the correlation between the level of economic prosperity (measured in GDP per capita) and fossil CO_2 emissions. Source: Emission data taken from EDGARv7.0 (2022, reference year 2019), GDP data – per capita values for 2019, measured in constant 2015 prices – taken from FIGARO database (Eurostat 2021a). Own illustration.

Regions also differ substantially in their levels of economic prosperity. The highest levels of GDP per capita are observed in regions in Western and Northern Europe, the lowest in Eastern and Southern Europe. In all EU member states, urban and metropolitan regions have a higher GDP per capita than rural areas. When looking at the levels of fossil CO_2 emissions (see Figure 2 Figure 2, right panel), regions with the highest emissions tend to be among the less developed regions.[1] Conversely, not all less developed regions show high levels of emissions – for this group these can range from very low to high. While less developed regions represent only 17 % of EU GDP, they account for about 27 %

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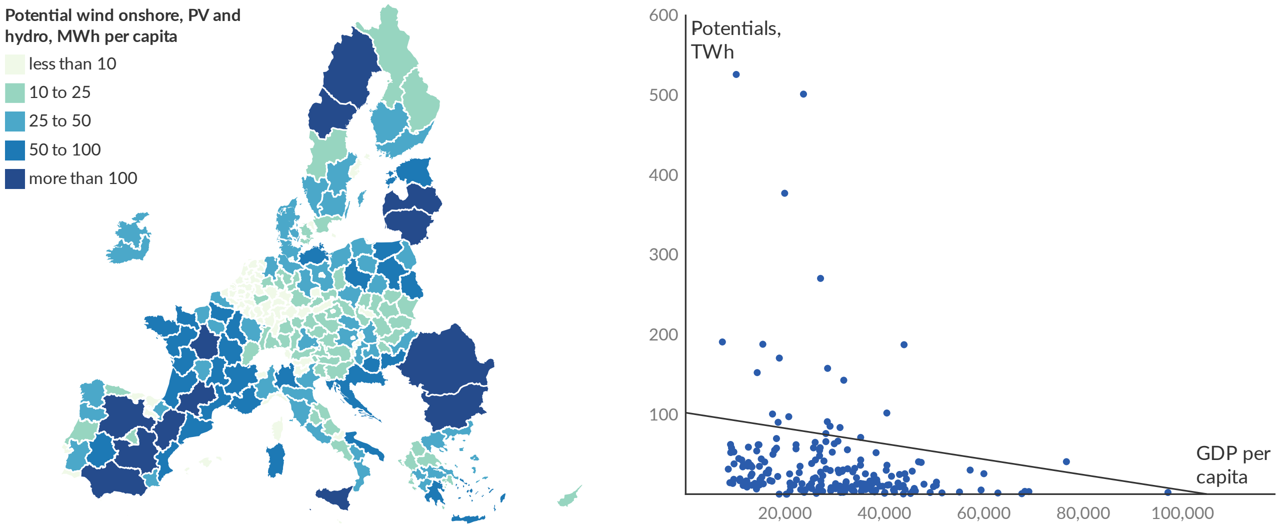
[1] Cohesion policy categorises EU NUTS-2 regions in more developed regions (GDP per capita above EU average), transition regions (GDP per capita between 75% and 100% of EU average) and less developed regions (GDP per capita less than 75% of EU average), see Regulation (EU) 2021/1060 (common provisions).

of fossil-based CO_2 emissions – pointing to a higher carbon intensity. More developed regions already exhibit lower carbon intensities. Thus, regions with a high CO_2 intensity and consequentially high investment needs if they are to meet the renewable energy transition tend not to be able to finance it.

What's more, the technical potential for renewable energy production differs substantially across European regions as seen in Figure 3. Regions differ, e.g., in available space, hours of sunshine and wind potential. All these factors determine how much renewable energy from solar, wind and hydropower sources could be produced technically if all opportunities in a given region were to be exploited (Kakoulaki et al. 2021).[2] Overall, the technological potential is lowest across large parts of central Europe, but high in many peripheral regions. The highest potential for renewable energy production is, with over 45 % of the sum total, found in onshore wind. It is highest in German, French and Swedish regions. The potential for offshore wind is highest along the coastline of the North and Baltic Seas. As for solar panels, Southern European regions in Spain, France, Italy, and Greece show strong potential naturally but some German, Polish and Romanian regions are suitable. Substantial hydropower potential is prevalent in mountainous areas, for example in Sweden, Austria, and France.

Figure 3: Economically lagging regions with highest technical potential for renewable energy



Notes: The left panel shows the sum total of annual technical potential for solar panels (ground mounted and rooftops), onshore wind and hydropower (MWh per capita). The right panel shows the correlation between the level of economic prosperity (measured in GDP per capita) and the technical potential for renewable energy production (measured in TWh per year). Source: Technical potential taken from Kakoulaki et al. (2021), GDP data – per capita values for 2019, measured in constant 2015 prices – taken from FIGARO database (Eurostat 2021a). Own illustration.

Noticeably, renewable energy potential is often low in urban regions. These typically prosperous regions are less endowed technically for renewable energy production than neighbours facing similar geographical and climate conditions. Their highest potential is found in rooftop solar panels – typically less than 20 % of the total potential in other regions (Kakoulaki et al. 2021). At the same time, urban regions exhibit highest energy demands in absolute terms. In contrast, the technical potential is high in less developed regions that tend to be blessed with many more locations suitable for renewable

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[2] Kakoulaki et al. (2021) assess the technical potential of these renewable energy technologies at NUTS-2 level considering environmental constraints, land use limitations and various techno-economic parameters. The level of technical potential is independent of the extent to which renewable energies are already being used.

energy production but also with more hours of sunshine (in particular in Southern European regions) or greater volumes of wind (regions along the Atlantic coast, the North Sea and the Baltic Sea).

The transition to a carbon neutral energy system impacts upon economic structures and comes with both challenges and opportunities. This transition is expected to boost employment in sectors along the value chain of renewable energy technologies: From manufacturing via systems installation to continuous operation and maintenance. However, the number of jobs needed in today's carbon intensive energy sector will decrease. This particularly affects regions highly dependent on the coal industry (Alves Dias et al. 2018; European Commission 2022).

The emerging regional differences in the transition's macroeconomic effects have been the subject of several previous studies. For example, studies on the so-called *Energiewende* in Germany conclude that northern and eastern German states with high wind and solar panel capacities can look forward to higher economic growth (Ulrich et al. 2018; Sievers et al. 2019; Ulrich 2022). The required phasing-out of coal was examined using the RHOMOLO-IO modelling framework to analyse differences in employment vulnerability across European regions revealing much higher costs for coal-dependent regions (Mandras et al. 2019).

Taken together, the energy transition could alter economic cohesion across Europe as we know it today. The geographical distribution of related opportunities and challenges will affect the future economic prosperity of individual regions. As a central element of the European Green Deal, the renewable energy transition will shape and more than likely reshape the distribution of economic disparities. As a consequence, cohesion policy will have to adapt if it is to sustain and expand progress made in achieving convergence.

4 How to measure the economic effects of the energy transition

The renewable energy transition could transform the European economy root-and-branch. On the one hand, phasing out fossil fuel-based energy production displaces associated activities in exploration, refining, and distribution. On the other hand, expanding renewable energy production increases economic activities in producing, installing, distributing and maintaining wind turbines, solar panels and hydropower technology.

The geographical distribution of renewable energy resources plays a crucial role in this transition. The spatial distribution of an energy system wholly reliant on renewables will differ from that of our current fossil-dominated system. This also implies that the structural changes in the economy will be spatially dispersed: Phasing out fossil fuel-based energy production and expanding renewable energy are not necessarily spatially congruent. Since European regions are intertwined in many ways, the positive economic effects of expanding renewable energy in one region may spill over to its neighbours: an energy-rich region can export to neighbouring regions which in turn benefit from cheap energy. Plus, negative spill-over effects can arise when the loss of economic activity in one region spreads to other regions.

All these dependencies and interdependencies should be acknowledged when assessing the transition's economic effects. Using a multi-regional input-output (MRIO) model approach allows us to trace value chains within and across European regions as well as with non-EU countries. For example, we can trace in the model how much of the output from the electronic sector in Noord-Holland (NL) – e.g. microchips – is used as intermediate products (input) by the chemicals sector in Rheinhessen-Pfalz (DE) – e.g. for a digitalised chemicals production plant – to produce output. This allows us to calculate the direct effect in sectors and regions and indirect effects in other sectors and regions of the energy transition on value added and employment.

Our MRIO model is a new approach to quantifying the potential effects on value added and employment across EU regions created by phasing out fossil fuel-based energy and expanding renewable energy. To the best of our knowledge, no such quantification has been conducted yet. Previous studies either analysed the feasibility of the energy transition or focussed on the effects within individual EU member states (Ulrich et al. 2018; Mandras et al. 2019; Kochanek 2021; Ulrich et al. 2022). An exception is Sasse and Trutnevyte (2023) who analyse the energy transition in the EU's electricity market. While they model electricity supply (generation, storage, transmission) and demand in great detail, the interaction with other industries and, thus, the related indirect and induced effects are not considered.

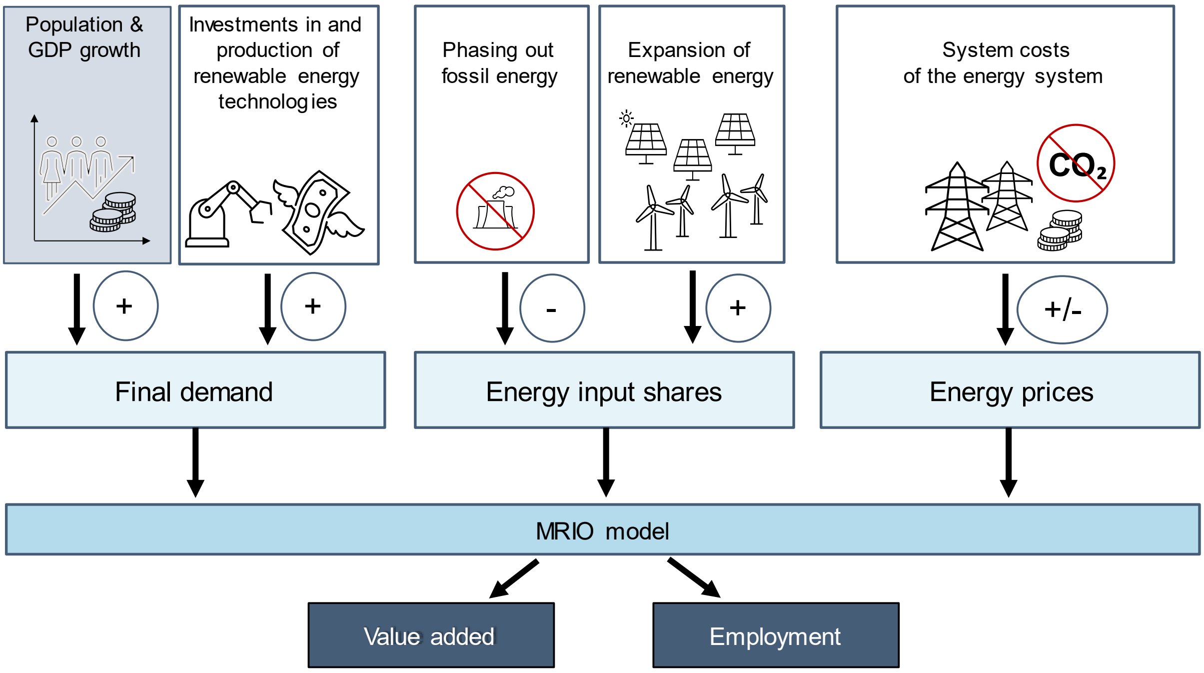
4.1 Setting up a model to assess structural changes in European regions

In our MRIO-based assessment, we consider both general economic development and different scenarios for expanding renewable energy. We apply a "what-if" approach as developed by Wiebe et al. (2018). We take into account the economic structure of 213 EU regions and their supply chains with other European regions and the rest of the world. Our model's three main scenario parameters simulate the levers of decarbonisation as discussed in Section 2:

- **Phasing out fossil fuel-based energy:** Fossil fuel-based energy (coal, oil and gas and electricity generated from them) consumed by industries and final consumers is gradually replaced by renewable energy. These shifts relate to all energy-consuming sectors (electricity, heating, transport) and are considered in the model in all inter-industrial value chains and final consumer demand.
- **Expansion of renewable energy:** The mix in installed renewable energy technologies will depend on regions' geography. Thus, the production of renewable energy and technologies will spread unevenly across European regions. For example, areas with strong winds like coastal regions will have higher shares of wind energy while sunny areas in the South are likely to install more solar panels. Overall, regions with high technical potential but low energy demand will be in a position to export their energy surplus to regions with low potential but high demand, a process requiring investment in transmission grids and energy storage.
- **Changing energy costs:** The necessary investments for the transition to a renewable energy system affect energy prices and, thus, industries' production costs and household living costs. At the same time, costs associated with the old fossil-based energy system like carbon pricing become obsolete and hence constitute a saving.

By simulating the structural changes associated with the decarbonisation of the EU's energy sector, we assess how these changes affect the regional distribution of economic prosperity as measured by value added and employment. In our simulations of different scenarios of the renewable energy transition (see Section 4.3), we exogenously vary the main scenario parameters across regional economies to account for inherent uncertainties. Figure 4 provides an overview of the model's basic structure.

Figure 4: Model structure for simulating the renewable energy transition



Notes: The grey box on the left shows the two exogenous parameters population and GDP growth. The white boxes show the main scenario parameters (from left to right): Investments in and production of renewable energy technologies; phasing out fossil energy; the expansion of renewable energy and system costs of the energy system. The bubbles with plus and/or minus symbols indicate a positive and/or negative effects of the parameters on three model components: Final demand, energy input shares and energy prices. Those components all feed into the MRIO model which calculates the effects on value added and employment.

We consider general economic developments until 2050.[3] For this, we take into account demographic trends and long-term forecasts for regional economic dynamics represented by the exogenously set parameters population and GDP growth. The population forecasts are taken from Eurostat (2021b) and the GDP-growth trajectories from the EU Reference Scenario. Since the EU Reference Scenario entails GDP-growth trajectories only on a national scale, we adjusted the region-specific outlook using the regional economic growth potentials published in Bertelsmann Stiftung (2022).[4] The general economic developments are not varied across scenarios as we focus in our simulations on the effects of the transition towards a carbon neutral energy system only.

Our model does not explain the dynamics of the decarbonisation process and how these are interrelated with economic growth, nor do we model the complex interplay of different technologies in the EU's future energy system and what that means for the development of energy costs. The related parameters are set exogenously to assess the economic consequences. Further, we assume that the political ambitions for decarbonising the European energy sector are backed up by sufficient funding.

For our "what-if" analysis, we closely follow the projections of the EU Reference Scenario to define central model assumptions. In particular, we use the following projections:

- The share of renewable energy in electricity, heating, and transport, which, at the same time, determines decarbonisation trajectories
- The mix of renewable energy technologies employed to replace phased out fossil fuel-based energy
- The development of end-user prices for electricity covering both the system costs due to the expansion of renewable energy technologies as well as costs of carbon of the remaining fossil energy consumption

While most projections are done on a national scale, we consider region-specific characteristics like technical potential for renewable energy, which includes, for example, solar radiation and available space for solar panels (taken from Pfenninger and Staffell (2016) and Staffell and Pfenninger (2016)). In our model, we define carbon neutrality as the share of renewable energy in final energy consumption of 95 % in all energy sectors, which is in line with global net-zero accounting frameworks (DeAngelo et al. 2021).

The MRIO model is outlined in full detail in Section A.1 (set-up), Section A.2 (mechanisms) and Section A.3 (scenario design) in the Appendix.

4.2 Calculating the effects on value added and employment

The core of our model is the MRIO table from FIGARO. Since the FIGARO MRIO table only covers EU countries at national level, we regionalised it to the European NUTS-2 level by combining data from structural business statistics, regional economic accounts and information on interregional trade

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[3] The starting point of our projection is 2019 which leaves out the economic fluctuations caused by Covid-19 and the Russian invasion in Ukraine.

[4] Bertelsmann (2022) uses a scoring approach based on five key factors of economic development: high-skilled employment, innovation, investment, regional infrastructure, and institutional quality. The authors find that high-income European NUTS-2 regions have, on average, a higher potential for economic growth than low-income regions. We also carried out a robustness check assuming national GDP growth trajectories for all regions of each EU member state (see Section 5.4).

flows from the EUREGIO database published by Thissen et al. (2018).[5] In addition, we extended the sectoral resolution of the MRIO table by adding detailed information on input structures of the operation and maintenance, installation, and production of nine renewable electricity and heating technologies (onshore wind, offshore wind, hydropower, solar, biomass, biogas, ambient heat, solar, thermal and geothermal). Our extended MRIO table distinguishes 62 industries (nine renewable energy sectors and 53 other sectors, see Section A.2 in the Appendix for a detailed overview) in 213 EU regions (210 European NUTS-2 regions as well as Bulgaria, Romania, and Croatia without regional detail[6]), plus 12 of the EU's major non-EU trading partners.[7]

To apply our "what-if" approach for assessing the potential future direct and indirect effects of the EU energy transition, we alter the quantities in the MRIO table. Technically, we apply a *demand-pull* input-output quantity model (Miller and Blair 2009), which links final demand by industry, $\mathbf{y}$, to effects by industry and region, $\mathbf{x}$:

$$\mathbf{x} = \mathbf{f}\left(\mathbf{I} - \widehat{\mathbf{A}}\mathbf{T}\right)^{-\mathbf{1}}\mathbf{y} = \mathbf{f}\,(\mathbf{L}\,\mathbf{y})$$

where the elements of the technological matrix $\widehat{\mathbf{A}}$, a_{ij}^{s}, denote the amount of product *i* used as an intermediate input by sector *j* in region *s*, and the trade matrix $\mathbf{T}$, t_i^{rs}, denotes the import shares and represents the trade linkages between regions s and r for product i. $\mathbf{f}$ is a vector of impact intensities for employment and value added per unit of output. $\mathbf{L}$ is the Leontief-Inverse. Its elements, l_{ij}^{rs}, denote the total (direct and indirect) production requirements of sector *i* in region *r* per Euro of final demand for products of sector *j* in region *s*.

To assess the impacts transmitted through price changes, we couple the *demand-pull* quantity model with the *cost-push* price model, which provides the overall impact on consumer prices of an initial shock in production costs, assuming that these are fully passed on to consumers. The demand responses of intermediate and final consumers to changed consumer prices are modelled by price elasticities in household consumption and trade elasticities (Muhammad et al. 2011). These reflect both price-induced changes in household consumption patterns and shifts in import shares due to shifts in the relative competitiveness of producing regions. Changes in consumption patterns and trade shares are then assessed in terms of their impact on employment and value added using the demand-pull quantity model.

For our calculations, we vary the scenario parameters outlined in Section 4.1. In the following, an overview of the scenario implementation is provided.[8]

Phasing out fossil fuel-based energy: The reduction of fossil fuel-based energy for electricity generation, heating and private transportation is modelled by exogenously lowering the input coefficients of coal, refined petroleum, and gas in the technology matrix $\widehat{\mathbf{A}}$ and replacing them with renewable electricity and heating from the new renewable energy sectors. We assume that industries and

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[5] Appendix A.1 outlines the regionalisation procedure in full detail.

[6] Information on interregional trade is missing for Bulgaria, Romania, and Croatia as they are not included in the EUREGIO input-output tables at a regional level. The update of the MRIO table provided by Huang and Koutroumpis (2023) was published too late to be integrated in the model.

[7] The 12 non-EU trading partners are Australia, Brazil, Canada, China, Great Britain, Indonesia, India, Japan, South Korea, Mexico, Turkey and the United States of America. All other countries are summed up as rest of the world. Data source for the non-EU countries is the SSP database (SSP2 scenario, Riahi et al. 2017).

[8] A more detailed overview of the MRIO model is provided in Appendix A.2.

households do not have control about the renewable energy technology mix used to generate this demand. Therefore, we only specify the percentage of reduction in fossil fuel inputs, while the technology mix used to supply the required energy is specified separately (see *Expansion of renewable energy* below). We focus on fossil fuel-based energy use for private transportation, heating, and energy consumption by energy-intensive industries (basic metals, chemicals, cement, and paper).

Expansion of renewable energy: The exogenous decarbonisation pathways for cutting back fossil fuel-based energy in electricity and heat generation as well as private mobility determine demand for renewable energies. The technology mix used to generate renewable energies in each region is exogenously specified as well. We use a two-step approach and, first, specify the energy mix at the country level based on the EU Reference Scenario and, thereafter, allocate renewable energy supply technology specific to European NUTS-2 regions based on exogenously specified shares. Here these shares are based on the technical potential for the different technologies. For each region, scenario-dependent generation capacities are used to calculate the required investment in the different renewable energy technologies. We assume that planning and installation of renewable energy technologies are carried out by local firms, while the production of renewable energy technologies is often limited to specific locations, which are either inside or outside the EU (the latter especially for solar panel components). Taking into account the specific installation mix of technologies in a given region, we specify the market shares of the different renewable energy technology producing regions. We, then, reallocate the demand for renewable energy technologies from the region of installation to the region where the technology is produced.

Changing costs of energy system: Depending on the mix of renewable energy technologies, regional technical potentials and energy demand, investments in transmission grids and energy storage are necessary to balance energy supply and demand. These investments result in higher system costs which need to be covered. The geographical dispersion of renewable energy production requires better connected grids to transport energy from one region to another. In the model, we assume that investment costs are passed on through the value chains and are covered by an energy price mark-up. At the same time, a higher share of renewable energy in the energy system will lower the system costs by reducing the costs associated with carbon pricing. Depending on both energy price components, the mark-up to cover renewable energy investment costs and carbon pricing, the total energy costs for energy consumers change. As a result, industries and households face changes in production and living costs. If the costs of the renewable energy price mark-up outweigh the savings from the elimination of carbon pricing, industries face higher production costs and households' living costs increase as well.

4.3 Considering different scenarios for a renewable energy future

The EU Reference Scenario offers an extensive analysis of potential pathways of Europe’s energy system and emissions up to 2050. It presents a wide range of feasible trajectories for the transition to renewable energy, drawing from various policy measures that have been implemented and those planned for the future. Given our projection that current policies are not sufficient to reach carbon neutrality in 2050, we define two main scenarios for our analysis. First, a baseline scenario that follows the decarbonisation pathways as described in the EU Reference Scenario. Second, a decarbonisation scenario where carbon neutrality *is* reached in 2050. Interdependencies between model parameters determine that a quicker phase-out of fossil fuel-based energy and concomitantly greater ambition towards reaching carbon neutrality, are accompanied by a more rapid expansion of renewable energy production, but also higher system costs. Therefore, the two main scenarios also differ in terms of the required investments in renewable energies, transmission, and storage capacities as well as associated system costs. In our analysis we focus on the difference between these two main scenarios to determine the economic effects caused by closing the gap between current political ambition (baseline scenario) and the goals outlined by the European Green Deal (decarbonisation scenario).

However, the assumptions conditioning the setting of each scenario parameters contain a degree of uncertainty, as multiple paths for the renewable energy transition are possible and it is unclear when and how the renewable energy transition will be put into operation in the coming years. To assess the impact of this uncertainty on our results, we simulate additional scenarios by varying the following assumptions:

- Higher efforts in the renewable energy transition such that climate neutrality will be reached as early as 2040
- No renewable price mark-up and, thus, no increase in system costs
- Faster decline in renewable energy technologies and associated system costs, no renewable energy price mark-up
- Installation of new renewable energy technologies driven by political will rather than technical potential alone
- Higher share of EU-wide production of renewable energy technologies and, thus, lower import share
- Fossil fuel price shock that makes the use of renewable energy comparatively cheaper

The technical details on these scenario variations are summarised in Section A.3 in the Appendix. How these variations affect the results of our calculations is discussed in Section 5.4.

5 How the renewable energy transition reshapes EU cohesion

Our simulations show that, for the EU as a whole, positive and negative economic effects of the renewable energy transition more or less balance each other out with only a negligible impact. Pushing the renewable energy transition towards full decarbonisation translates into a fall in value added of -0.3 % (-140 Euro per capita) and in employment of -0.1 % (-310,000 jobs) in 2050. The effects increase over time. In 2030, the effects of decarbonising the energy system are virtually indiscernible: Value added and employment are only 0.04 % and 0.02 % lower, implying no real change.[9] In 2040, the effects increase to -0.2 % for value added and -0.1 % for employment. Thus, a more ambitious energy transition has, on average, no distinct effect on EU-wide economic performance and job creation.

Our results for value added at EU aggregate level are in line with previous studies. For example, Su et al. (2022) analyse China's green transition and find a small loss of GDP growth equivalent to a lag in growth of less than one year. Studying the energy system transition in the EU in 2030, Vrontisi et al. (2020) identify small losses in GDP of about -0.2 % due to competitiveness losses triggered by asymmetric emission reduction targets across regions. For 2050, the impact on GDP is still low at -0.6 % if mitigation policies are only implemented in the EU and -0.4 % if mitigation actions are undertaken globally (ibid.). However, our effects are less negative than the findings of Dejuán et al. (2022). Under the condition of worldwide decarbonisation, the authors find a Europe-wide decrease in value added between -0.8 % and -2.7 %.

Previous evidence on the employment effects of decarbonisation is inconclusive. Some studies outline that the impact of decarbonisation and structural change in the energy system is, in total, positive for employment (ILO 2018, 2022). Vrontisi et al. (2020) provide mixed results with employment losses in 2050 of -0.5 % under EU policy action and gains of 0.3 % under global policy action. A lack of employment growth for the EU was also found by Kiss-Dobronyi and Fazekas (2022) as well as Dejuán et al. (2022). While the former estimate minor losses for economy-wide employment, the latter show employment declines of -1.7 to -4 %. Luo et al. (2023) estimate the effect of net-zero emissions in the electricity sector in China to be negative as well, as positive job creation in the renewable energy sectors is outweighed by direct and indirect losses in carbon-related sectors.

Overall, our estimated effects on value added and employment are minute at the aggregate EU level. But as the renewable energy transition progresses, different sectors of the economy face different challenges and adaptation requirements. The effects on value added and employment vary considerably among economic sectors and thus, regions. This makes the renewable energy transition primarily a matter of distribution and, thus, cohesion.

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[9] As these are only simulations and not forecasts the differences in the values for the scenarios can be interpreted as negligible.

5.1 Certain industries face a significant impact

A more ambitious renewable energy transition decreases the output of fossil-fuel based energy sectors compensated by increased output in renewable energy sectors further. The economic activities directly hit are mining and quarrying, electricity, gas, steam, and air conditioning supply, as well as the manufacture of coke and refined petroleum products. These industries will have 35 % less value added in 2050 in the decarbonisation scenario compared to the baseline scenario. However, renewable energy related economic activities in industries such as solar, wind turbines or heat pumps more than compensate for the losses in the fossil-fuel based energy industries. Due to higher value added and employment intensities, these values in the energy sector (including mining for energy carriers) are about 16 % and 40 % higher in the decarbonisation scenario than in the baseline scenario.

The changes in the output of energy sectors indirectly affect upstream and downstream industries that either provide important inputs to or use output from those industries that are directly affected. Moreover, changes in energy prices via decarbonisation will also change system costs. Changes in system costs, however, boost overall consumer prices and finally lead to consumer responses, which again affect value added and employment throughout the economy. The impact of these effects on other industries' value added and employment across regions comparing the decarbonisation to the baseline scenario is shown in Figure 5. The colouring of the bubbles denotes whether a region is urban or rural.[10] The non-energy sectors of our model have been aggregated to six categories, namely *Primary* (agriculture, forestry and fisheries), *Low-tech manufacturing* (food, textiles, furniture etc.), *Energy-intensive manufacturing* (chemical products, basic metals etc.), *High-tech manufacturing* (machinery, transport equipment, etc.), *Knowledge-intensive services* (IT services, research & development, engineering services etc.) and *Other services* (trade services, hospitality, other personal services etc.).

Our results show that, among the indirectly affected industries, high-tech manufacturing and knowledge-intensive service sectors in particular benefit in almost all regions and that the largest positive effects are observed for rural regions. However, the EU-wide impact in these sectors is relatively small: High-tech manufacturing shows increases in value added and employment of 1 % and 1.4 %, respectively. Knowledge-intensive services decrease by 0.1 % in value added but increase by about 0.5 % in employment. The reason for such low overall effects is that positive effects are predominantly observed in rural regions, which have only a small presence in these sectors today. Urban regions, where knowledge-intensive services by and large prevail, benefit to a much lesser extent.

For energy-intensive manufacturing industries, we observe mixed results with a significant number of regions on both the positive and the negative sides for value added and employment. Unlike high-tech manufacturing and knowledge-intensive services there is no clear pattern regarding the urban nature of a region. Overall, we observe that value added (-1 %) and employment (-0.7 %) are only slightly lower in the decarbonisation scenario compared to the baseline scenario. Thus, the impact of a fully-fledged renewable energy transition on energy-intensive industries is highly heterogeneous. While the total effects almost cancel each other out, some energy-intensive industries clearly benefit from producing inputs for the renewable energy system, whereas the negative effects due to losing

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[10] We classify areas as urban areas if the population density is at least 300 inhabitants per km². This corresponds to the definition of EUROSTAT for urban clusters (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Territorial_typologies#Typologies).

customers from fossil fuel-based energy sectors and especially the effects of increased energy costs dominate for others.

The remaining sectors show mostly – or even exclusively – lower value added and employment in the decarbonisation scenario compared to the baseline scenario. However, the overall effects as well as the effects on individual regional sectors are small. The strongest effects are observed for the *Primary* sector (-2.1 % for value added and -2.2 % for employment) followed by *Low-tech manufacturing* (-1.2 % in value added and employment) and *Other services* (-0.8 % in value added and employment). These sectors are particularly affected by changes in household consumption patterns induced by energy price-driven changes in consumer prices. Since these increases particularly impact necessities such as housing or transportation, consumers tend to reduce their spending on goods they view as more of a luxury such as restaurants or clothing to compensate.

Figure 5: High-tech manufacturing and knowledge-intensive services with high prospects to gain in rural regions in 2050

Note: The colour of the bubbles represents the urban (blue)/rural (red) status of a region. Regions are classified as urban if their population density exceeds 300 inhabitants per km². The classification of the economic sectors is listed in Section A.2 in the Appendix. Source: Own calculations based on MRIO model. Own illustration.

5.2 Lagging regions catch up in economic prosperity and employment

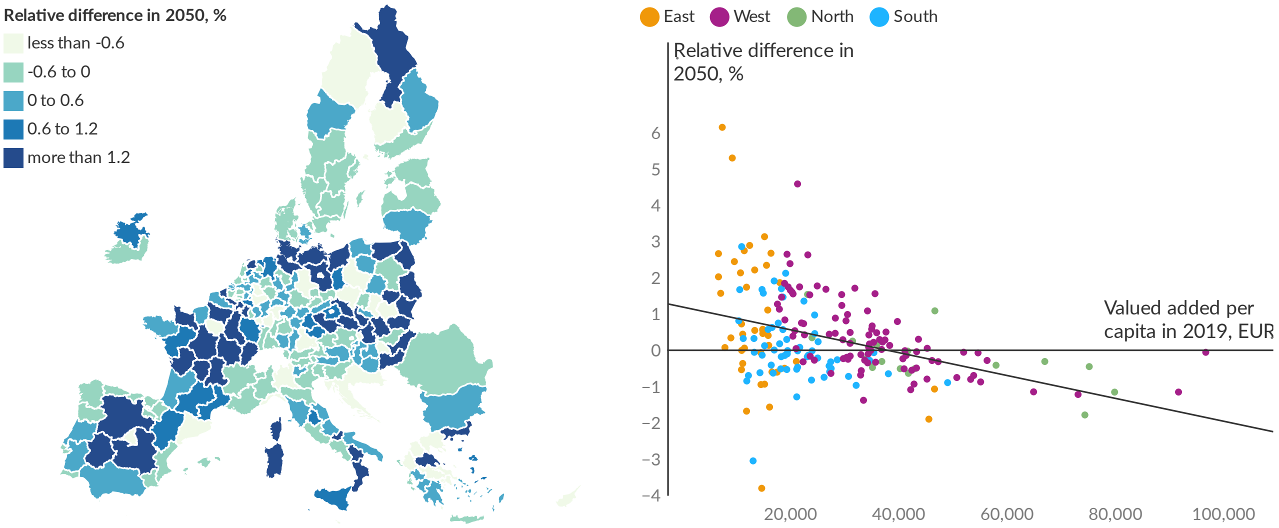
The effects of the renewable energy transition in the decarbonisation scenario compared to the baseline scenario on regional value added and employment are shown in Figure 6 and Figure 7. The scatterplots show the relative impact on value added and employment on the y-axis and value added per capita in the base year of 2019 as a measure for today's prosperity on the x-axis. The choropleth maps show that a small majority of regions benefit from the renewable energy transition in having a higher value added per capita and higher net employment by 2050 (109 out of 213 in terms of value added, 116 for employment). However, there are considerable differences in effects across regions ranging from -3.8 % to +6.2 % for value added and -2.1 % to +4.9 % for employment. Therefore, our results suggest that a fully-fledged renewable energy transition is primarily a question of regional distribution and economic cohesion.

On average, regions in Central and Eastern Europe as well as Western Europe show slightly positive effects on value added with an increase of 0.8 % (70 Euro per capita) and 0.4 % (70 Euro per capita). respectively. In contrast, regions in Northern and Southern Europe show negative average effects. Comparing the decarbonisation scenario to the baseline, the value added per capita in Northern Europe is on average -0.2 % or -34 Euro lower and in Southern European regions it is -0.1 % (-10 Euro per capita). Except for Central and Eastern European regions, where employment is 1.1 % higher in the decarbonisation scenario compared to the baseline, relative average effects on employment are even smaller than those on value added with a slight increase in Western and Southern Europe (+0.2 % and +0.1 %) and a decline of just -0.1 % in Northern Europe. The differences in the results for value added and employment can be attributed to differences in labour productivity across regions and sectors.

Compared to these average differences, the range of regional impact is much larger within these groups of countries. The widest range is observed for Central and Eastern Europe, where effects range from -3.8 % to +6.2 % (-2,450 and +920 Euro per capita) for value added and from -2.1 % to +4.9 % (from -57,000 to +38,000 persons) for employment. In Western and Southern regions, the effects on value added range between -1.4 % and +4.6 % (-1,960 and +1,570 Euro per capita) and -3.1 % to +2.9 % (-750 to +860 Euro per capita), respectively, and between -1.1 % and +2.8 % (from -206,000 to +27,000 persons) as well as -1 % and +2.6 % (from -51,000 to +27,000 persons) for employment. By contrast, the effects across Northern European regions are more aligned with a range from -1.8 % to +1.5 % (-2400 to +920 Euro per capita) for value added and -1.6 % and +1 % (from -38,000 to +7,000 persons) for employment.

The large differences between regions within European macroregions can be explained by variations in economic characteristics and starting position for the decarbonisation process. These are key determinants for how regional economies are affected by the renewable energy transition. The right panels of Figure 6 and Figure 7 outline a negative relationship between regions' prosperity today and the effects on value added and employment caused by the energy transition. The negative slope of the regression line indicates that regions with a higher initial economic performance are more likely to be negatively affected, experiencing a decrease in future value added and employment. This negative relationship could reduce economic disparities across European regions if the renewable energy transition if fully materialised.

Figure 6: Lagging regions to catch up in economic prosperity in the renewable energy transition



Notes: The left panel displays the relative difference (%) on value added per capita when closing the gap in the renewable energy transition by 2050, i.e. the percentage difference between the baseline scenario of implemented policy measures and the decarbonisation scenario. Values bigger than zero indicate that the renewable energy transition supports the region's economic performance. Values smaller than zero indicate challenges for economic performance. The right panel displays the initial value added per capita in 2019 on the x-axis and the change (in percentage) in value added per capita between the baseline and decarbonisation scenario in 2050 on the y-axis. The straight line represents a regression line for the relationship between the x-axis and the y-axis. Region-specific results are listed in Section A.8 in the Appendix. Own illustration.

Figure 6 and Figure 7 show that the overall pattern that economically strong regions gain relatively less in value added and employment compared to less developed regions is largely shaped by urban regions. This result is also confirmed by a cluster analysis.[11] The negative effects are concentrated in densely populated and highly industrialised regions in the Netherlands and Belgium, Western and Southern Germany and Northern Italy. Urban regions that face particularly strong negative effects are Śląskie (PL) and Bratislavský kraj (SK), Île de France (FR), Région de Bruxelles-Capitale/Brussels Hoofdstedelijk Gewest (BE) and Hamburg (DE), but also Lombardy (IT) and Attica (GR). These enjoy relatively strong economic performance and high shares in high technology manufacturing and knowledge intensive services. Except for Śląskie and Bratislavský kraj, which have high shares of employment in energy intensive industries such as refined petroleum, chemicals, basic metals and other non-metallic minerals, they also share below average CO_2 intensities measured as carbon emissions per unit GDP. However, despite their favourable condition for decarbonisation, the technical potential for renewable energy production is way below average in these regions, as their large population density predominantly allows for the installation of roof-mounted solar panels, not so much other technologies.[12] At the same time, energy demand is higher than the amount that can be generated by renewables, forcing them to import energy from surrounding regions. This reduces the positive effects in urban areas while at the same time these regions experience above average negative effects from the increase in overall consumer prices driven by rising energy costs.[13]

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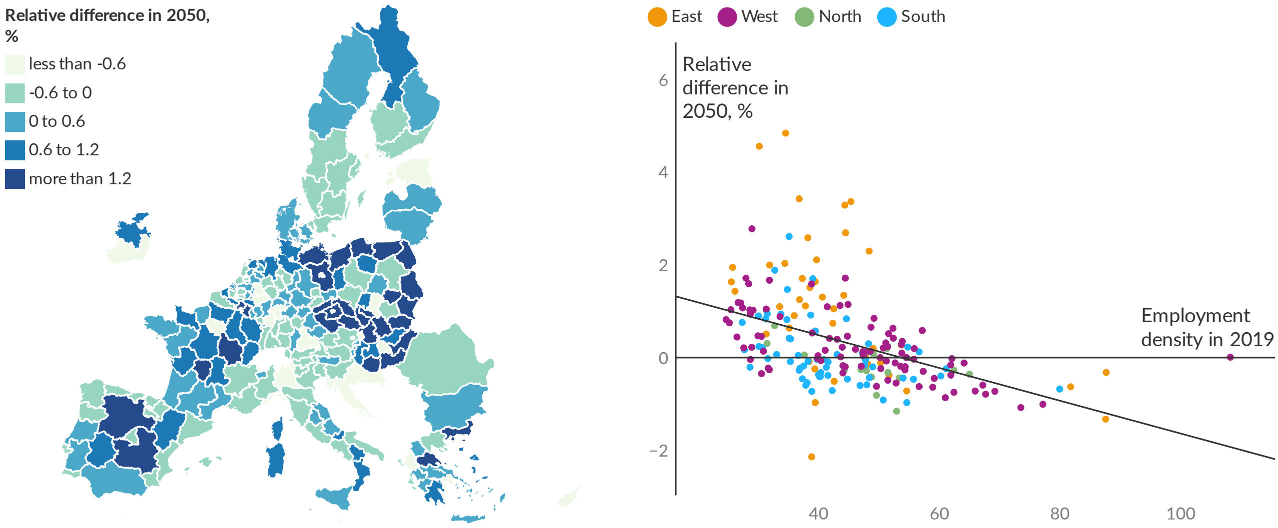
[11] See Section A.5 in the Appendix.

[12] The technical potential of other renewable energy technologies is – on average – substantially higher.

[13] The negative impacts on urban and, in particular, capital regions might also explain the relatively low average performance of countries without regional detail such as Romania, Bulgaria, Croatia or Estonia and Latvia where GDP is strongly concentrated in the capital regions.

Figure 7: The renewable energy transition leads to more employment in lagging regions



Notes: The left-hand panel displays the relative difference (in %) on employment when closing the gap in the renewable energy transition by 2050, i.e. the percentage difference between the baseline scenario of implemented policy measures and the decarbonisation scenario. Values bigger than zero indicate that the renewable energy transition creates new employment in the region. Values smaller than zero indicate challenges for employment. The right-hand panel displays the initial employment density in 2019 (number of employed persons per 100 inhabitants) on the x-axis and the percentage change in employment between the baseline and decarbonisation scenario in 2050 on the y-axis. The straight line represents a regression line for the relationship between the x-axis and the y-axis. Region-specific results are listed in Section A.8 in the Appendix. Own illustration.

Rural regions, in particular those with high potential for renewable energies, experience the strongest positive effects on value added per capita and employment in 2050 comparing the decarbonisation scenario to the baseline. Most of the best performing regions have a per capita GDP below the national average and their economic structure is diverse without being dominated by specific sectors and characterised by rather low shares in industrial jobs. Our results show particularly strong gains in value added and employment for Podlaskie (PL), Warmińsko-Mazurskie (PL), and Střední Morava (CZ) in Central and Eastern Europe as well as for Thessalia (GR), Castilla y León (ES), Castilla-La Mancha (ES) and Molise (IT) in Southern Europe. In Western and Northern Europe the provinces Luxembourg and Namur in Belgium and Friesland in The Netherlands, but also Pohjois-Suomi (FI) and Border, Midland and Western (IE) benefit most. These regions benefit, on the one hand, by their big potential for renewable energy which comes with opportunities for new jobs and value creation and, on the other hand, by their diverse economic structure making them less prone to losses of value added and jobs indirectly linked to the phase out of fossil fuel-based energy and the rise in consumer prices driven by greater energy costs. Swedish and Austrian regions show that it is not the potential for renewable energy per se that is driving the results but how far renewable energies expand in the decarbonisation scenario compared to the baseline. Regions in both countries already have high shares of renewable energy production today such that relatively low additional investments are necessary to decarbonise the energy system. At the same time, they have a strong industrial base and are highly integrated in interregional supply chains, which makes them liable to spill-over effects from other EU regions.

5.3 Greater convergence at the cost of today's richer regions

Section 5.2 has shown that the renewable energy transition is likely to benefit less developed rural regions while it challenges more developed metropolitan regions. However, the overall effect on economic cohesion across European regions is initially unclear. To quantify it, various indices of inequality can be considered (see Section A.6 in the Appendix for the definition of the indices and more results).

Counting challenged and benefitting regions reveals that 51 % of the EU regions show positive effects of the renewable energy transition. Less developed regions figure very strongly in this group – overall, 40 out of 59 (68 %) show positive deviations. Plus, the majority of transition regions (43 out of 69 or 62 %) show positive effects in the decarbonisation scenario. In contrast, only about one third (26 out of 85 or 31 %) of the more developed regions are better off in 2050 if the renewable energy transition was stepped up.

The most prominent indicator for measuring inequality is the Gini coefficient. It measures the inequality of a distribution with a value between 0 and 1. A value of 0 represents a perfectly equal distribution with all regions on a level playing field. A value of 1, on the contrary, implies that all value added and employment is concentrated in a single region. In the baseline scenario of no renewable energy transition, the Gini coefficient increases from 0.491 in the base year 2019 to 0.516 in 2050. This implies a potential increase in inequality among EU regions as the distribution of value added and population becomes more concentrated. In the decarbonisation scenario, the Gini coefficient is 0.514 in 2050, resulting in a more equal distribution compared to the baseline scenario. A full decarbonisation of the European energy system can thus reduce territorial inequality across EU regions by 0.4 % compared to current political decarbonisation ambitions. Given we are talking about just a single policy, this potential for reduction is remarkable.

The 90/10 ratio, another common statistic for measuring inequality, relates the level value added per capita level at the 90th percentile with that at the 10th percentile. The higher the resulting value, the greater the territorial inequality across regions. The quotient of the 90- and 10-percentile of value added per capita in all EU-regions is 3.73 in the baseline scenario in 2050. This implies that value added per capita in better-off regions is 3.73 times higher than those at the bottom levels of the distribution. In the decarbonisation scenario, the value slightly decreases to 3.7, which implies a reduction of regional inequality of 1%.

The Theil index is also commonly used to measure inequality. It measures inequality within a range of 0 and infinity. Perfect equality is denoted by a value of 0. In our context, the Theil index takes a value of 0.598 in the baseline scenario and 0.592 in the decarbonisation scenario. This points to a reduction in inequality across European regions of about 1%. Again, this is a significant reduction wrought by an individual policy.

Taken together, our results show that the renewable energy transition can reduce economic inequalities across EU regions. The drivers of this reduction are less developed regions which face opportunities to catch up and, somewhat worryingly, more developed regions could fall back slightly. Hence, stepping up the renewable energy transition could lead to more convergence among EU regions, but not trending upwards for all in the spirit of Pareto - a hardly desirable outcome.

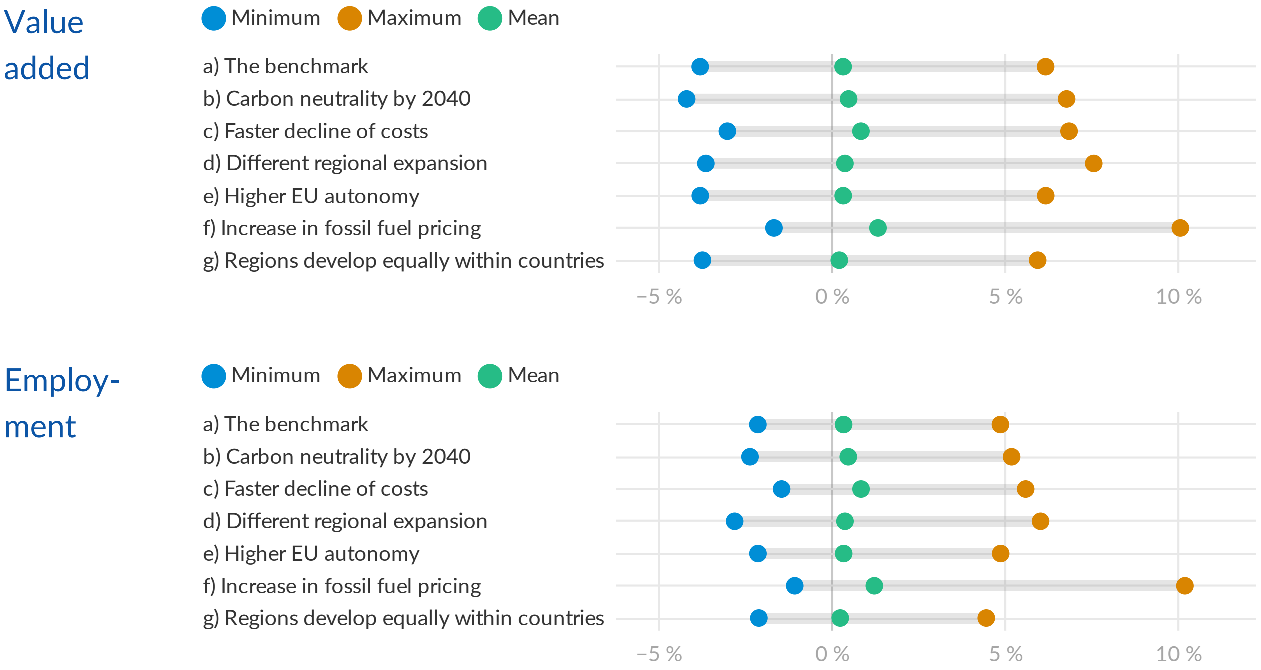
5.4 Taking uncertainty into account

Our MRIO model-based scenario analysis depends on several assumptions as outlined in Section 4.3. Some of these could strongly influence the results by skewing the path of the renewable energy transition or driving the strength of effects on value added and employment. This, in turn, could impact the overall results. To test the validity of our results, we varied critical parameters of the scenarios. In the following, we present the results of our checks on robustness, which also allow us to indicate ranges of the observed effects in value added and employment.

Figure 8 shows the minimum, mean and maximum of relative impacts on value added (upper panel) and employment (lower panel) for our benchmark scenario and seven scenario variants across regions:

a) **The benchmark:** Main decarbonisation scenario, carbon neutrality is reached in 2050.
b) **Carbon neutrality by 2040:** More ambitious decarbonisation scenario.
c) **Faster decline of costs:** Renewable energy system with low system costs, no renewable energy price mark-up.
d) **Different regional expansion:** Political will determines distribution of new renewable energy technologies.
e) **Higher EU autonomy:** Lower import shares and more EU-wide production of renewable energy technologies.
f) **Increase in fossil fuel pricing:** Price shock making renewable energy comparatively cheaper.
g) **Regions develop equally within countries:** National GDP growth trajectories only, no regionalisation.

Figure 8: Similar patterns for the resulting effects in different renewable energy transition pathways



Note: The plots (a to g) show the minimum, median and maximum of the relative impacts across regions of the modelled energy transition in seven scenario variants compared to their respective baseline scenario (difference-in-difference): Accumulations of dots around zero mean that most regions are not affected by the renewable energy transition.

For most regions, the differences between the scenario variants are negligible. The average percentage difference between a scenario variant and the main decarbonisation scenario, our benchmark, is near to zero for most regions in terms of both value added per capita and employment. This means that our main results are robust and not affected by the choice of parameter values. Only in the scenarios with low system costs (variant c) and a fossil fuel price shock (variant f) the mean values differ significantly from zero. In these two scenarios, the average increase in value added per capita in 2050 is 0.8 % and 1.3 %, while in our benchmark results the average impact is only +0.3 % for each[14]. For employment the average effect in variant c) and f) is 0.8 % and 1.2 % and thus significantly higher than in the benchmark. These results highlight the importance (and impact) of the cost of a renewable energy system and of carbon pricing on how the transition to renewables affects different regions.

a) The benchmark

The effect of the main analysis, that is the relative difference between the main decarbonisation scenario and the baseline scenario, is taken as benchmark. On average, regions face an increase in value added per capita and employment of 0.3 % in 2050. The effects for individual regions range from -3.8 % to +6.2 % for value added and from -2.2 % to +4.9 % for employment. Overall, 109 out of 213 regions (51 %) show a better economic performance due to the renewable energy transition and 116 (54 %) have a positive impact on employment. All scenario variants (b to g) are compared to this benchmark.

b) Carbon neutrality by 2040

We speed up the renewable energy transition and assume that a fully decarbonised energy system is already in place by 2040. Accordingly, there are steeper slopes in structural changes, price developments and investments.

Our results show that the differences in value added per capita and employment in a scenario of carbon neutrality by 2040 are comparable with those to our baseline results with an accomplishment of the transition in 2050. On average, regions will in 2040 experience a change in value added per capita and employment of +0.5 % compared to +0.3 % in 2040 in the benchmark scenario. However, regional differences are slightly larger in the more ambitious decarbonisation scenario ranging from -4.2 % to +6.8 % for value added (benchmark: -3.8 % to +6.2 %) and from -2.4 % to +5.2 % for employment (benchmark: -2.2 % to +4.9 %). Slightly more regions are better off than in the benchmark: 124 regions compared to 109 have a positive effect on value added per capita and 131 versus 116 have a positive impact on jobs. The regional distribution of the impacts remains pretty constant.

c) Faster decline of costs

For our benchmark results, we assume that electricity prices will increase more strongly than they would without the renewable energy transition. According to our assumptions, this increase in electricity prices is due to the fact that, although the cost of new renewable energy capacity will go down modestly, this decrease will be more than offset by the rising cost of building new storage capacity and interregional grids. To test these assumptions, in this scenario variant we assume that electricity

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[14] Note that the average effects across regions differs from the overall effect for the EU (-0.3 % for value added and -0.1 % for employment).

prices are the same as in the benchmark scenario and thus leave aside any rising costs of storage and grids.

Our results show that lower energy prices lead to even more positive changes on average (+0.8 % each for value added per capita and employment) than in the benchmark (+0.3 % each). Lower system costs reinforce the effects while reducing regional differences, so that the range of the relative impact is positively shifted in relation to the benchmark: from -3 % to +6.8 % for value added per capita (benchmark: -3.8 % to +6.2 %) and from -1.5 % to +5.6 % for employment (benchmark: -2.2 % to +4.9 %). Significantly more regions are better off than in the benchmark: 170 versus 109 in the benchmark enjoy a positive impact on value added per capita and 182 versus 116 on employment.

d) Different regional expansion

The regional distribution of renewable energy production is incorporated in several parameters in our model. We closely follow the national pathways outlined in the EU Reference Scenario and assume within countries an expansion of renewables according to the technology-specific potential of its regions. For this scenario variant, we vary this distribution at the sub-national level, so that greater cohesion within countries is the condition for the distribution of investments across regions. This means that least developed regions as well as those expected to face very high challenges due to the renewable energy transition, get higher shares of national electricity capacity than in the benchmark decarbonisation scenario. We apply the following scheme to identify the regions to be addressed: having a GDP per capita below 60 % of the EU average or between 60 % and 75 % of the EU average respectively and/or is one of the 34 *coal regions in transition* as defined by European Commission (2018). If the region lags in GDP and is a coal region in transition the subnational share in technical potential is increased by 50 %. For less developed coal regions in transition and other least developed regions the share is increased by 25 %.

The results show that the differences in value added per capita and employment are comparable with the benchmark results: the average effects for valued added and employment are +0.4 % compared to +0.3 % in the benchmark. Regional differences are slightly larger especially in the upper bound in the alternative regional distribution scenario, resulting in a range of effects from -3.7 % to +7.6 % for value added per capita (benchmark: -3.8 % to +6.2 %) and from -2.8 % to +6 % for employment (benchmark: -2.2 % to +4.9 %). Almost the same number of regions are better off as in the benchmark: 107 versus 109 have a positive effect on value added per capita and 115 versus 116 have a positive impact on jobs.

e) Higher EU autonomy

The sources of supply and places of manufacture of renewable energy technologies influence the economic impact in European regions. Much of the equipment and components needed for the expansion of renewable energy is imported. Solar panels are a good example. As the importance of green industrial policy increases, the production capacity could shift to Europe. Therefore, we change the assumption on import shares of renewable energy technologies to assess the impact of increased autonomy within the EU. We therefore assume in this scenario that the shares of imports from non-EU countries are halved for all renewable energy technologies.

We observe, on average, no significant differences. The average impact remains at +0.3 % for value added per capita and employment (same as in the same benchmark scenario). Further, the distribution of impacts across regions resembles that of the main decarbonisation scenario very closely. The main reason for this result is that there is a redistribution of renewable technology production among European regions. Some regions benefit from the increased demand for European-produced technologies by serving that demand. Others, which primarily produce intermediate products and components for renewable energy technologies that are exported to non-EU producers, face demand losses as a result of a shift away from non-EU imports. Both effects balance each other out, so that this variant and the benchmark have similar overall effects. However, slightly more regions are better off than in the benchmark: 111 versus 109 in the benchmark have a positive effect on value added per capita and 117 versus 116 on employment.

f) Increase in fossil fuel pricing

With this scenario variant, we examine the effects of a significant increase in the cost of fossil fuels. A price shock can be caused by global developments such as a war or by surcharges such as a significantly higher CO_2 tax. We assume that the price of fossil fuels increases by 100 Euro per ton of CO_2 emitted.

The results for the fossil fuels price increase scenario variant show that the effects on value added and employment critically depend on the costs of emitting CO_2. This holds true for region-specific and overall results. The average effect on value added per capita and employment for EU regions is far better than in the benchmark: On average, economic prosperity rises by 1.3 % compared to 0.3 % in the benchmark. Employment in this variant is 1.2 % higher in 2050 (benchmark: +0.3 %). The range of relative impacts has also shifted significantly upward in relation to the benchmark: it takes values from -1.7 % to +10.1 % for value added per capita (benchmark: -3.8 % to +6.2 %) and from -1.1 % to +10.2 % for employment (benchmark: -2.2 % to +4.9 %). As a result, significantly more regions are better off than in the benchmark: 176 versus 109 in the benchmark have a positive impact on value added per capita and 178 versus 116 on employment. Unlike the benchmark results, carbon intensive regions and less developed regions are more positively affected.

g) Regions develop equally within countries

The projection of general economic development at the country level in our benchmark scenario follows the results from the specifications of the EU Reference Scenario. It is regionalised by combining national trends with the general growth potential indices of Bertelsmann Stiftung (2022) for the subnational level. In order to exclude the case of a critical parameter choice, we assume in this variant that GDP per capita at the sub-national level grows at the national rate of the respective member state. The alternative GDP projections are applied to the benchmark as well as to the decarbonisation scenario.

We find with +0.2 % very similar average effects for value added per capita and employment (+0.3 % in the benchmark). The range of relative differences across regions is slightly lower with values between -3.8 % and +5.9 % capita for value added per capita (benchmark: -3.8 % to +6.2 %) and -2.1 % and +4.4 % for employment (benchmark: -2.2 % to +4.9 %). Almost as many regions are better off: 108 compared to 109 in the benchmark have a positive effect on value added per capita and 110 compared to 116 on jobs.

6 Conclusions and recommendations

A fully-fledged renewable energy transition is imperative if the EU is to reach the European Green Deal's ambitious goal of achieving a climate-neutral economy by 2050. With more than 80 % of carbon emissions linked to the energy sector, the shift from fossil fuels to renewable sources represents a seismic economic transformation. Established industries will undergo significant changes to adapt to a climate-neutral economy, while the renewable energy industry will gain even more in importance – also in economic terms. The EU must manage this process without harming European cohesion, leaving no parts of the continent behind.

In our study, we assessed the economic challenges and opportunities in the renewable energy transition using an innovative multi-regional input-output model (MRIO). We projected changes in regional economies and worked out their implications for economic prosperity in the EU. Our assumption was that the gap between current political ambition and the necessary measures to achieve climate neutrality will be bridged. Our findings reveal that

(1) Full decarbonisation of the energy system varies significantly across regions, with employment shifts ranging from -2.1 % to +4.9 %, and per capita value added fluctuating between -2,450 EUR and +1,570 EUR.
(2) Rural regions, many of which are less developed but rich in renewable energy potential, stand to benefit from fresh economic opportunities.
(3) Conversely, urban regions, often economically advanced but with limited renewable energy potential, will grapple with structural changes, potentially affecting their economic well-being.
(4) Closing the gap in the renewable energy transition will balance out the positive and negative effects across individual regions, with virtually no impact on Europe's economy as a whole.
(5) A quicker, more ambitious renewable energy transition would contribute even more to economic cohesion across European regions. Increasing costs of fossil fuels (e.g. via higher carbon prices) would amplify this positive effect.

Overall, stepping up the renewable energy transition can boost economic cohesion across European regions. Unusually, this occurs not only due to less developed regions catching up, but at the potential expense of stronger parts of Europe. EU policy on renewable energies, then, aligns at least partially with the objectives of European cohesion policy, albeit by coincidence rather than design.

Policy implications: Expansion of Cohesion Policy's scope and leveraging synergies with Energy Policy

Our results provide a glimpse into potential outcomes in the absence of policy action. European cohesion policy, designed to address challenges in struggling regions and provide new opportunities, must adapt to the evolving landscape introduced by the renewable energy transition. This requires a broadening of the scope of cohesion policy and a leveraging of its synergies with EU energy policy.

For less developed regions, many of them rural ones, the expansion of renewable energies can act as a catalyst for catching up. However, realising their potential requires knowledge exchange, technical support, and, of course, tangible investments. By capitalizing on synergies between renewable energy policies and strategic cohesion fund usage, the investments can be ramped up for progress in energy *and* cohesion policy. Channelling funds into regions with the greatest needs lies at the heart of cohesion policy. But ensuring that value added remains in these regions is equally vital. Concepts like *Energy Communities* can contribute to such adherence, benefitting local stakeholders.

Conversely, more developed urban regions face unforeseen challenges that demand proactive management. The risk of compromising economic prosperity may undermine their support for the renewable energy transition. Maintaining their current level of economic prosperity is crucial for overall upward convergence across the continent and continued support for the renewable energy transition. Cohesion policy, with an expanded scope and suitable policy instruments, can play a pivotal role to this effect. While more developed regions are not lacking funds, they lack the technical potential for renewable energy production. Collaborations between less developed rural regions with high technical potential and energy-demanding urban regions can result in win-win-situations for all regions. Initiatives like Interreg's underutilized *Renewable Energy Partnerships* showcase urban regions benefiting from fossil-fuel-free energy, and rural regions gaining much-needed investment certainty.

Cohesion policy, then, emerges as a key player in the renewable energy transition. While the success of the European Green Deal may hinge on decarbonisation, ensuring citizens' support for the accompanying economic upheaval will in turn hinge on fulfilling the EU's Treaty enshrined objective of European cohesion. Failure to align these parallel objectives will jeopardize the success of both – a Europe that is greener whilst also fairer.

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Appendix

A.1 Setting up the MRIO table

First, we developed the database for modelling the impacts of the renewable energy transition on cohesion in the EU. The economic structure of the EU's NUTS-2 regions, and interregional as well as international trade dependencies between them, are mapped by multiregional input-output (MRIO) tables, distinguishing between 53 industries in 213 EU Regions (210 NUTS-2 regions and the three EU member states Bulgaria, Romania, and Croatia with no regional detail) and 12 major non-EU economies[15]. We compile and update the MRIO table for the base year 2019 by regionalising EU countries within the FIGARO MRIO based on Thissen et al. (2018) and by combining regional economic accounts data with interregional trade flows from the EUREGIO database.

Figure A1 shows a simplified two-region representation of the MRIO table used in the project. The blue blocks represent inter-industry transactions, i.e. intermediate inputs of one sector used for production by another sector, as well as elements of final demand, which includes household consumption, government spending, and capital formation. The diagonal blocks (dark blue) show economic interrelations between producers and consumers within the same region, i.e. intraregional transactions. The off-diagonal blocks show trade interrelations between producers and consumers in different regions. This covers interregional trade relationships between regions within the same country as well as trade between regions of different countries. The yellow block at the bottom of the MRIO table represents value added comprising employee compensation, taxes, and net profits. We have highlighted some of the sectors in the inter-industry and final demand blocks that provide fossil fuel based energy, namely (1) mining of energy carriers (especially coal), (2) refined petroleum products, and (3) electricity and gas, which are due to be replaced by renewables during the EU's energy transition.

We assume that the technology of regional sectors as well as composition of household consumption, government spending and capital formation is the same as the national average (Miller and Blair 2009). Therefore, we estimate gross output, x_j^s, value added va_j^s and total (i.e., irrespective of regional origin) intermediate inputs $z_{ij}^{\cdot s}$ of sectors at NUTS-2 level by scaling the national values proportionally by a regional sector's share in national wages. We prefer to scale by wages over scaling by employment, since wages better reflect regional productivity differences within a country (Lahr 2001). Data on sectoral wages at NUTS-2 level are taken from Eurostat's structural business statistics and regional accounts. Final demand of households, $h_i^{\cdot s}$, and capital formation, $cf_i^{\cdot s}$ are estimated using data on disposable income and total gross fixed capital formation at NUTS-2 level. Regional government spending $g_i^{\cdot s}$ is estimated using regional shares in national GDP.

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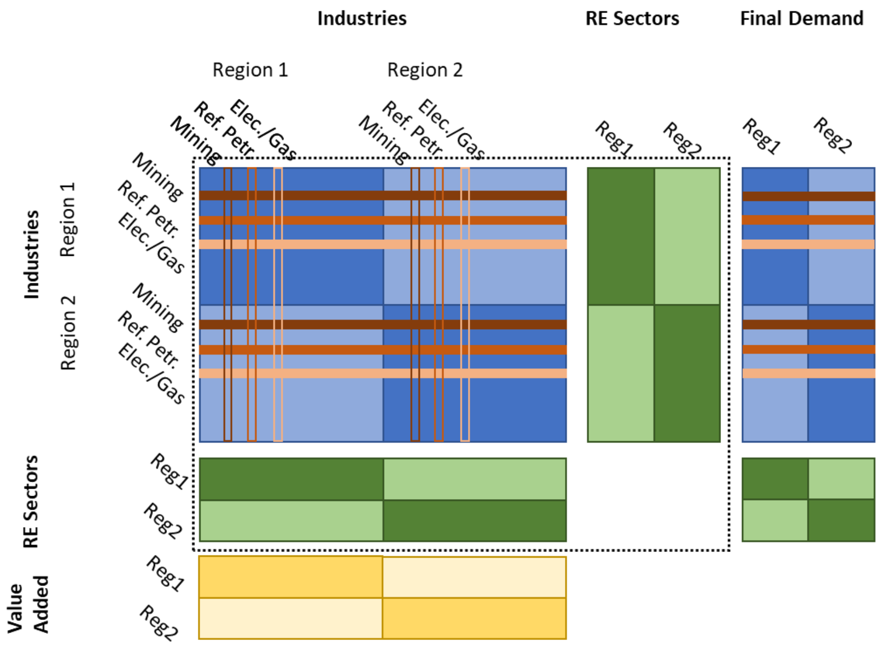
[15] These are Great Britain, Turkey, USA, Canada, Mexico, Brazil, Australia, Japan, Korea, China, India, Indonesia and an aggregate *Rest of World* region.

Figure A1: Structure of the multi-regional input-output model (MRIO) table for the European NUTS-2 regions



Notes: Simplified two-region representation of the MRIO table. Own illustration.

In a second step, we estimate intra- and inter-regional as well as international trade flows using a three-dimensional RAS algorithm. We distinguish between trade between regions *r* and *s* in intermediates $z_{i.}^{rs}$ and in final products $y_{i.}^{rs}$. The estimation problem can be described by following non-linear programming problem, which minimizes the distance between an initial, (0), and the final estimate, (1), of a trade flow measured by cross-entropy (Golan et al. 1997):

$$\min D = z_{i.}^{rs}(1)\ln\frac{z_{i.}^{rs}(1)}{z_{i.}^{rs}(0)} + y_{i.}^{rs}(1)\ln\frac{y_{i.}^{rs}(1)}{y_{i.}^{rs}(0)} \tag{1a}$$

s.t.

$$\textstyle\sum^{r} z_{i.}^{rs}(1) + \sum^{r} y_{i.}^{rs}(1) = d_i^s \tag{1b}$$

$$\textstyle\sum^{s} z_{i.}^{rs}(1) + \sum^{s} y_{i.}^{rs}(1) = x_i^r \tag{1c}$$

$$\textstyle\sum^{r\in M}\sum^{s\in N} z_{i.}^{rs}(1) = z_{i.}^{MN} \tag{1d}$$

$$\textstyle\sum^{r\in M}\sum^{s\in N} y_{i.}^{rs}(1) = y_{i.}^{MN} \tag{1e}$$

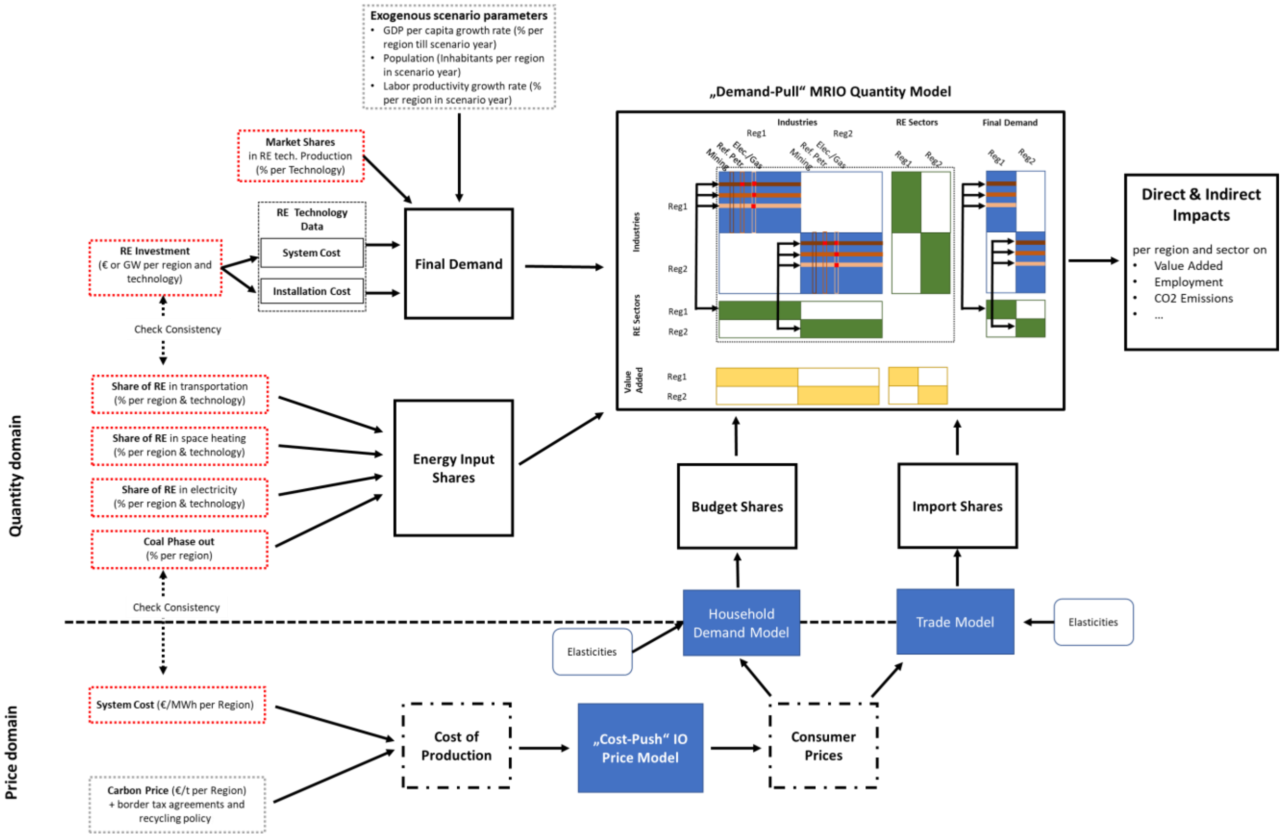
The first two constraints ensure that all intermediate and final products purchased by region *s* from other regions (including from the own region) add up to total domestic demand $d_i^s = z_i^{\cdot s} + y_i^{\cdot s}$ and that all products sold by region r to other regions (including to the own region) add up to gross output x_i^s. Total domestic demand and gross output by region and sector were estimated in step 1. The final two constraints ensure that intermediate or final deliveries, respectively, of all regions belonging to country *M* to all regions belonging to country *N* adhere to the respective intermediate or final deliveries in the FIGARO data.

A.2 MRIO model

The projection model is based on the approach developed in Wiebe et al. (2018) and the modelling of the four impact channels is based on Többen (2017). For the scenarios of the expansion of renewable energy, we estimate impact channels for the direct and indirect effects on the own region but also spill-over effects on other regions via interregional trade. All software code for data processing, modelling, scenario evaluation and results visualisation is written in *R*.

The structure of the MRIO modelling tool is shown in Figure A2. The boxes with dotted lines show the exogenous scenario parameters. The grey dotted boxes show scenario parameters that describe the evolution of regional demographic and economic developments, i.e. GDP, population, labour productivity. These parameters describe the future world in which the energy transition takes place. The red dotted boxes list the main scenario parameters for modelling the regional energy transition. These are (1) the shares of fossil-based energy carriers (coal, oil and gas and electricity generated from them) consumed by industry and final consumers that are replaced by renewable energies, (2) the mix of renewable energy technologies that can satisfy the demand for renewable energy (shares of renewable energy technologies), (3) the location of newly installed renewable energy capacities and related investment, and (4) the distribution of system costs.

Figure A2: Structure and exogenous scenario parameters of the impact assessment model for the EU's renewable energy transition



Notes: Overview of the MIRO-based model framework. Source: Own illustration.

A2.1 Projection model

The MRIO table for the base year of 2019 is projected into the future based on exogenous scenario specifications. Population and GDP growth trajectories from the *EU Reference Scenario 2020* (European Commission 2021) are translated into changes in household demand, government spending and capital formation and lead to projections of sectoral production and value added via input-output (technology) and interregional trade relations.

We use an multi-regional input-output quantity model (Miller and Blair 2009), that links final demand by industry, $\mathbf{Y}$, to output by industry, **q**, via the technical coefficient matrix, **A**:

$$\mathbf{q} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}\mathbf{i} = \left(\mathbf{I} - \mathbf{T}\widehat{\mathbf{A}}\right)^{-\mathbf{1}} \mathbf{T}\left(\widehat{\mathbf{H}} + \widehat{\mathbf{G}} + \widehat{\mathbf{CF}}\right)\mathbf{i}, \tag{A1}$$

where the final demand $\mathbf{Y}$ can be further decomposed into household consumption $\widehat{\mathbf{H}}$, government spending $\widehat{\mathbf{G}}$ and gross fixed capital formation $\widehat{\mathbf{CF}}$. We use **i'** or $\mathbf{i}$ to represent a unit vector of appropriate length for summation across rows or columns. The input coefficient matrix $\mathbf{A}$ is the product of the matrix of import shares $\mathbf{T}$ and the technological matrix $\widehat{\mathbf{A}}$.

We assume constant ratios regarding the distribution of the individual products and the producing countries in the baseline case. Thus, the technical coefficient matrix $\mathbf{A}$ is kept constant with $a_{ij}^{rs} \in \mathbf{A}$:

$$a_{ij}^{rs} = t_i^{rs}\, a_{ij}^{s}, \tag{A2}$$

where $a_{ij}^{s} = \sum^{r} a_{ij}^{rs}$ as technical coefficient denotes total demand for product i per unit of output of industry *j* in region s irrespective of product i's origin (summed up across all regions *r*). t_i^{rs} denotes the import shares and represents trade linkages between regions s and r for product i. The sum of all import shares t sums up to 1 over all regions r.

The quantity model delivers the total demand-pull effects, i.e. the production required from each sector and country to satisfy a given final demand. The current year components of the government spending $\widehat{\mathbf{G}}$ and capital formation matrices $\widehat{\mathbf{CF}}$ are adjusted based on the previous year's components taking into account an exogenously given growth rate γ. There are no interdependencies in time.

We expect change in final household demand due to a change in energy prices. Investment in renewable energy technologies and higher system costs cause an energy price shock e which results in an exogenously driven price shock to households and a change in consumption patterns. The composition of the change in consumption patterns over time are modelled by means of expenditure elasticities based on Muhammad et al. (2011). The model equation is

$$c_i^s(t+1) = c_i^s(t)(1 + \Delta h_{\cdot}^{\cdot s})^{\gamma_i^s}, \tag{A3}$$

where $\Delta h_{\cdot}^{\cdot s}$ denotes the changes of total household expenditures summed up over all regions r and industries i in region s due to the change in the energy system and γ_i^s denotes expenditure elasticity for consumption good i in region s.

Expenditure elasticities are taken from the World Bank's International Comparison Programme, which provides compensated expenditure elasticities differentiating between nine broad consumption categories for 144 countries as well as three (low, middle and high) income group averages (Muhammad et al. 2011). Given that our database is more detailed, we take averages to assign elasticities to the specific regions and goods categories. We base the expenditure elasticities in the European NUTS-2-regions on the countries' averages and the elasticities of goods categories on the averages of the assigned sectors. When implemented into the model, the region and sector specific elasticities are assigned to the respective importing region and importing sector.

A2.2 Impact channels

Production and Installation of Renewable Energy Technologies

The production and installation of renewable energy technologies affects regional economies via demand for intermediate products and labour. From scenario dependent installation rates, capacities and local energy demand, we can compute investments into the nine different renewable energy technologies in each region. We assume that planning and installation is carried out by local firms, whereas the renewable energy technologies are often produced at specific places and in many cases outside the EU (especially solar and increasingly wind). The market shares of the different renewable energy technologies producing destinations in the region of installation per technology is exogenously specified. The intermediate demands of renewable energy producers, planning and installation firms form the exogenous capital formation matrix $\widehat{\boldsymbol{CF}}_{\boldsymbol{RE}}$, whereas the labour compensation of their workers is used in combination with Equation A3 to form the household consumption matrix $\widehat{\boldsymbol{H}}_{\boldsymbol{RE}}$.

The direct, indirect and spill-over effects on value added and employment by sector and region associated with the resulting final demand shocks are estimated using the demand-driven quantity MRIO model.

To summarise: the main scenario parameters that drive the impact of the production and installation of renewable energy technologies are (1) investments in renewable energy technologies by technology in a region (generation and other energy transition-related technologies) and (2) the market share of renewable energy producers by region.

Structural change in the energy system

In the MRIO table, the energy sector lumps together gas and electricity and therefore lacks detail to map structural changes in regional energy sectors associated with the energy transition. For this reason, we decided not to disaggregate the existing energy sector in the regions using survey-based cost structures from O'Sullivan and Edler (2020), but rather to expand the technological coefficient matrix $\boldsymbol{A}$ by introducing the operation of the different renewable energy technologies as new sectors, i.e.

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_{\boldsymbol{ij}} & \mathbf{A}_{\boldsymbol{i,RE}} \\ \mathbf{A}_{\boldsymbol{RE,j}} & \mathbf{0} \end{bmatrix}$$

where $\boldsymbol{A}_{\boldsymbol{i,RE}}$ denotes intermediate inputs from sector i used for operating renewable energy technologies in each region. To generate these coefficients, we multiply the total intermediate demand $\widehat{\mathbf{A}}_{\boldsymbol{i,RE}}$ by the matrix of import shares **T.** We assume that the renewable energy input structures are the same per technology across all EU regions and that import shares per type of input *i* and exporter *r* are the same as of other sectors in the same region.

The market shares of these new renewable energy sectors relative to that of the current energy sector are exogenously specified scenario parameters and depend on technology mix in the energy producing region (driven by investment into new renewable energy technologies) as well as on import shares for energy in the consuming region (driven by investments in grids and energy storage facilitie). We assume that all consumers of electricity and heat generated in a certain region consume the same energy mix. Similarly, the product dimension *i* of the final demand matrix $\mathbf{Y}$ needs to be expanded by the new renewable energy sectors as well.

To be clear, the "old" energy sector of 2019 consists of – to a varying degree – different electricity generation technologies (fossil) including today's renewable energy capacities. Hence, the distinction is made solely between power plants operated today and those to be installed and operated in future. The main advantage of this approach compared to disaggregating sectors within matrix *A* is that we do not need to reconcile the database to ensure consistency between input structures of the aggregate energy sectors and the estimated input structures of the subsectors as, e.g., in Lindner et al. (2012).

The major structural changes within the current aggregate energy sector concern the shares of fossil fuelled powerplants and natural gas in the future. The phasing out of coal-fired power plants and the reduction in natural gas consumption are modelled by reducing the technological input coefficients for mining products (sector B) and products of the *coke and refined petroleum sector* (sector C21) of the "old" aggregate energy sector as well as its share relative to the new renewable energy sectors.

The direct, indirect and spill-over effects on value added and employment by sector and region associated with these structural changes in the energy system are estimated using the demand-driven quantity MRIO model.

To summarise: the main scenario parameters that drive the impact of the structural changes in the energy sector are (1) the market share of the old versus the new energy sectors in energy generation in a region, (2) the shares of energy imports (old and new sectors) to a region, and (3) trajectories for phasing out of fossil fuelled powerplants and natural gas heating in a region.

Price effects

The transition from mostly centralised fossil-based energy generation towards a more decentralised energy system based on renewable energy has a significant impact on system costs and, thus, energy prices. Today energy prices, in particular for electricity, are homogenous within most European countries. Spatial energy price differences mostly exist between EU member states and are important determinants of economic competitiveness. There is a large body of literature assessing the costs of an energy system based on renewables for EU countries, which can be used to specify exogenous changes in energy prices.

Energy prices are dependent on scenario-specific developments and represent changes in energy system costs due to political decisions, the expansion of renewable energy, technical aspects of renewable energy technology and/or political schemes like carbon pricing. An increase in energy costs has a cascading effect since each energy user (each industry) will increase their prices to cover their increased energy expenses. By raising their prices each industry passes on its increase in energy costs to customers. Thus, prices in all sectors will increase due to direct and indirect effects of changes in energy prices. The price model links the exogenously given scenario-specific increases in energy prices $\Delta\boldsymbol{\rho}$ to changes in the industries' production prices $\mathbf{p}$:

$$\Delta\,\mathbf{p} = \Delta\boldsymbol{\rho}(\mathbf{I}-\mathbf{A})^{-\mathbf{1}} = \Delta\boldsymbol{\rho}\left(\mathbf{I}-\mathbf{T}\widehat{\mathbf{A}}\right)^{-\mathbf{1}} \tag{A4}$$

By default, in the current year and given the variables in nominal prices, the price vector $\mathbf{p}$ is a vector of ones. If, however, cost of production (e.g. energy prices) exogenously change the resulting cost-push effect on the overall price-level $\mathbf{p}$, can be calculated through pre-multiplying with $(\mathbf{I}-\mathbf{A})^{-\mathbf{1}}$.

The price model that determines the change in household consumption and import shares consists of the following four steps:

1. Investment in renewable energy and energy price elasticities: Technical coefficients for each region and sector, $\mathbf{A_0}$ change due to direct efficiency effects between energy inputs of technologies. Import shares $\mathbf{T}$ are left constant.

2. Calculate total price effects $\Delta\mathbf{p}$ due to an increase in energy prices using the input-output price model with $\mathbf{A_0}$, and exogenous changes in production cost, $\Delta\boldsymbol{\rho}$.

3. Households respond to energy price changes, changing the product composition captured in Δc_i^s**.** Calculate short-run responses to global price changes by changing import shares $\mathbf{T}$, keeping technology $\widehat{\mathbf{A}}$ constant. This results in $\mathbf{A_1}$**.**

4. Calculate industry- and region-specific output and employment effects for a renewable energy scenario using the input-output quantity models.

Consumption of products from industry i in region s, $\hat{c}_i^s$, is dependent on the industry i' prices $p_{i\prime}^s$ and the own- (i.e. $i = i$') and cross price elasticates $\varepsilon_{ii\prime}$ (Muhammad et al. 2011):

$$c_i^s(\mathrm{t}+1) = c_i^s(t)\sum\nolimits_{i\prime}\tfrac{1}{I\prime}(1+\Delta p_{i\prime}^s)^{\varepsilon_{ii\prime}^s} \tag{A5}$$

Again, we multiply c_i^s by the average across all the partial effects i' on each c_i^s through the own and cross-price effects.

The short-run adjustments of the global production structure are assumed to be due to changes in bilateral trade shares driven by global price changes. For now, the respective elasticities are taken from Muhammad et al. (2011). The new input coefficients are computed by

$$\hat{t}_i^{rs}(t+1) = t_i^{rs}(t)\,\Delta {p_i^r}^{(\sigma_i-1)}\,\Delta {P_{ij}^s}^{(1-\sigma_i)} \tag{A6}$$

where Δp_i^r denotes the price change of sector i from region r, ΔP_{ij}^s denotes the change in the weighted average price of input i in industry j from region s (using import shares as weights), and σ_i denotes the constant elasticity of substitution (CES) output elasticity.

Spatial price differences within regions are an exogenous scenario parameter. Exogenous price changes can be used as an input to estimate the overall impacts on production costs by region and sector when the MRIO price model takes the cost-push effect along supply chains into account. The changes in production costs lead to a change in relative competitiveness of regional sectors and thus to a change in interregional and international trade shares. This effect is modelled using the trade elasticities of substitution.

The direct, indirect, and spill-over effects on value added and employment by sector and region associated with these price-driven structural changes in bilateral trade, energy efficiency and household consumption pattern are estimated using the demand-driven quantity MRIO model.

To summarise: the main scenario parameters that shape the price related impacts of renewable energy technologies are price increases relative to the base year reflecting changed costs of the energy system (old and new sectors) in a region.

Decomposing impacts by impacts channel

Finally, the effects of the structural impacts of the four discussed impact channels on regional economic and social indicators are assessed using the MRIO quantity model. More specifically we get the following impacts on output for each of the different impact channels of the investment in renewable energy. In the following, the suffix *base* denotes vectors and matrices before any changes were made:

Changes in final household consumption due to technical change and trade effects:

- Own- and cross-price effects $\Delta\mathbf{x}_{c_i^s} = (\mathbf{I} - \mathbf{A_1})^{-1}\Delta\mathbf{c}_\mathrm{i}^\mathrm{s} = \mathbf{L_1}\ \Delta\mathbf{c}_\mathrm{i}^\mathrm{s}$ (A7i)
- Income effects $\Delta\mathbf{x}_{h\_income} = (\mathbf{I} - \mathbf{A_1})^{-1}\Delta\mathbf{h}_{income} = \mathbf{L_1}\ \Delta\mathbf{h}_{income}$ (A7ii)

Changes in government spending:

$$\Delta\mathbf{x}_{gov} = (\mathbf{I} - \mathbf{A_1})^{-1}\Delta\mathbf{g} = \mathbf{L_1}\ \Delta\mathbf{g} \tag{A8}$$

Changes in energy use and trade shares:

- Own- and cross-price effects $\Delta\mathbf{x}_{tech} = \left[(\mathbf{I} - \mathbf{A_0})^{-1} - (\mathbf{I} - \mathbf{A}_{base})^{-1}\right] \boldsymbol{y}_{base} = [\mathbf{L_0} - \mathbf{L}_{base}]\ \boldsymbol{y}_{base}$ (A9i)
- Trade effects $\Delta\mathbf{x}_{trade} = \left[(\mathbf{I} - \mathbf{A_1})^{-1} - (\mathbf{I} - \mathbf{A_0})^{-1}\right] \boldsymbol{y}_{base} = [\mathbf{L_1} - \mathbf{L_0}]\ \boldsymbol{y}_{base}$ (A9ii)

By summing up these five separate effects, we end up with the total effect on output for an energy transition scenario.

A2.3 Sector classification and groups of industries

Table A1 shows the sector classification of the MRIO-model. The first 53 sectors are defined within the NACE-R2 classification, as reported by official statistics. The renewable energy sectors (54 to 62) are defined based on O'Sullivan and Edler (2020). Structural changes within decarbonisation are modelled by shifting input shares between energy sectors (see third column) – fossil energy to renewable energy sectors.

Table A1: Sector classification and groups of industries

Sector	Description	Industry
A	Agriculture, forestry and fishing	Primary
B	Mining and quarrying	Energy
C10T12	Manufacture of food products, beverages and tobacco products	Low-tech
C13T15	Manufacture of textiles, wearing apparel and leather	Low-tech
C16	Manufacture of wood and of products of wood and cork	Low-tech
C17	Manufacture of paper and paper products	Energy-intensive
C18	Printing and reproduction of recorded media	Low-tech
C19	Manufacture of coke and refined petroleum products	Energy
C20	Manufacture of chemicals and chemical products	Energy-intensive
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	High-tech
C22	Manufacture of rubber and plastic products	Energy-intensive
C23	Manufacture of other non-metallic mineral products	Energy-intensive
C24	Manufacture of basic metals	Energy-intensive
C25	Manufacture of fabricated metal products	High-tech
C26	Manufacture of computer, electronic and optical products	High-tech
C27	Manufacture of electrical equipment	High-tech
C28	Manufacture of machinery and equipment n.e.c.	High-tech
C29	Manufacture of motor vehicles, trailers and semi-trailers	High-tech
C30	Manufacture of other transport equipment	High-tech
C31_32	Manufacture of furniture; other manufacturing	Low-tech
C33	Repair and installation of machinery and equipment	Low-tech
D35	Electricity, gas, steam and air conditioning supply	Energy
E36	Water collection, treatment and supply	Other services
E37T39	Sewerage; waste collection, treatment and disposal; remediation activities	Other services
F	Construction	Other services
G45	Trade and repair of motor vehicles and motorcycles	Other services

Sector	Description	Industry
G46	Wholesale trade	Other services
G47	Retail trade, except of motor vehicles and motorcycles	Other services
H49	Land transport and transport via pipelines	Other services
H50	Water transport	Knowledge-intensive
H51	Air transport	Knowledge-intensive
H52	Warehousing and support activities for transportation	Other services
H53	Postal and courier activities	Other services
I	Accommodation and food service activities	Other services
J58	Publishing activities	Knowledge-intensive
J59_60	Media production and broadcasting activities	Knowledge-intensive
J61	Telecommunications	Knowledge-intensive
J62_63	Computer programming and information services	Knowledge-intensive
K64	Financial service activities, except insurance and pension funding	Knowledge-intensive
K65	Insurance, reinsurance and pension funding, except compulsory social security	Knowledge-intensive
K66	Activities auxiliary to financial services and insurance activities	Knowledge-intensive
L	Real estate activities	Other services
M69_70	Legal and accounting activities	Knowledge-intensive
M71	Architectural and engineering activities; technical testing and analysis	Knowledge-intensive
M72	Scientific research and development	Knowledge-intensive
M73	Advertising and market research	Knowledge-intensive
M74_75	Other professional, scientific and technical activities	Knowledge-intensive
N77	Rental and leasing activities	Other services
N78	Employment activities	Knowledge-intensive
N79	Travel agency, tour operator and other reservation service and related activities	Other services
N80T82	Other services	Knowledge-intensive
O-Q	Public administration; education; human health and social work	Other services
R-U	Arts, entertainment and recreation; other service activities; activities of households; extraterritorial organisations	Other services
Won	Onshore Wind	Energy

Sector	Description	Industry
Wof	Offshore Wind	Energy
Pv	Solar	Energy
Hy	Hydropower	Energy
St	Solarthermal	Energy
Hp	Heatpumps	Energy
Bhs	Biomass, small scale heating	Energy
Bg	Biomass, electricity	Energy
Gd	Geothermal	Energy

A.3 Scenario Definitions

Table A2: Overview of the different scenario variants and their assumptions

		Exogenous parameters		Scenario parameters						
	Scenario	Population	GDP growth trajectories	Ambition	Tech mix	Investment	System costs	Distribution	Import	Fossil mark-up
	Baseline variants									
	Baseline	base	EU REF regionalised	EU REF	EU REF	EU REF	EU REF	capacities/ potentials	base	-
	Baseline *national GDP*	base	EU REF *(national)*	EU REF	EU REF	EU REF	EU REF	capacities/ potentials	base	-
	Baseline *fossil price shock*	base	EU REF (national)	EU REF	EU REF	EU REF	EU REF	capacities/ potentials	base	100 €/t CO_2-emission
	Decarbonisation variants									
a)	Main decarbonisation *("The benchmark")*	base	EU REF regionalised	CN50	EU REF	CN50	high	capacities/ potentials	base	-
b)	Carbon neutrality in 2040	base	EU REF regionalised	CN40	EU REF	CN40	high	capacities/ potentials	base	-
c)	Faster decline of costs	base	regionalised	CN50	EU REF	CN50	EU REF	capacities/ potentials	base	-
d)	Different regional expansion	base	regionalised	CN50	EU REF	CN50	high	policy driven	base	-
e)	Higher EU autonomy	base	regionalised	CN50	EU REF	CN50	high	capacities/ potentials	low	-
f)	Increase in fossil fuel pricing	base	regionalised	CN50	EU REF	CN50	high	capacities/ potentials	base	100 €/t CO_2-emission
g)	Regions develop similar within countries	base	national	CN50	EU REF	CN50	high	capacities/ potentials	base	-

Notes: *Population* is based on projections from Eurostat at NUTS-3 level (base year 2019) for EU member states (Eurostat 2021b) and the SSP database (SSP2 scenario) for non-EU countries (Riahi et al. 2017). *GDP growth* trajectories are based on the EU REF for EU countries (European Commission 2021) and SSP database (SSP2 scenario) for non-EU countries (Riahi et al. 2017). Regionalisation of the national GDP growth trajectories is based on the regional potential for economic growth as published in Bertelsmann Stiftung (2022). *Ambition* describes whether decarbonisation is achieved and how fast. CN50 and CN40 denote the setting of scenario parameters such that carbon neutrality is reached by 2050 or 2040, respectively. *Tech mix* describes the renewable energy technology mix. *Investment* is based on the EU REF (or scaled up) and denotes the necessary investments in renewable energy technologies to meet the targets of the scenario. *System costs* describes the increase in costs when increasing renewable energy production. We assume that a more ambitious increase in the share of renewable energy will lead to higher system costs (reflected by higher electricity prices) than stated in EU REF because of necessary expansion in transmission and storage. Sensfuß et al. (2021) expect investments for transmission and distribution 2.4 times higher than today (scenario "TN-Strom") and, consequently, electricity costs being 40% higher when carbon neutrality is achieved. *Distribution* refers to the spatial distribution of renewable energy expansion. *Import* describes the share of renewable energy technologies imported to the EU. *Fossil markup* denotes the surcharge on fossil energy prices. Effects are measured by comparing different scenario variants (a) to e) with baseline, f) and g) with varied baselines).

A.4 Data

Table A3: Data sources

Dataset	Description	Source
FIGARO	FIGARO MRIO table for 2019 jointly developed by Eurostat and the European Commission, which was extended for this project to improve both the spatial and sectoral resolution.	Eurostat (2021a)
EUREGIO	MRIO table for NUTS2-Region for information on interregional trade flows	Thissen et al. (2018)
SBS	Structural business statistics on NUTS2- level	Eurostat (2023b)
NAMA	Regional economic accounts (NUTS 2-level): value added and employment	Eurostat (2023a)
Input structures renewable energy	Input structures of the operation and maintenance, installation, and production of nine renewable electricity and heating technologies (onshore wind, offshore wind, hydropower, solar, biomass, biogas, ambient heat, solar thermal and geothermal)	O'Sullivan and Edler 2020
Population projection	Population at the NUTS-2 level is based on projections from Eurostat at NUTS-3 level (base year 2019)	Eurostat (2021b)
Regional growth potentials	GDP-growth trajectories on NUTS-2 level based on the regional economic growth potentials	Bertelsmann Stiftung (2022)
EU Reference Scenario	Data on the national level for all EU countries (historical as well as projected until 2050): GDP, population, energy demand, electricity and energy mix	European Commission (2021)
SSP2 scenario	Data source for economic data on 13 non-EU trading partners (Australia, Brazil, Canada, China, Great-Britain, Indonesia, India, Japan, South-Korea, Mexico, Russia, Turkey, and the United States of America)	Riahi et al. (2017)
Regional emissions	CO_2 emissions from the Emissions Database for Global Atmospheric Research (EDGAR), where information on energy related emissions is available up to NUTS-2-level	EDGARv7.0 (2022)
Energy balances	Energy data in form of country specific energy balances which comprise details on the supply and demand of energy carriers	IEA (2021)
Carbon footprints, sectoral	FIGARO application provides detailed information on carbon footprints on the sectoral level	Eurostat (2020)
Technical potentials renewable energy technologies	Subnational distributions of solar and wind energy capacities are derived from data on capacity factors and land area of NUTS 2-regions	Staffell and Pfenninger (2016), Pfenninger and Staffell (2016)

A.5 Cluster analysis

The spatial pattern in the maps of Figure 6 and Figure 7 suggest that urban regions are worse affected by the renewable energy transition than rural regions. To verify this visual impression, we identify clusters for urban regions and compare their specific characteristics.

The cluster analysis is based on indicators listed in Table A4. Regions with missing values were excluded from the analysis. The indicators are scaled and the dimensions are reduced to four using a principal component analysis. The four principal components explain 80 % of the variation in the data.

Table A4: Indicators used for the cluster analysis

Indicator	Explanation	Reference year	Data source
Impact intensity	Impact of decarbonisation scenario compared to baseline in a region relative to the impact on EU-wide level	2050	Own estimation
GDP	GDP per capita in relation to EU average (=100)	2019	Eurostat Databrowser (ESTAT): NAMA_10R_2GDP$DEFAULTVIEW, NAMA_10R_3POPGDP$DEFAULTVIEW
Density	Inhabitants per km² in relation to EU average (=100)	2019	Eurostat Databrowser (ESTAT): REG_AREA3$DEFAULTVIEW, NAMA_10R_3POPGDP$DEFAULTVIEW
Urban	Regions with at least 300 inhabitants per km²	2019	Own calculation based on density
High-tech sector	Share of people employed in high-tech sector in total employment in relation to EU average (=100)	2019	Eurostat Databrowser (ESTAT): HTEC_EMP_REG2__custom_7609238
Unemployment	Unemployment rate in relation to EU average (=100)	2019	Eurostat Databrowser (ESTAT): LFST_R_LFU3RT__custom_7632831
Potential renewable energy	Technical potential for renewable energy technologies (kWh per capita) in relation to EU average (=100)		Kakoulaki et al. (2021), Eurostat Databrowser (ESTAT): NAMA_10R_3POPGDP$DEFAULTVIEW
CO_2 intensity	CO_2 emissions per output GDP (t per million Euro) in relation to EU average (=100)		EDGARv7.0 Eurostat Databrowser (ESTAT): NAMA_10R_2GDP$DEFAULTVIEW

The cluster were estimated in *R* using the package *mclust* (Scrucca et al. 2016). The result is an ellipsoidal, equal shape model with three clusters. The three clusters are of size 31, 4 and 23. The outcome was validated using k-means and hierarchical clustering. The mean values for the respective clusters are given in Table A5.

Table A5: Characteristics of the clusters

Indicator	Cluster 1	Cluster 2	Cluster 3
Impact intensity	-1.9	-5.3	-1.2
GDP	129	147	100
Density	732	2944	123
Urban	0.8	0.8	0
High-tech sector	133	113	83
Unemployment	66	113	113
Potential renewable energy	21	472	95
CO_2 intensity	118	128	111

Notes: Except for the indicators Urban and Impact intensity values above 100 are higher than the EU-average (=100). Values below 100 are lower than average. For Impact intensity values greater than 0 are above the EU-average and values lower than 0 below the average. For Urban = 1 a region is classified as urban area.

A.6 Inequality statistics

Table A6: Inequality indicators for all scenarios

Scenario + year	Gini-coefficient		Proportion of 90- to 10-percentile	Theil index (without population weights)	Share of value added in *less developed* regions	Reference and year to compare to
	un-weighted	population weights				
Base year, 2019	0.531	0.491	3.84	0.543	12.96	
Baseline, 2050	0.556	0.516	3.73	0.598	11.50	
Baseline, 2040	0.547	0.507	3.61	0.577	12.11	
Baseline for *Increase in fossil fuel pricing* (variant f), 2050	0.557	0.517	3.82	0.601	11.40	
Baseline for *Regions develop similar within countries* (variant g), 2050	0.537	0.498	3.38	0.553	12.29	
a) The benchmark, 2050	0.553	0.514	3.70	0.592	11.55	Baseline, 2050
b) Carbon neutrality in 2040	0.544	0.504	3.58	0.571	12.17	Baseline, 2040
c) Faster decline in costs, 2050	0.553	0.514	3.69	0.592	11.57	Baseline, 2050
d) Different regional expansion, 2050	0.553	0.514	3.70	0.592	11.57	Baseline, 2050
e) Higher EU autonomy	0.553	0.514	3.70	0.592	11.55	Baseline, 2050
f) Increase in fossil fuel pricing	0.554	0.514	3.70	0.593	11.55	Baseline for *Increase in fossil fuel pricing* (variant f), 2050
g) Regions develop similar within countries, 2050	0.535	0.496	3.34	0.549	12.33	Baseline for *Regions develop similar within countries* (variant g), 2050

Notes: The Gini coefficient is calculated as $G = \frac{1}{n^2\mu}\sum_{i=1}^{n} x_i(2i-n-1)$, with x_i equal to value added per capita in region i, n referring the number of observations (in our case 213 regions) and μ displaying the mean value of value added per capita. The Theil index is calculated as $T = \frac{1}{n}\sum_{i=1}^{n}(\frac{y_i}{\beta} * \ln\left(\frac{y_i}{\beta}\right))$, with y_i equal to value added in region i, n referring the number of observations and β corresponding to the mean value of value added across regions. The 90/10 ratio is given as $R = x_{0.9}/x_{0.1}$, with $x_{0.9}$ marking the 90th percentile of the distribution of value added per capita and $x_{0.1}$ marking the 10th percentile respectively.

A.7 Case studies

Romania

Romania is a predominantly rural country with below-average economic performance and low disposable income. The high-tech sector figures at a below-average level while public sector services, real estate activities, construction, retail trade, land transport and transport via pipelines, food and beverage production and agriculture contribute greatly to economic performance. There are strong differences between the capital region of Bucharest and the rest of the country: Bucharest is a European hot spot for high-tech industry sectors being particularly strong in software development.

Energy production in Romania is more carbon intensive than the EU average although the share of renewable energy is above average. This is a result of the high share of coal in the fossil fuel-based energy mix. At the same time, Romania offers above-average potential for the expansion of renewable technologies. However, the country struggles to make good use of this potential as the EU Reference Scenario illustrates. Overall, the renewable energy transition has a low negative impact on economic performance mainly caused by private consumption. The negative impact is driven by higher consumption prices which cannot be compensated for. In addition, imported consumer goods to Romania will have higher prices reinforcing the negative impact on private consumption. As a result, economic activities generating lower value added will be prioritised.

Unfortunately, we do not have region-specific results for Romania due to poor data. However, our results for European NUTS-2 regions in other countries show negative impacts on urban areas, in particular metropolitan areas and capital regions, and this probably holds true for Bucharest. The overall negative result for Romania may well reflect the strong concentration of the country's economy on the capital region, which accounts for about 25 % of GDP in 2022 according to Eurostat.

Sweden

All Swedish regions are characterised by above-average economic performance and disposable income. High-tech economic sectors are comparatively strong in half of the Swedish regions (Stockholm, Östra Mellansverige, Sydsverige and Västsverige). Except for the metropolitan area Stockholm and the region Sydsverige (above EU-wide density), Sweden is rural with very low population density.

Swedish rural regions have an above-average potential for renewable energy technologies. At the same time, energy production in all regions is already characterised by low CO_2 intensity. This means that the additional renewable energy expansion required to close the gap between current efforts and the Green Deal's goal of climate neutrality is minute, leading to only low additional economic benefits. At the same time private households are confronted with higher prices for consumer goods imported from other regions. This changes the consumption structure, which negatively affects intermediate consumption, production structures and economic performance. Overall, the economic performance of Swedish regions remains almost unchanged.

A.8 Region-specific results

Table A7: Effects of the renewable energy transition on value added and employment, 2050

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
AT11	Burgenland (A)	0.5	230	0.0	30
AT12	Niederösterreich	-0.1	-70	-0.2	-2,490
AT13	Wien	-0.8	-770	-0.6	-14,160
AT21	Kärnten	0.2	100	0.0	190
AT22	Steiermark	0.2	140	0.0	-20
AT31	Oberösterreich	0.0	-10	-0.1	-930
AT32	Salzburg	-0.3	-210	-0.3	-1,590
AT33	Tirol	-0.1	-90	-0.2	-1,330
AT34	Vorarlberg	-0.2	-150	-0.2	-820
BE10	Région de Bruxelles-Capitale/Brussels Hoofdstedelijk Gewest	-1.2	-1,390	-0.8	-11,650
BE21	Prov. Antwerpen	-0.6	-410	-0.3	-5,030
BE22	Prov. Limburg (B)	0.5	260	0.5	2,990
BE23	Prov. Oost-Vlaanderen	-0.3	-200	0.0	-250
BE24	Prov. Vlaams-Brabant	0.0	-30	-0.1	-570
BE25	Prov. West-Vlaanderen	1.6	960	1.1	9,850
BE31	Prov. Brabant Wallon	-0.1	-50	0.0	130
BE32	Prov. Hainaut	1.5	580	1.0	6,360
BE33	Prov. Liège	0.9	410	0.9	5,370
BE34	Prov. Luxembourg (B)	4.6	1,570	2.8	3,750
BE35	Prov. Namur	2.6	1,030	1.7	4,470
BG	Balgarija	0.1	10	0.0	1,800
CY	Kýpros	-0.8	-390	-0.9	-9,710
CZ01	Praha	-1.1	-1,050	-0.3	-9,320
CZ02	Střední Čechy	1.1	330	1.6	19,550
CZ03	Jihozápad	2.7	740	3.4	32,610
CZ04	Severozápad	0.5	130	1.7	11,410
CZ05	Severovýchod	2.3	650	2.7	31,130
CZ06	Jihovýchod	1.9	660	2.3	36,270
CZ07	Střední Morava	3.1	870	3.3	29,500

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
CZ08	Moravskoslezsko	0.1	40	1.3	12,470
DE11	Stuttgart	-0.3	-270	-0.4	-17,870
DE12	Karlsruhe	-0.5	-370	-0.5	-13,900
DE13	Freiburg	0.0	0	-0.1	-2,340
DE14	Tübingen	0.1	90	0.0	0
DE21	Oberbayern	-0.7	-800	-0.7	-54,160
DE22	Niederbayern	0.7	380	0.5	5,140
DE23	Oberpfalz	0.8	550	0.6	6,390
DE24	Oberfranken	0.6	340	0.3	3,040
DE25	Mittelfranken	0.1	50	0.0	-460
DE26	Unterfranken	0.5	290	0.3	3,210
DE27	Schwaben	0.3	190	0.1	1,670
DE30	Berlin	-0.8	-620	-0.6	-26,430
DE40	Brandenburg	1.7	850	1.6	27,340
DE50	Bremen	-0.8	-600	-0.6	-4,490
DE60	Hamburg	-1.1	-1,320	-1.0	-28,060
DE71	Darmstadt	-0.9	-850	-0.7	-34,150
DE72	Gießen	0.1	50	0.1	1,220
DE73	Kassel	0.2	120	0.2	2,200
DE80	Mecklenburg-Vorpommern	1.5	770	1.7	19,830
DE91	Braunschweig	0.3	140	0.2	2,280
DE92	Hannover	-0.1	-60	-0.2	-3,710
DE93	Lüneburg	1.8	790	1.1	12,750
DE94	Weser-Ems	1.0	490	0.6	13,560
DEA1	Düsseldorf	-1.1	-700	-0.9	-41,030
DEA2	Köln	-0.9	-660	-0.8	-34,370
DEA3	Münster	-0.6	-280	-0.5	-10,030
DEA4	Detmold	0.0	10	0.0	-590
DEA5	Arnsberg	-0.3	-180	-0.3	-7,780
DEB1	Koblenz	0.2	100	0.1	1,470
DEB2	Trier	0.4	190	0.1	560
DEB3	Rheinhessen-Pfalz	-0.7	-410	-0.6	-10,930

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
DEC0	Saarland	-1.4	-690	-0.6	-4,130
DED1	Chemnitz	-0.2	-130	-0.2	-2,410
DED2	Dresden	-0.2	-100	0.0	440
DED3	Leipzig	-0.3	-160	-0.2	-1,540
DEE0	Sachsen-Anhalt	-0.6	-280	0.2	2,180
DEF0	Schleswig-Holstein	1.2	600	0.8	18,580
DEG0	Thüringen	-0.2	-120	0.2	3,340
DK01	Hovedstaden	-0.3	-450	-0.3	-7,440
DK02	Sjælland	0.3	150	0.1	330
DK03	Jylland	0.0	-20	0.0	450
EE	Eesti	-0.5	-250	-0.6	-17,570
ES11	Galicia	0.0	0	0.0	-660
ES12	Principado de Asturias	-0.5	-210	-0.2	-1,390
ES13	Cantabria	-0.1	-40	-0.1	-330
ES21	País Vasco	-0.3	-160	-0.2	-4,610
ES22	Comunidad Foral de Navarra	-0.3	-160	-0.2	-1,040
ES23	La Rioja	0.0	-10	-0.1	-250
ES24	Aragón	1.0	500	0.8	10,060
ES30	Comunidad de Madrid	-0.6	-470	-0.4	-38,590
ES41	Castilla y León	2.1	850	1.7	27,140
ES42	Castilla-La Mancha	1.9	680	1.5	19,840
ES43	Extremadura	1.6	520	0.8	5,680
ES51	Cataluña	-0.7	-420	-0.6	-47,450
ES52	Comunidad Valenciana	-0.5	-170	-0.4	-13,150
ES53	Illes Balears	-0.6	-230	-0.5	-4,660
ES61	Andalucía	0.2	60	0.0	2,600
ES62	Región de Murcia	-0.2	-60	-0.4	-4,270
ES63	Ciudad Autónoma de Ceuta	-0.5	-160	-0.5	-310
ES64	Ciudad Autónoma de Melilla	-0.6	-250	-0.6	-480
ES70	Canarias	-0.5	-180	-0.4	-7,750
FI13	Itä-Suomi	0.3	150	0.3	2,230
FI18	Etelä-Suomi	-0.5	-260	-0.3	-3,620

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
FI19	Länsi-Suomi	-1.2	-1,950	-0.3	-2,910
FI1A	Pohjois-Suomi	1.5	660	1.0	6,510
FI20	Åland	-1.8	-2,400	-1.2	-380
FR10	Île de France	-1.2	-1,960	-1.1	-205,970
FR21	Champagne-Ardenne	1.6	540	0.9	5,610
FR22	Picardie	1.3	370	0.8	6,130
FR23	Haute-Normandie	0.4	130	0.2	1,660
FR24	Centre	1.7	550	1.2	12,760
FR25	Basse-Normandie	1.6	480	1.0	5,880
FR26	Bourgogne	2.4	790	1.6	11,170
FR30	Nord – Pas-de-Calais	0.0	20	0.0	-770
FR41	Lorraine	1.1	310	0.8	6,200
FR42	Alsace	-0.3	-110	-0.3	-3,390
FR43	Franche-Comté	1.5	420	1.0	4,470
FR51	Pays de la Loire	0.8	260	0.5	8,790
FR52	Bretagne	0.5	180	0.2	3,450
FR53	Poitou-Charentes	1.8	530	1.1	7,830
FR61	Aquitaine	0.4	150	0.1	2,490
FR62	Midi-Pyrénées	0.7	280	0.5	8,040
FR63	Limousin	2.7	790	1.7	5,000
FR71	Rhône-Alpes	-0.3	-120	-0.3	-10,870
FR72	Auvergne	1.8	590	1.2	7,210
FR81	Languedoc-Roussillon	0.8	250	0.4	5,800
FR82	Provence-Alpes-Côte d'Azur	-0.2	-70	-0.2	-7,050
FR83	Corse	1.8	590	1.1	2,020
GR11	Anatoliki Makedonia, Thraki	1.7	260	1.9	5,240
GR12	Kentriki Makedonia	-0.7	-140	-0.5	-4,610
GR13	Dytiki Makedonia	-3.1	-620	0.1	80
GR14	Thessalia	2.9	540	2.6	4,590
GR21	Ipeiros	-0.8	-180	-0.7	-3,070
GR22	Ionia Nisia	-0.1	-30	-0.1	-70
GR23	Dytiki Ellada	0.3	60	0.4	1,340

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
GR24	Sterea Ellada	-0.6	-150	0.6	2,030
GR25	Peloponnisos	0.3	70	0.9	2,970
GR30	Attiki	-1.3	-580	-1.0	-35,170
GR41	Voreio Aigaio	0.8	110	0.9	1,360
GR42	Notio Aigaio	0.0	0	0.2	670
GR43	Kriti	-0.1	-10	0.1	300
HR	Hrvatska	-1.7	-500	-1.0	-33,310
HU10	Közép-Magyarország	-0.9	-300	-0.7	-25,810
HU21	Közép-Dunántúl	0.5	160	1.1	8,410
HU22	Nyugat-Dunántúl	0.5	130	0.7	5,750
HU23	Dél-Dunántúl	0.1	10	1.3	7,060
HU31	Észak-Magyarország	0.0	0	1.1	6,900
HU32	Észak-Alföld	2.1	440	2.0	16,780
HU33	Dél-Alföld	1.7	410	1.5	12,900
IE01	Border, Midland and Western	1.1	920	0.7	4,520
IE02	Southern and Eastern	-0.5	-620	-0.8	-38,150
ITC1	Piemonte	-0.3	-180	-0.2	-6,520
ITC2	Valle d'Aosta/Vallée d'Aoste	-0.1	-40	0.3	300
ITC3	Liguria	-1.0	-610	-0.7	-8,470
ITC4	Lombardia	-0.9	-750	-0.6	-51,140
ITD1	Provincia Autonoma Bolzano/Bozen	-0.3	-150	-0.5	-2,590
ITD2	Provincia Autonoma Trento	0.2	100	0.0	-180
ITD3	Veneto	-0.2	-70	-0.3	-8,610
ITD4	Friuli-Venezia Giulia	0.0	-10	-0.2	-1,510
ITD5	Emilia-Romagna	-0.2	-90	-0.3	-10,420
ITE1	Toscana	0.1	30	-0.1	-1,750
ITE2	Umbria	0.8	220	0.2	890
ITE3	Marche	0.6	180	0.2	1,710
ITE4	Lazio	-0.4	-190	-0.4	-15,590
ITF1	Abruzzo	0.5	170	0.4	2,660
ITF2	Molise	1.7	520	0.9	1,190
ITF3	Campania	-0.1	-40	-0.2	-5,040

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
ITF4	Puglia	0.3	90	0.0	-380
ITF5	Basilicata	1.5	500	0.8	2,210
ITF6	Calabria	1.7	370	0.8	5,590
ITG1	Sicilia	0.6	170	0.2	3,330
ITG2	Sardegna	1.4	510	0.9	7,330
LT	Lietuva	0.4	150	0.3	6,990
LU	Luxembourg (Grand-Duché)	-0.1	-100	0.0	120
LV	Latvija	-0.1	-20	0.2	2,820
MT	Malta	-0.7	-410	-0.7	-7,770
NL11	Groningen	1.1	650	0.7	2,930
NL12	Friesland (NL)	1.7	960	1.2	5,500
NL13	Drenthe	-0.2	-80	0.4	1,260
NL21	Overijssel	0.5	310	0.4	4,150
NL22	Gelderland	0.3	180	0.2	3,800
NL23	Flevoland	0.8	470	0.4	1,420
NL31	Utrecht	-0.1	-70	-0.1	-1,990
NL32	Noord-Holland	-0.3	-280	-0.2	-5,140
NL33	Zuid-Holland	-0.5	-370	-0.2	-9,050
NL34	Zeeland	0.4	250	0.5	1,310
NL41	Noord-Brabant	0.3	230	0.2	4,860
NL42	Limburg (NL)	0.2	160	0.3	2,850
PL11	Łódzkie	0.3	60	0.5	6,090
PL12	Mazowieckie	-0.6	-200	-0.4	-21,580
PL21	Małopolskie	-0.9	-240	-0.2	-5,630
PL22	Śląskie	-3.8	-1,000	-2.1	-57,400
PL31	Lubelskie	2.7	310	2.0	15,700
PL32	Podkarpackie	1.6	190	1.4	12,080
PL33	Świętokrzyskie	2.0	230	1.6	7,110
PL34	Podlaskie	6.2	890	4.6	27,850
PL41	Wielkopolskie	-0.6	-190	-0.1	-3,330
PL42	Zachodniopomorskie	2.8	610	3.4	34,700
PL43	Lubuskie	0.7	140	1.1	6,490

European NUTS-2 regions		Value added		Employment	
		relative difference (%)	absolute difference (€/head)	relative difference (%)	absolute difference (persons)
PL51	Dolnośląskie	-1.6	-480	-0.5	-10,640
PL52	Opolskie	-0.4	-70	0.6	3,240
PL61	Kujawsko-Pomorskie	0.4	90	0.9	10,480
PL62	Warmińsko-Mazurskie	5.3	920	4.9	38,110
PL63	Pomorskie	0.6	180	1.3	25,460
PT11	Norte	-0.4	-110	-0.4	-11,000
PT15	Algarve	-0.1	-40	-0.2	-980
PT16	Centro (P)	0.1	30	0.1	1,420
PT17	Lisboa	-0.5	-250	-0.4	-13,500
PT18	Alentejo	0.6	170	0.1	740
RO	Romania	-0.5	-120	-0.1	-11,100
SE11	Stockholm	-0.4	-500	-0.4	-15,180
SE12	Östra Mellansverige	-0.4	-230	-0.3	-4,630
SE21	Småland med öarna	-0.3	-190	-0.3	-2,760
SE22	Sydsverige	-0.5	-380	-0.4	-7,210
SE23	Västsverige	-0.5	-390	-0.4	-10,630
SE31	Norra Mellansverige	-0.2	-140	-0.2	-1,650
SE32	Mellersta Norrland	0.2	110	0.1	230
SE33	Övre Norrland	-0.6	-550	0.2	1,180
SI	Slovenija	-0.3	-140	-0.1	-3,080
SK01	Bratislavský kraj	-1.9	-2,450	-1.3	-27,440
SK02	Západné Slovensko	2.2	570	2.1	25,880
SK03	Stredné Slovensko	2.9	640	2.6	21,410
SK04	Východné Slovensko	2.5	430	2.0	19,000

Notes: The values show the absolute and relative difference between the baseline scenario of implemented policy measures and the decarbonisation scenario for the year 2050. The values of the absolute deviation are rounded to 10.

Experts' contribution

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