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## Economic Effects of Regional Energy System Transformations: An Application to the Bavarian Oberland Region

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# Economic Effects of Regional Energy System Transformations: An Application to the Bavarian Oberland Region

## Abstract

This paper analyzes the effects of different energy transition paths on regional value added and on employment. We extend traditional input-output analysis by taking into account the scarcity of factors of production, and construct a dataset incorporating the regional dimension and specific electricity producing technologies. We find that the three observed districts in the German Oberland region benefit (to varying degrees) from investments towards regional energy transition, both in terms of additional value added and employment. Yet, the positive development comes at the expense of value added and employment in the rest of the country. Moreover, our analysis shows that medium-skilled employment increases most across all scenarios. This finding deserves attention in light of the current shortage of medium-skilled labor in Germany.

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# 1 Introduction

The lack of ambitious responses to climate change from the international community and from national governments motivates subnational entities to set their own goals and formulate their own plans towards the reductions of greenhouse gas emissions in their jurisdictions. From an economics perspective, national unilateral efforts (not to mention subnational unilateralism) are by no means the first best response to a global problem. Yet, it is laudable that civil society comes together and becomes active when they hold the view that they can do more. This is the case of three districts in the Bavarian Oberland Region, who set themselves the target to generate as much electricity and heat from renewable sources as they consume by the year 2035. Since 2014, a research consortium has accompanied the region in identifying its potential for renewables generation, the degree of acceptability of the different technologies. Based on this, possible scenarios were formulated for how the transformation path might look like from now until 2035, and the economic effects were quantified.

As it is often the case in the policy debate, there is a strong interest from local decision makers in the economic effects of the transition to an energy system based on renewable energies. Thus, the purpose of this study is to analyze the effects of the different energy transition paths on regional value added and on employment, divided into three qualification levels: low-skilled, medium-skilled, and high-skilled employment. This endeavor poses four main challenges, whose solutions constitute our contributions to the literature. Our first and most important contribution lies in taking into account the scarcity of factors of production and of financial resources needed to undertake the investments, giving rise to crowding out effects. Related to that, our second contribution involves an extension of Fisher and Marshall (2011), Benz et al. (2014), and von Schickfus and Zimmer (2018) aiming at satisfying the needs of a regional analysis. Third, we base the analysis on an input-output (IO) table where the energy sector is disaggregated to better account for the specificities of each generation technology and its interconnections with the rest of the economy. Our fourth contribution consists in taking into account the fact that the three districts are not economically isolated but interact with each other and with other regions.

We find that the three districts on the Oberland region benefit from investments towards the regional energy transition, both in terms of additional value added and employment. Yet, there are some differences in the extent to which the districts benefit and the positive development comes at the expense of value added and employment in the rest of the country. Moreover, our analysis shows that medium-skilled employment increases most across all scenarios. In the light of the current shortage of medium-skilled labor in

Germany (Stippler et al. 2019), this finding represents an alarm signal that calls for integrating labor market considerations into climate policy strategies.

Previous work on the economic impacts of (renewable) energy policy can be summarized in three main strands: input-output analysis; ex-post econometric studies, focusing on specific regions or policies; and more complex models or meta-studies. A number of often policy-commissioned reports use standard input-output analysis, evaluating the additional demand for products in other sectors due to the construction (and sometimes operation) of renewable energy facilities (Bickel et al. 2009; Böhmer et al. 2015; Breitschopf et al. 2015; Hirschl et al. 2015; Höher et al. 2015; Lehr et al. 2015; Lehr et al. 2011; Lutz et al. 2014; O’Sullivan et al. 2014; Ulrich and Lehr 2014). Their contribution lies in the construction of a demand vector specific to the installation (or operation) of different renewable energy technologies. These studies suffer from three limitations: first, they often focus on the construction of renewable energy plants, therefore concentrating on a one-off effect and neglecting the phase of operations, in particular their structural effect changing the interlinkages and production structure in the economy. Second, they disregard scarcity aspects: in these models, the demand created due to renewables expansion is always additional and does not come at the expense of other economic activities. Third, these studies do not take cross-country interlinkages into account, ignoring the dimension of internationally traded intermediate and final goods. The same is true for scholarly articles using an input-output approach, such as Allan et al. (2007) or Lehr et al. (2008). Heindl and Voigt (2012) represent an exception with respect to the consideration of crowding out effects, yet the interlinkages between countries and regions are not accounted for in this study.

The second strand of literature concerned with the economic effects of renewables expansion is econometric. For example, in an ex-post econometric exercise controlling for economic structure and other socio-economic variables, Brown et al. (2012) confirm the positive economic and employment effects of wind power expansions found in input-output studies. However, such econometric studies also mostly focus on one-off effects induced by policies (i.e., the effects of constructing or installing power equipment). In a recent analysis, Buchheim et al. (2019) show that the employment effects of increased solar energy installations depend on the tightness of the labor market, the effects being larger when unemployment is high. The authors conclude that crowding out is the most plausible explanation for small job effects. This finding in an ex-post study further motivates our consideration of crowding out effects in a forward-looking method.

More complex models such as CGE, PANTA RHEI or E3ME can take “crowding-out” effects as well as international economic linkages into account (see, e.g., IRENA (2016b), the chapter on net effects in Lehr et al. (2011), or the special issue of the *Energy Journal*

on “Hybrid Modeling of Energy-Environment Policies”). However, these models rely on a number of assumptions made “in the background” and are not replicable without access to the computational model. They are also usually not available at the regional level. Meta-studies have combined results on job gains in renewable industries and job losses in conventional energy to estimate trade-offs (e.g., Meyer and Sommer 2014; Wei et al. 2010). The results of their spreadsheet models are useful, but not replicable as they rely on the availability of previous studies.

Our approach consists in an IO analysis which we extend in several dimensions. The advantage of IO analysis over other methods that are commonly used to estimate the economic effects of sectoral developments, like the analysis of value-added chains, lies in the ability to consider indirect besides direct effects on other sectors. That means that if a sector faces an increased demand for its goods, expanding production does not only increase demand for its direct inputs, but also for the intermediate inputs used to produce these inputs and so on. This can only be considered up to a limited extent in an analysis of the value-added chain, as done in (Hirschl et al. 2010; Hirschl et al. 2015). Thus, to be able to use this approach and based on the German IO table, we construct IO tables for the three districts in the Bavarian Oberland following the method proposed by Többen and Kronenberg (2015). It allows us to model trade between the districts as well as with the rest of the country and the rest of the world, which is important considering that the districts are open economies that interact with other regions. Thus, the additional demand generated by investments (in renewable energies) is not satisfied exclusively by the local economy but also by sectors outside of their borders. Ignoring this would lead to an overestimation of the economic effects derived from the investments.

One of the extensions of the traditional IO analysis, which also allows us to rule out further sources of overestimation of the economic effects, is considering scarcity of financial resources and production factors. We distinguish between investments by private households and investments by institutional investors. Moreover, for the latter, we further differentiate between the investment and the operation phase. In the case of private households, investments (in renewables, renovations and storage capacity) and the corresponding expenditures during the operation phase crowd out consumption in the same amount.<sup>1</sup> Similarly, investments by institutional investors crowd out alternative investments. This distinction allows us to take into consideration the different structure of these two final demand components (consumption by private households and investments by private organizations) and, thus, to explicitly consider the increasingly important role of private households as investors in the electricity and heating sectors.

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<sup>1</sup>This can be seen as a simple representation of a policy instrument financed by a surcharge on the electricity price for all consumers, as in the German Renewable Energy Law (EEG)

For the operations phase, we take into account that the investments increase the capital stock of the concerned sectors. Assuming full employment of the factors of production and fixed factor input coefficients, the increased capital attracts labor from other sectors, reducing their production. For the analysis of the economic effects in the operations phase we further develop the approaches of Fisher and Marshall (2011), Benz et al. (2014), and von Schickfus and Zimmer (2018) to make them applicable in a context when small regions (which in our case are the three German districts) are embedded in a system with much larger regions such as the rest of the country and the rest of the world.

An important characteristic of our analysis is that it is made prior to the investments, allowing to take measures targeted at attenuating possible negative developments. For instance, the identification of sectors that might be negatively affected makes possible to support them in the appropriate manner before or during the transition. Moreover, identifying the sectors where labor requirements might increase most strongly allows a proactive approach to solve and prevent shortage problems.

The contributions of this paper do not only refer to the three districts in the Bavarian Oberland region. On the contrary, they can be applied to other regions, either at the same or other levels of regional sub-division, and also to other research and policy questions. Thus, the methodology, which was further developed to satisfy the needs of a regional analysis, is by no means exclusive to investments in the energy sector or to the Oberland region. Following the method described in Section 2.2, we can construct IO tables for other subnational regions. The method described in Section 2.3 can be applied to analyze the economic effects of all types of investments.

In the following sections we first outline our approach to produce the multi-regional IO table, to disaggregate the energy sector, and to assess the effects of the energy transition. Section 3 describes the data sources and Section 4 presents the effects on value added and employment. Finally, Section 5 concludes.

## 2 Methodology

For the analysis of the effects of the energy transition we want to consider the impact on the whole regional economy, taking into account the direct and indirect effects. Thus we rely on input-output analysis for the assessment. This confronts us with three methodological challenges. First, since subnational tables are not available in Germany, we are required to produce IO tables for each of the districts and link them to each other and to the tables for the other two regions. This requires estimating trade between the three districts of analysis but also of each of the districts with the other two regions. Second, the energy sector of the multi-regional IO table needs to be disaggregated in such a way



that the different renewable energy technologies and conventional technologies are considered as individual sectors. This disaggregation is necessary to account for the different input structures and, therefore, for the specific interconnections of each technology with the rest of the economy. The third challenge is concerned with the calculation of the economic effects. In this respect, we extend the traditional IO analysis to consider scarcities of financial resources and production factors and, therefore, to account for the fact that investments in renewables energies crowd out other investments and production in other sectors. In the following we describe how we address each of these challenges.

## 2.1 Disaggregation of the energy sector

We start by disaggregating the energy sector in both source IO tables: the tables for Germany and the rest of the world from the World Input-Output Database (WIOD) (Timmer et al. 2015) and the German input-output table (GIOT) from the German statistical office. Thus, for instance, the sector “Electricity, steam and hot water, production and distribution services thereof” from the GIOT is disaggregated into nine subsectors.<sup>2</sup> These consists of different renewable and conventional technologies, transmission and distribution of electricity.<sup>3</sup> For disaggregation, we use the information contained in the IO table for Germany from EXIOBASE 2 (Wood et al. 2015), where the energy sector is disaggregated.<sup>4</sup>

To arrive at a matrix like in Table 1, we need to calculate the elements in the shaded areas, where  $z_{ih}$  represents the input from the non-electricity sector  $i$  required in the electricity subsector  $h$ , and  $z_{ej}$  represents the input from the electricity subsector  $e$  required in sector  $j$ . Thus, to calculate  $z_{ih}$  we scale the input from  $i$  required in the (only) electricity sector from the GIOT,  $z_{ih}^{GIOT}$ :

$$z_{ih} = z_{ih}^{GIOT} \frac{z_{ih}^{Exio}}{\sum_h z_{ih}^{Exio}} \quad \forall \quad i \neq e, \quad (1)$$

where  $\sum_h z_{ih}^{Exio}$  is the sum of interindustry sales of sector  $i$  to all electricity sectors. The superscripts  $GIOT$  and  $Exio$  indicate that the variables are obtained from the German IO table from the German statistical office and from the German EXIOBASE table,

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<sup>2</sup>For simplicity, in the following we will refer to the “Electricity, steam and hot water, production and distribution services thereof” sector as the electricity sector, although it also includes activities different to electricity generation.

<sup>3</sup>For a complete description of the energy sectors see Table 3 in Appendix A.1 (Sectors 10-18).

<sup>4</sup>Note that we first need to aggregate the sectors in the EXIOBASE table and in the GIOT to be consistent with our final sector aggregation, described in Table 3.

**Table 1:** Disaggregation of the intersectoral transactions of the energy sector

		Electricity								Total intermediate Use	
		Coal			Solar		Distribution				
		Sector 1	...	Sector j	Sector h	...	Sector H	...	Sector J		
Electricity		Sector 1	$z_{11}$	...	$z_{1j}$	$z_{1h}$	...	$z_{1H}$	...	$z_{1J}$	$z_{1\cdot}$
		$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$		
		Sector i	$z_{i1}$	$\vdots$	$z_{ij}$	$z_{ih}$		$z_{iH}$	$\vdots$	$\vdots$	
	Coal	Sector e	$z_{e1}$	...	$z_{ej}$	$z_{eh}$	...	$z_{eH}$	...	$z_{ej}$	$z_{e\cdot}$
	Solar	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
	Distribution	Sector E	$z_{E1}$	...	$z_{Ej}$	$z_{Eh}$	...	$z_{EH}$	...	$z_{Ej}$	$z_{E\cdot}$
		$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$		
		Sector I	$z_{I1}$	...	...	$z_{Ih}$	...	$z_{IH}$	...	$z_{IJ}$	
		Total inputs	$z_{\cdot 1}$			$z_{\cdot h}$	...	$z_{\cdot H}$			

respectively. Accordingly, we calculate  $z_{ej}$  as

$$z_{ej} = z_{ej}^{GIOT} \frac{z_{ej}^{Exio}}{\sum_e z_{ej}^{Exio}} \quad \forall \quad j \neq h. \quad (2)$$

To calculate the entries of the intersectoral transactions between the energy subsectors (i.e., in the darker area in Table 1) we need to proceed slightly differently:

$$z_{eh} = z_{eh}^{GIOT} \frac{z_{eh}^{Exio}}{\sum_e \sum_h z_{eh}^{Exio}}, \quad (3)$$

where  $z_{eh}$  is the input from the electricity subsector  $e$  required in the electricity subsector  $h$ .

The remaining components of the IO table for the electricity subsectors, that is, value added, output, imports of similar final goods, the different components of final demand (consumption of private households, consumption of private organizations, consumption of state organizations, investment and changes in stocks, exports), as well as total final demand are calculated in a similar manner. So, for instance, for value added,  $w_e$ , we scale  $w_h^{GIOT}$  by multiplying it with the share of  $w_h^{Exio}$  in total value added of all electricity

subsectors,  $\sum_h w_h^{Exio}$ .

## 2.2 Construction of the multi-regional IO table

The goal of the process described in this section is creating a multi-regional IO table consisting of the IO tables of Miesbach (MB), Bad Tölz-Wolfratshausen (BW), Weilheim-Schongau (WS) (together, the Oberland region<sup>5</sup>), the rest of Germany and the rest of the world. Their “internal” IO tables are on the main diagonal of the multi-regional matrix; the intermediates traded interregionally are in the off-diagonal parts. The construction of the multi-regional matrix follows four major steps. First, we construct regional IO tables by adjusting the German coefficients with regional output figures and scaling numbers for final goods use. In a second step we employ the modified “cross-hauling adjusted regionalization method” (CHARM) approach developed by Többen and Kronenberg (2015) to estimate each district’s sectoral trade flows with the rest of Germany and with the rest of the world. Applying a simple gravity approach in a third step, we model the multi-regional trade flows: sectoral trade flows between the districts and between each district and non-Oberland Germany. Finally, using the “proportionality assumption”, we create the multi-regional IO (MRIO) matrix by combining the data on sectoral trade flows and input coefficients.

So, the first and the last step are concerned with input-output tables. There we assume that the production technology in the districts is equal to Germany’s production technology. The inner two steps are about estimating inner-country trade flows.

Note that the regions we are interested in (the Oberland region) do *not* sum up to the national level. We index our districts by  $b$ ,  $m$ , and  $w$  and denote the national totals by  $n$ . From the perspective of each district  $r$ , the rest of the country is denoted by  $q$ , such that, e.g., output is  $x_{i,r} + x_{i,q} = x_{i,n}$ . Similarly, if we look at all three districts together and the respective rest of the country, this is denoted by  $roc$  (the rest of the country, or “non-Oberland region”). The set  $G$  comprises these sub-regions and the rest:  $g = b, m, w, roc$ .

### 2.2.1 Construction of regional IO tables

**Gross value added** We start with regional data on gross value added, as this measure is the closest proxy to output that is available from administrative sources. Since regional value added data is only available at a highly aggregated sectoral level, we disaggregate

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<sup>5</sup>To be precise, the district Garmisch-Partenkirchen is also part of the administrative Oberland region, but did not take part in the INOLA research project. For simplicity, we use the terms “Oberland region” and “INOLA region” interchangeably.

the data using employment figures.<sup>6</sup> First, we compute preliminary disaggregated value added figures,  $w_{i,r}^p$ , by multiplying with the labor shares of the disaggregated sectors:

$$w_{i,r}^p = w_{a,r} \cdot \frac{L_{i,r}}{L_{a,r}} \cdot \frac{w_{i,n}/L_{i,n}}{w_{a,n}/L_{a,n}}, \quad (4)$$

where the subscript  $a$  stands for the aggregated sector containing sector  $i$ . The third term on the right hand side (RHS) captures the national productivity differences. It is used as a correction factor to account for potential differences in labor productivity across subsectors.

In a second step, we scale the preliminary values so they match the totals of the aggregated sectors:

$$w_{i,r} = w_{i,r}^p \cdot \frac{w_{a,r}}{\sum_{i \in a} w_{i,r}^p}. \quad (5)$$

**Regional output of non-energy sectors** From the sectoral values on regional  $w$ , we compute output by scaling national sectoral output using regional to national  $w$  shares:

$$x_{i,r} = x_{i,n} \cdot \frac{w_{i,r}}{w_{i,n}}, \quad (6)$$

where  $x$  denotes output of intermediate and final goods.

The output values of the rest of the country can be calculated as a residual:

$$x_i^{roc} = x_{i,n} - \sum_r x_{i,r}. \quad (7)$$

**Regional output of the energy sectors** To take advantage of the fact that we have detailed information on the energy sectors in the region, we proceed differently when regionalizing these sectors. For each of the electricity and heat generation sectors we scale German output down to the district level by multiplying it with the ratio of generation (in GWh) in the district,  $g_{i,r}$  to generation in Germany,  $g_{i,n}$  per sector:

$$x_{i,r} = x_{i,n} \cdot \frac{g_{i,r}}{g_{i,n}}. \quad (8)$$

The scaling factor for regionalization of the “Transmission of electricity” and “Distribution and trade of electricity” sectors is based on the length of the transmission or the distribution network located in the region and in the whole of Germany.

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<sup>6</sup>Table 4 provides an overview of the highly aggregated sector level and the comprised sectors.

**Regional input-output matrix** For the (technical) regional IO matrix capturing the use of intermediates, we multiply the input-output coefficients of the German IO table ( $c_{ij,n}$ ) with the regional output values, assuming identical production technology at the national and regional level:

$$z_{ij,r} = x_{j,r} \cdot c_{ij,n}, \quad (9)$$

where  $z_{ij,r}$  denotes the input from sector  $i$  required in region  $r$ 's sector  $j$ .

Note that each of the regional matrices constructed in this way is “technical” in the sense that it doesn’t distinguish between sources of intermediates. It simply states that in a region  $r$  and sector  $j$ , a certain amount of inputs from other sectors  $i$  is needed to produce this region’s sectoral output. It does not make a statement on where these inputs come from. The technical regional input-output matrix derived here is used later on to construct the interregional and intraregional IO matrices.

**Regional domestic final use** Final goods use per sector and use item is only available at the national level.<sup>7</sup> We therefore need to scale it using Bavarian data on total final goods use, and regional data on disposable income in the case of household consumption.

For private household consumption, we start from the national sectoral value and scale it by Bavarian consumption shares, as well as regional disposable income in comparison to Bavaria:

$$d_{i,r}^{ph} = d_{i,n}^{ph} \cdot \frac{d_{by}^p}{d_n^p} \cdot \frac{di_r}{di_{by}}, \quad (10)$$

with  $d_{ph}$  denoting consumption (final demand) of private households,  $d_p$  denoting total private consumption,  $di$  denoting disposable income, and  $by$  denoting Bavaria.

For investment and consumption by private and state organizations, we again scale by Bavarian shares following Heindl and Voigt (2012) and then use regional GDP to scale to regional level:

$$d_{i,r}^k = d_{i,n}^k \cdot \frac{d_{by}^k}{d_n^k} \cdot \frac{GDP_r}{GDP_{by}} \quad \forall \quad k \neq cs, \quad (11)$$

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<sup>7</sup>For simplicity we refer to the different final use items of the IO table as follows:

“Final consumption expenditure by households”= private household consumption;

“Final consumption expenditure by non-profit organizations serving households”= consumption of private organizations;

“Final consumption expenditure by government”= consumption of state organizations;

“Gross fixed capital formation”= investments;

“Changes in inventories and valuables”= changes in stocks.

where  $GDP$  denotes gross domestic product. The index  $k = cpo, cso, inv, cs$  denotes consumption of private organizations, consumption of state organizations, investments, and changes in stocks. We scale down changes in stocks, using the regional GDP share only.

**Regional (domestic) total use** By summing up intermediate use and domestic final use (by private households, denoted by  $ph$ , and organizations, denoted by  $k$ ) we can derive total regional domestic use  $d_{i,r}^t$ :

$$d_{i,r}^t = z_{i,r} + d_{i,r}^{ph} + \sum_k d_{i,r}^k = z_{i,r} + d_{i,r}. \quad (12)$$

**Rest of country** The values for intermediate use, domestic final use, value added and output for the rest of the country are calculated as residuals, subtracting the values for the three districts from the national figures.

### Estimation of interregional trade: application of modified CHARM

As noted by Kronenberg (2009), trade of regions with the rest of the country and the rest of the world is characterized by surplus imports and exports (trade balance) as well as substantial amounts of cross-hauling, which is the simultaneous imports and exports of goods or services of the same sector. The more heterogeneous the products within a sector are, the more cross-hauling takes place (Kronenberg 2009).

The adjusted CHARM as suggested by Többen and Kronenberg (2015) allows to estimate trade flows between each region and the rest of the country (“biregional trade”), as well as between each region and abroad, while taking into account cross hauling. An important assumption made in Kronenberg’s CHARM and of the modified CHARM is that product heterogeneity in the region is the same as in the country, which is based on the argument that heterogeneity is a characteristic of the commodity and not of the geographical location (Kronenberg 2009). This assumption is criticized by Jackson (2014) who emphasizes that the product mix within an aggregate commodity might well be a function of the geographical location, since the region might not produce all commodity sub-types while the country does. According to the authors, the consequences of this assumption will depend on three aspects: First, the level of aggregation in the commodities classification; second, the unique character of different commodities; and third, the economic size of the subnational regions. Since our regions are rather small and we have a high level of aggregation, there are potentially consequences for regionalization in our framework. However, the lack of administrative data on trade between the districts and with the rest of the country and the world makes it impossible to quantify the

consequences. Thus, we have to keep in mind that the estimates for the interregional transactions might be inaccurate.

**Estimating regional foreign trade** As a first step, we estimate each region’s foreign trade. The basic assumptions are that foreign imports are proportional to domestic demand, and foreign exports are proportional to domestic output. Then regional foreign exports (denoted by  $e_{i,r}^f$ ) and imports (denoted by  $m_{i,r}^f$ ) can be approximated as

$$m_{i,r}^f = m_{i,n} \frac{z_{i,r} + d_{i,r}}{z_{i,n} + d_{i,n}}, \quad (13)$$

$$e_{i,r}^f = e_{i,n} \frac{x_{i,r}}{x_{i,n}}. \quad (14)$$

We use foreign trade data from the German IO table and scale it with regional demand or supply figures, respectively. Foreign imports and exports for the rest of the country *roc* are calculated as a residual.

**Estimating total interregional trade** The second step is concerned with estimating trade within the country, between regions. The adjusted CHARM formula only works for a bi-regional setting. Therefore, we calculate cross-hauling between each of the districts and, from its perspective, the rest of the country, as suggested by Többen and Kronenberg (2015). These biregional values are what we refer to as “interregional”.

The adjusted CHARM defines the cross-hauling potential as the minimum of output and domestic use. The intuition behind this is that the highest possible amount of cross-hauling occurs if the region with relatively small output figures exports all its output, and imports the same amount of goods. The (maximum) cross-hauling potential,  $q_i$  is then twice the amount of the region’s output.

Correspondingly, the method defines the cross-hauling potential at national level to be constrained as  $\max q_{i,n} = 2 \min(x_i; z_i + d_i)$ .<sup>8</sup> Then the national product heterogeneity measure is calculated as

$$h_{i,n} = \frac{q_{i,n}}{2 \min(x_{i,n}; z_{i,n} + d_{i,n})}. \quad (15)$$

Following the above reasoning and in order to ensure accounting balances between the two regions, the adjusted CHARM sets upper limits for the cross-hauling potential. Denoting

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<sup>8</sup>Note that, since there is a large quantity of variables and parameters to be estimated in the regionalization of the IO table and calculation of the economic effects, some letters are used twice: once to denote a variable and once to denote an index. While this is not optimal, please note that there is no implicit relation between the index and the variable, although they are denoted by the same letter.

the cross-hauling in interregional trade between regions  $r$  and  $q$  by  $q_i$ , their maximum CH potential can be written as

$$\max\left(\frac{q_i}{2}\right) = \min(x_{i,r} - e_{i,r}^f; z_{i,r} + d_{i,r} - m_{i,r}^f; x_{i,q} - e_{i,q}^f; z_{i,q} + d_{i,q} - m_{i,q}^f). \quad (16)$$

Assuming that  $h_{i,n} = h_{i,r}$ , biregional cross-hauling can be estimated as the national heterogeneity parameter (which is the share of national cross-hauling in national cross-hauling potential) times the regional cross-hauling potential:

$$q_i = 2h_{i,r} \min(x_{i,r} - e_{i,r}^f; z_{i,r} + d_{i,r} - m_{i,r}^f; x_{i,q} - e_{i,q}^f). \quad (17)$$

In a further step we calculate interregional gross trade flows, which are interregional gross exports and imports and are defined bilaterally:  $t_{rq}$  is the trade flow from region  $r$  to region  $q$ . To calculate them, we need to combine our estimate of cross-hauling with the commodity balance. The commodity balance,  $b$ , is usually defined as the difference between regional supply and demand (resulting in a value for net regional imports or exports), and in the subnational case it needs to be corrected for foreign imports and exports:

$$b_{i,r} = -b_{i,q} = (x_{i,r} - e_{i,r}^f) - (z_{i,r} + d_{i,r} - m_{i,r}^f). \quad (18)$$

Then, the gross trade flows between the two sub-regions are given by<sup>9</sup>

$$t_{i,rq} = \frac{q_i + |b_{i,r}| + b_{i,r}}{2}, \quad (19)$$

$$t_{i,qr} = \frac{q_i + |b_{i,q}| + b_{i,q}}{2}. \quad (20)$$

### Estimation of multi-regional trade: gravity

As we have more than two regions in our setting, we need to distribute the interregional (or biregional) trade flows calculated above among the several regions. We apply a simple gravity framework for this: we assume that trade between sub-regions is proportional to their economic size and their distance from each other. Moreover, we estimate the trade share  $ts$  of one region with another as the quotient of estimated trade flows between

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<sup>9</sup>Note that we need to divide cross hauling by 2 because we are interested in one-directional flows from  $r$  to  $q$ , whereas cross-hauling gives the sum of simultaneous imports and exports.



regions  $r$  and  $s$  and the estimated trade flows of region  $r$  with all other regions:

$$ts_{rs}^1 = \frac{\ln(GDP_r GDP_s) - \ln(dist_{rs})}{\sum_{u \neq r} (\ln(GDP_r GDP_u) - \ln(dist_{ru}))}. \quad (21)$$

The denominator is similar to the “multilateral resistance” term in gravity trade models.<sup>10</sup> Here,  $u$  is an index over all districts other than  $r$  - so it refers to the rest of the country from  $r$ ’s perspective. It is similar to the index  $q$  as in the notation for the modified CHARM formula further above, but in the trade share calculations we actually use data on each of the 380 other German districts individually. Therefore, we use another index here to avoid confusion.

Note that we could also have a denominator based on region  $s$ ’s multilateral trade. Essentially, we can follow two approaches, which result in different trade shares. The first is to use  $r$ ’s trade share for estimating all of  $r$ ’s exports, which means that each region  $s$ ’s imports from  $r$  are scaled by  $r$ ’s multilateral resistance. The second approach is to use  $s$ ’s trade share for estimating all of  $s$ ’s imports, which means that  $r$ ’s exports to  $s$  are scaled by  $s$ ’s multilateral resistance.

Approach 2 reads:

$$ts_{rs}^2 = \frac{\ln(GDP_r GDP_s) - \ln(dist_{rs})}{\sum_{u \neq s} (\ln(GDP_s GDP_u) - \ln(dist_{su}))}. \quad (22)$$

Combining the multi-regional trade share with interregional trade flows gives the multi-regional trade flows (shown here according to approach 1):

$$t_{i,rs}^1 = t_{i,rq} \cdot ts_{rs}^1. \quad (23)$$

Trade between each district and the non-INOLA region is calculated as a residual. So, for instance for district  $b$

$$t_{b,roc} = t_{bq} - t_{bm} - t_{bw}, \quad (24)$$

where  $q$  denotes the rest of the country from the perspective of the exporting district, and  $m$  and  $w$  denote the other two Oberland districts.

Since both approaches for the calculation of the districts’ trade flows lead to different estimates, we chose to combine the two approaches. To guarantee that the calculation for the rest of the country in (24) does not deliver negative values, we always use the

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<sup>10</sup>The specification in (21) implies trade elasticities of one with respect to GDP and distance.

smaller of the two:

$$t_{i,rs} = \min(t_{i,rs}^1; t_{i,rs}^2). \quad (25)$$

### 2.2.2 Construction of the multi-regional IO matrix

**Imported intermediates - proportionality assumption** To construct the MRIO matrix from the technical IO matrix and the multi-regional trade flows, we use the proportionality assumption also used by Benz et al. (2014) among others. According to this assumptions “an industry uses an import of a particular product in proportion to its total use of that product” (OECD 2002, p. 12). For example, if the motor vehicles industry in region A uses steel in production and 10% of all steel is imported from a particular region B, then 10% of the steel used by the motor vehicles industry in region A is imported from region B.

So the intermediate inputs used by region  $r$ ’s sector  $i$  from region  $s$ ’s sector  $j$  read as

$$z_{ij,rs} = z_{ij,r} \frac{t_{j,sr}}{d_{j,r}^t}, \quad (26)$$

where  $d_{j,r}^t$  denotes total use of product  $j$  in region  $r$ . In a similar manner, we calculate the intermediate inputs used by region  $r$ ’s sector  $i$  from sector  $j$  of the rest of the world (ROW), using the foreign imports  $m_{i,r}^f$  calculated above and the proportionality assumption, and denote them  $z_{ij,r}^{row}$ .

**Intersectoral transactions within each district** We then calculate the within-district IO matrix as the residual of the “technical” matrix calculated above, and all imported intermediates from the other districts, the rest of the country and the rest of the world

$$z_{ij,rr} = z_{ij,r} - \sum_{s \neq r} z_{ij,rs} - z_{ij,rowr}. \quad (27)$$

**Linking the regional and German tables to the rest of the world** Having the MRIO table for the districts and the rest of the country, we proceed to link it to the rest of the world. We aggregate the individual countries of the WIOD table (except Germany) to form the ROW region and the sectors to match the sectors of the IO tables for the districts. Aggregated WIOD tables are taken as the base table. We then disaggregate the intersectoral transaction within Germany from the WIOD table,  $z_{ij,n}^{WIOD}$  using origin-destination shares that can be calculated from the MRIO table generated

using the methodology described above:

$$z_{ij,rs} = z_{ij,n}^{WIOD} \frac{z_{ij,rs}^{GIOT}}{\sum_r \sum_s z_{ij}^{GIOT}}, \quad (28)$$

where the superscript *GIOT* denotes the variables that were calculated above using the German IO table from the German statistical office. The intersectoral transactions between German sectors and ROW's sectors are regionalized in proportion to output, that is:  $z_{ij,rr\text{ow}} = z_{ij,nrow}^{WIOD} \frac{x_{i,r}^{GIOT}}{x_{i,n}^{GIOT}}$ .

### 2.2.3 Factors of production

Starting from the production factor figures for Germany, we scale down the respective factor to the district level using the sectoral factor coefficients for Germany and sectoral output for the districts. For instance, we compute  $K_{ir}$ , the capital stock in region  $r$ 's sector  $i$ , as

$$K_{ir} = K_{in} \frac{x_{i,r}}{x_{i,n}}, \quad (29)$$

where  $K_{in}$  denotes the sectoral capital stock for the whole of Germany. The factors of production for the rest of the world are calculated in a similar way.

## 2.3 Economic effects: extended IO analysis

Being placed in an IO framework, we implicitly assume a Leontief production function with fixed input coefficients and constant returns to scale. Furthermore, although the period of analysis is relatively long (from 2015 to 2035), we also need to make the assumption that the input coefficients and factors coefficients will stay the same throughout the period of analysis, that is, the production technology of the economy will remain unchanged. This assumption becomes more realistic for other possible applications with shorter periods of analysis.

For the assessment, we consider both the one-off effects of the investment (or construction) phase as well as the effects of the operations phase. Importantly, we take into account scarcity of financial resources and of the factors of production, thus in the investment and in the operation phase crowding out of other activities occurs. Specifically, investments in the energy transition crowd out other investments by companies or consumption by private households. Here we assume that financial resources do not only come from the region where investments take place but also from other regions. The rationale behind this assumption is that investments in the energy transition are typically financed by national climate policy instruments that redistribute funds from the whole of the country to the

actual investment location.<sup>11</sup> Similarly, in the operations phase factors of production that could be employed otherwise, are used in the operation and maintenance of renewables, reducing their activity (and therefore output) in other sectors.

The next subsections describe our methodology. First, we introduce the general method to compute the amount of output necessary to meet the additional investment demand generated by the energy transition. We then present the method to consider scarcities in the investment phase and the operation phase. Finally, we show how we calculate the effects on value added and employment, starting from the additional output figures.

### 2.3.1 Additional output

The starting point of our analysis are the future investments in renewable energies for electricity and heat generation, energy efficiency measures and electricity storage appliances.<sup>12</sup> We denote these by  $\mathbf{f}$ , which is a  $N \times 1$  column vector, where  $N$  is the total number of sectors per region. The vector  $\mathbf{f}$  describes how total demand for investment goods is composed of investment goods from other specific sectors, thus it breaks down the overall investment in region  $r$  into the components needed from each sector  $i$ . Note that this vector does not provide information on the geographical origin of the components yet, thus we use the intrasectoral transactions in intermediates from the MRIO table as a proxy to distribute the sectoral investment demand among the regions and obtain the additional investment demand:

$$\Delta \mathbf{d}^{\text{inv}} = \mathbf{U} \mathbf{f}. \quad (30)$$

where  $\mathbf{d}^{\text{inv}}$  is a  $IR \times 1$  column vector, and  $R$  is the total number of regions.  $\mathbf{U}$  is a  $IR \times IR$  matrix whose elements,  $u_{ij,rs}$ , describe the share of  $z_{ij,rs}$  (i.e., of inputs from region  $r$ 's sector  $i$  used in regions  $s$ 's sector  $j$ ), in the intrasectoral transactions:

$$u_{ij,rs} = \frac{z_{ij,rs}}{\sum_{r=1}^R \sum_{s=1}^R z_{ij,rs}} \quad \forall \quad i = 1, \dots, N \quad \text{and} \quad j = i. \quad (31)$$

Following classical IO analysis, the amount of output of final goods and intermediates,  $\Delta \mathbf{x}$ , that its necessary to satisfy the additional investment demand can be computed as follows:

$$\Delta \mathbf{x} = (\mathbf{I} - \mathbf{L})^{-1} \Delta \mathbf{d}^{\text{inv}}, \quad (32)$$

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<sup>11</sup>An example for such a redistribution mechanism is the German EEG which finances the investments via a surcharge on the electricity price paid by all consumers (with some exceptions). In the case where policies are financed by the national public budget, redistribution occurs through the tax system.

<sup>12</sup>For simplicity, in the following the expression *investment in renewables* will also mean energy efficiency measures and the deployment of storage capacity.

where  $\mathbf{I}$  is the unity matrix and  $\mathbf{L}$  is the matrix of fixed input coefficients, which shows the direct use of intermediates per unit of output. Leontief's inverse,  $(\mathbf{I} - \mathbf{L})^{-1}$ , is the matrix to which the infinite series of powers of  $\mathbf{L}$  converges. Accordingly, it accounts for the fact that, besides the directly used intermediates, output production also uses indirectly the intermediates used for production of the direct intermediates and so on. Thus, Leontief's inverse indicates the level of output needed to satisfy a unit vector of final demand after infinite rounds of this process.

To this point we have not considered any scarcity effects and have assumed that additional resources and factors of production are readily available and enter the system in an unlimited manner. However, it is more reasonable to assume that investments in renewables crowd out other types of demand, e.g., alternative investment or consumption by private households. Moreover, factors of production are not unlimited in stock and waiting to be employed. To consider scarcity effects we follow two different approaches depending on the actors undertaking the investment: private households or institutional investors. Moreover, we distinguish between the investment phase and the operation phase.

**Considering scarcity in the investment phase** Crowding out in the investment phase for both types of investors follows a similar principle: investments in renewables crowds out an alternative average investment (alternative average consumption) in the same amount as the total investment in renewables. Thus, the calculation of additional output, net of crowding out reads:

$$\Delta \mathbf{x}^{\text{inv,net}} = (\mathbf{I} - \mathbf{L})^{-1} (\Delta \mathbf{d}^{\text{inv,ii}} + \Delta \mathbf{d}^{\text{inv,ph}} - \Delta \mathbf{d}^{\text{invco}} - \Delta \mathbf{d}^{\text{phco}}), \quad (33)$$

where  $\Delta \mathbf{d}^{\text{inv,ii}}$  and  $\Delta \mathbf{d}^{\text{inv,ph}}$  denote the additional investment demand generated by institutional investors and by private households, respectively.  $\Delta \mathbf{d}^{\text{invco}}$  is a vector of crowded out investment demand and  $\Delta \mathbf{d}^{\text{phco}}$  is a vector of crowd out consumption by private households. The elements of  $\Delta \mathbf{d}^{\text{invco}}$  are defined as

$$\Delta d_{i,r}^{\text{invco}} = \frac{d_{i,r}^{\text{inv}}}{\sum_{i,r} d_{i,r}^{\text{inv}}} \sum_{i,r} \Delta d_{i,r}^{\text{inv,ii}}. \quad (34)$$

The fraction on the right hand side of (34) describes the proportional distribution of an average investment among sectors and regions.<sup>13</sup> In other words, it describes how many cents out of each Euro invested in any of the regions appear as investment demand in a specific regional sector. The last term on the right hand side is the sum of the

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<sup>13</sup>Recall that  $d_{i,r}^{\text{inv}}$  is investment demand and is readily available for the IO tables.

investments.  $\Delta \mathbf{d}^{\text{phco}}$  is similarly defined, yet in this case an average consumption vector is multiplied with the additional investment demand generated by private households.

**Considering scarcity in the operation phase** To consider crowding out in the operations phase we extend the approach introduced by Fisher and Marshall (2011) and further developed by von Schickfus and Zimmer (2018) to suit the requirements of an analysis of small regions embedded in an international IO table.

Before turning to the formal representation, consider first the intuition behind our approach. By investing in renewables the capital stock of each renewables sector increases by the amount of the respective investment. Assuming that there are no changes in technology, the capital stock increase attracts into the renewables sectors the amount of labor that is necessary to use the new capital stock in the production process. Assuming scarcity in the factors of production, which is a sensible assumption considering the current situation on the German labor market, labor is necessarily attracted from other sectors of the same or of other regions. Thus, output in these sectors decreases. This is, of course, a simplified representation of the whole process, since actually the adjustment consists of infinite rounds.

Formally, we assume the Leontief production function to be transregional as in Benz et al. (2014). That means that production of final goods in one region potentially uses factor inputs from all other regions by using intermediates from the other regions. The production function is then given by

$$y_{ir} = \min \left\{ \frac{v_{ir11}}{a_{ir11}}, \dots, \frac{v_{irfs}}{a_{irfs}}, \dots, \frac{v_{irFS}}{a_{irFS}} \right\} \quad \forall \quad i = 1, \dots, N \quad \text{and} \quad r = 1, \dots, R, \quad (35)$$

where  $y_{ir}$  is final goods output in sector  $i$  of region  $r$ .  $v_{irfs}$  is the amount of region  $s$ 's factor  $f$  used in region  $r$ 's sector  $i$ , and  $a_{irfs}$  the input coefficient that determines the amount of factor input  $f$  from region  $s$  which is required to produce one unit of output in sector  $i$  of region  $r$ . The number of factors is denoted by  $F$ .

Assuming full employment, scarcity and a positive remuneration of all production factors, implies that the employment of region  $r$ 's factor  $f$  in all regions in all sectors equals the endowment of region  $r$  with factor  $f$

$$v_{rf} = \sum_{s=1}^S \sum_{i=1}^I a_{irfs} y_{ir} \quad \forall \quad f = 1, \dots, F \quad \text{and} \quad r = 1, \dots, R. \quad (36)$$

Writing (36) in matrix notation leads to

$$\mathbf{v} = \mathbf{A}'\mathbf{y}, \quad (37)$$

where information on each region's factor endowment is contained in  $\mathbf{v}$ , which is a column vector of length  $FR$ . Furthermore, the column vector  $\mathbf{y}$  of length  $IR$  contains each region's final goods output in each sector.  $\mathbf{A}$  is a matrix of dimension  $IR \times FR$  containing the *direct* and *indirect* factor requirements expressed as factor input coefficients.

$\mathbf{A}$  is not readily available from the data, however, Fisher and Marshall (2011) show that it can be obtained by multiplying the matrix of direct factor inputs,  $\mathbf{B}$ , with the Leontief inverse:

$$\mathbf{A}' = \mathbf{B}'(\mathbf{I} - \mathbf{Z})^{-1}, \quad (38)$$

where  $\mathbf{B}$  is the matrix of *direct* factor inputs. It contains information on the factors of production directly employed to produce one unit of domestic total (intermediate and final goods) output,  $\mathbf{x}$ . Denoting low, medium and high-skilled labor as  $L$ ,  $M$  and  $H$ , respectively, and capital as  $K$ , and assuming mobile factors of production, that is, that factors of production of each region and each sector can be directly employed across sectors and regions,  $\mathbf{B}_m$  reads

$$\mathbf{B}_m = \begin{bmatrix} L_{11} & M_{11} & H_{11} & K_{11} \\ \vdots & \vdots & \vdots & \vdots \\ L_{ir} & M_{ir} & H_{ir} & K_{ir} \\ \vdots & \vdots & \vdots & \vdots \\ L_{NR} & M_{NR} & H_{NR} & K_{NR} \end{bmatrix}, \quad (39)$$

and its dimensions are  $IR \times F$ . However, we assume the factors of production to be partly mobile, that is, mobile within Germany and between sectors in Germany but not to be directly employed in the rest of the world.<sup>14</sup> Thus, there are two types of each factor, one for Germany and one for ROW, which means that  $\mathbf{B}_{pm}$  is of dimensions  $IR \times G$ , where  $G = 2F$  and the subscript *pm* stands for partly mobile. Assuming the rest of the world is the last region in the multi-regional matrix and letting  $(R - 1)$  denote the penultimate

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<sup>14</sup>This is a strict assumption, yet, in general, any mobility assumption would be possible. While we considered several different specifications, which serve as robustness checks, this specific assumption is the simplest setting that allows to cover our policy questions.

region,  $\mathbf{B}_{pm}$  reads

$$\mathbf{B}_{pm} = \begin{bmatrix} L_{11} & 0 & M_{11} & 0 & H_{11} & 0 & K_{11} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ L_{I(R-1)} & 0 & M_{I(R-1)} & 0 & H_{I(R-1)} & 0 & K_{I(R-1)} & 0 \\ 0 & L_{1R} & 0 & M_{1R} & 0 & H_{1R} & 0 & K_{1R} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & L_{IR} & 0 & M_{IR} & 0 & H_{IR} & 0 & K_{IR} \end{bmatrix}. \quad (40)$$

Fisher and Marshall (2011) further show that, although  $\mathbf{A}$  is not invertible because the number of factors  $F$  and the number of sector-region combinations  $IR$  are not equal, the full employment condition in (37) can be solved for  $\mathbf{y}$  with the Moore-Penrose Pseudo inverse of  $\mathbf{A}$  denoted by  $\mathbf{A}^+$ . Thus, it follows

$$\mathbf{y} = \mathbf{A}'^+ \mathbf{v} + (\mathbf{I} - \mathbf{A}'^+ \mathbf{A}') \mathbf{z}, \quad (41)$$

where  $\mathbf{z}$  is an arbitrary vector.

Taking the derivative with respect to factor endowment leads to the result that  $\mathbf{A}'^+$  indicates the output response in each region in each sector to a unit increase in each production factor. However, the approach of taking the derivative with respect to factor endowment at this stage is not appropriate in a context where the regions are so different in their size and the sectors in the different regions are assumed to have the same technology.<sup>15</sup> The reason is that in the process of reallocating factors so as to maximize output, there is no further information available than the production technology. Since we assume the production technology to be the same in the rest of Germany and the three districts, the same absolute amount of factors is assigned to a specific sector in all regions, leading to very implausible values for the regionalized sectors.<sup>16</sup> In this context,  $\mathbf{z}$  becomes relevant and although it is not further specified in Fisher and Marshall (2011), and we cannot solve for it analytically, we develop an algorithm to approximate its elements.

The routine starts by assigning an initial value to each element of  $\mathbf{z}$  and calculate the predicted  $\hat{\mathbf{y}}$  using (41). Since we know the actual  $\mathbf{y}$  we calculate  $\hat{y}_{ir}$ 's relative deviation from  $y_{ir}$ . The algorithm's goal is to find a vector  $\hat{\mathbf{z}}$  that minimizes the maximum relative

<sup>15</sup>As outlined in Section 2.2.1, lacking detailed administrative data at the regional level we need to make the "same technology assumption" to be able to produce IO tables and estimates of the production for the districts.

<sup>16</sup>Indeed, even if the production technology of sector  $i$  differs for the regions, the differences would not be substantial. Since  $\mathbf{A}'^+$  does not contain information on the size of the sector, very similar amounts of factors of production would be assigned to sector  $i$  in all regions.



deviations. Note that minimizing the absolute deviations as in a least squares estimation technique would give more importance, or even only consider, the deviations in the ROW region since the deviation in the three districts are technically insignificant in absolute terms in comparison to the ROW. However, we are particularly interested in the districts, so we minimize the relative deviations.

Specifically, after assigning an starting value of one to each element of  $\mathbf{z}$ , and initially defining a prediction,  $\hat{y}_{ir}$ , to be an outlier if it is 4 times larger (or 1/4 times smaller) than the actual  $y_{ir}$ ,<sup>17</sup> we proceed as follows:

1. Calculate  $\hat{\mathbf{y}}$  using (41) and inserting the current values for  $\hat{\mathbf{z}}$
2. Identify outlier sectors
3. Adjust the values of the  $\hat{\mathbf{z}}$  vector for the outlier sectors according to  $\Delta\hat{z}_{ir} = f(\hat{y}_{ir} - y_{ir})$ <sup>18</sup>
4. Adjust the threshold for the definition of outliers by 1%
5. Repeat steps 1 to 4 until there are no more improvements in the relative deviations within a chosen limit of iterations (1 million in our case)

We can then insert the estimated  $\hat{\mathbf{z}}$  in (41). We extend the right term of the right hand side by  $\mathbf{v}^+\mathbf{v} = 1$  to obtain

$$\mathbf{y} = (\mathbf{A}'^+ + (\mathbf{I} - \mathbf{A}'^+\mathbf{A}')\hat{\mathbf{z}}\mathbf{v}^+)\mathbf{v}. \quad (42)$$

This last transformation allows us to determine how sectoral final goods output,  $\mathbf{y}$ , reacts to changes in the factors of production. We define the outer parentheses on the right hand side of (42) as

$$\mathbf{\Lambda} = \mathbf{A}'^+ + (\mathbf{I} - \mathbf{A}'^+\mathbf{A}')\hat{\mathbf{z}}\mathbf{v}^+, \quad (43)$$

where  $\mathbf{\Lambda}$  is a matrix whose columns indicate the response in final goods output in each sector in each region to a unit increase in each factor of production. We extract the columns of  $\mathbf{\Lambda}$  to have eight single column vectors, one for each factor of production. So, for instance, the vector containing the effect of a unit increase in the capital stock in Germany on output is denoted as  $\lambda^{\mathbf{KG}}$ .

<sup>17</sup>The initial definition of an outlier sector can be chosen arbitrarily, but it should be in a range that only few outlier sectors exist.

<sup>18</sup>To ensure convergence it proved preferable to use only one percent of the total difference for the adjustment, thus:  $f(\hat{y}_{ir} - y_{ir}) = 0.01 \cdot (\hat{y}_{ir} - y_{ir})$

Having all the elements to compute the change in output of intermediate and final goods, we can now outline the procedure. First, we calculate the initial change in output without considering scarcities as follows:

$$\Delta \mathbf{x}^{op,p} = (\mathbf{I} - \mathbf{L})^{-1} \Delta \mathbf{d}^K, \quad (44)$$

where  $\Delta \mathbf{d}^K$  is a vector of the changes in final demand, whose elements are calculated by multiplying  $\Delta K_{ir}$  and the fraction of final demand per capital stock,  $\frac{d_{ir}}{K_{ir}}$ . Furthermore, we assume that  $\Delta K_{ir}$  is equal to the investment in each type of renewables.

The preliminary changes in  $\mathbf{x}$  require changes in the employment of production factors. We denote these preliminary changes  $\Delta K_{ir}^{op,p}$ ,  $\Delta L_{ir}^{op,p}$ ,  $\Delta M_{ir}^{op,p}$ ,  $\Delta H_{ir}^{op,p}$  and compute them as follows

$$\Delta H_{ir}^{op,p} = \Delta x_{ir}^{op,p} \frac{H_{ir}}{x_{ir}}, \quad (45)$$

where  $\frac{H_{ir}}{x_{ir}}$  is the factor coefficient, defined as the ratio of high-skilled labor per unit of output. Accordingly, we can calculate the changes in value added, as well as low and medium-skilled labor by inserting the appropriate factor coefficient. Aggregating the effects across sectors at the level of the regions where production factors are mobile, that is, within Germany and within ROW, we get the preliminary changes in high-skilled labor  $H^{G,op,p}$ .

To compute the net effects on  $\mathbf{x}$ , we subtract the effects generated by the scarcity of factors of production. However, we first need to translate the scarcity effects to express them in terms of intermediates and final goods output,  $\mathbf{x}$ , since they were computed in terms of final goods output,  $\mathbf{y}$ . Sticking to the example for high-skilled labor in Germany, we compute:

$$g_{ir}^{HG} = \lambda_{ir}^{HG} \frac{x_{ir}}{y_{ir}}. \quad (46)$$

Now, we can proceed as follows to calculate the net effect on  $\mathbf{x}$  in the operations phase:

$$\Delta x_{ir}^{op,net} = \Delta x_{ir}^{op,p} - g_{ir}^{LG} L^{G,op,p} - g_{ir}^{MG} M^{G,op,p} - g_{ir}^{HG} H^{G,op,p} - g_{ir}^{KG} K^{G,op,p}. \quad (47)$$

The total effect on output from the investment and the operations phase is then:

$$\Delta x_{ir}^{net} = \Delta x_{ir}^{inv,net} + \Delta x_{ir}^{op,net}. \quad (48)$$

### 2.3.2 Value added and employment effects

To evaluate the effects of investments in renewables on regional value added, low, medium and high-skilled employment we can now use the total changes in output from (48) and the factor coefficients as in the following example for high-skilled employment:

$$\Delta H_{ir} = \Delta x_{ir}^{net} \frac{H_{ir}}{x_{ir}}, \quad (49)$$

We can derive aggregate effects for the regions, by summing across the sectors in each region:

$$\Delta H_r = \sum_{i=1}^N \Delta H_{ir}. \quad (50)$$

Similarly, we can aggregate the effects to present results for the single sectors, across regions:

$$\Delta H_i = \sum_{r=1}^R \Delta H_{ir}, \quad (51)$$

or aggregate to consider only the three districts.

## 3 Data

### 3.1 Input-output table

The IO tables on which the analysis is based are the German IO table of inland production and imports for the year 2014 and the 2014 World IO Table from WIOD (Timmer et al. 2015). For disaggregation of the energy sector we use Exiobase 2 (Wood et al. 2015), which is, to our knowledge, the only table where the energy sector is disaggregated into several electricity production technologies, electricity transmission, electricity distribution, heat production, and gas distribution.

### 3.2 Regional data

From the Regional Accounts database of the federal and regional statistical offices we obtain data for the districts' GDP, aggregated gross value added data and disposable income of private households for the districts. GDP, government consumption, gross investments in equipment and buildings and private consumption for Germany and Bavaria are also obtained from this database. Employment statistics by sector both for Germany and the districts come from the federal employment statistics office.

Electricity and heat consumption, as well as data on electricity generation in the three districts was obtained from Reinhardt et al. (2017). Updated information was generously provided by the authors. Data on the length of electricity transmission lines in the districts were obtained from the Bavarian State Ministry of Economics and Energy (StMWi 2018). Data on electricity and heat generation by energy source in Germany comes from IEA (2017).

### 3.3 Factors of production

The three categories of labor input (low-, medium- and high-skilled) for Germany and the ROW are also from Exiobase 2 (Wood et al. 2015). Data for capital stocks for Germany was obtained from von Schickfus and Zimmer (2018), who in turn derive the data from various sources including Eurostat (2016), ENTSO-E (2017), IRENA (2016a), and Deutsche Energieagentur (2012).

### 3.4 Future renewables deployment and investments

Future deployment of renewables for electricity and heat generation, energy efficiency measures and electricity storage in each of the three districts were obtained from the simulations done in the framework of the project by two Geography Departments of LMU Munich. Thus, the deployment figures constitute an exogenous input in the present study. The simulations are based on the natural potential for renewable energy generation in the region, the available land use restrictions (e.g., due to conservation areas), the preferences of the population regarding technology types and installations' size, and the profitability of the measures, besides the usually considered factors like interest rates and energy prices. The scenarios are constructed along two dimensions: one describing the overall economic and social setting, and another outlining possible deployment paths. The first dimension considers, on the one hand, a business-as-usual (BAU) scenario and, on the other hand, a scenario with a trend towards a more sustainable economy and society (GREEN). The deployment paths differentiate between focusing primarily on small scale installations or on large scale installations of renewable energies. Combining both dimensions leads to 4 scenarios: BAU SMALL, BAU LARGE, GREEN SMALL, and GREEN LARGE.<sup>19</sup> From the simulations we obtain the annual average sum of renovation expenditures per district and information on the capacity (in kWp) installed per technology type and year from 2015 to 2035. In our analysis, we consider the average installed capacity per year.

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<sup>19</sup>For more information on the simulations see Danner et al. (2019). Table 5 in Appendix A.2 provides an overview of the scenarios. For a more detailed information of the scenario construction process see Musch and Streit (2017).

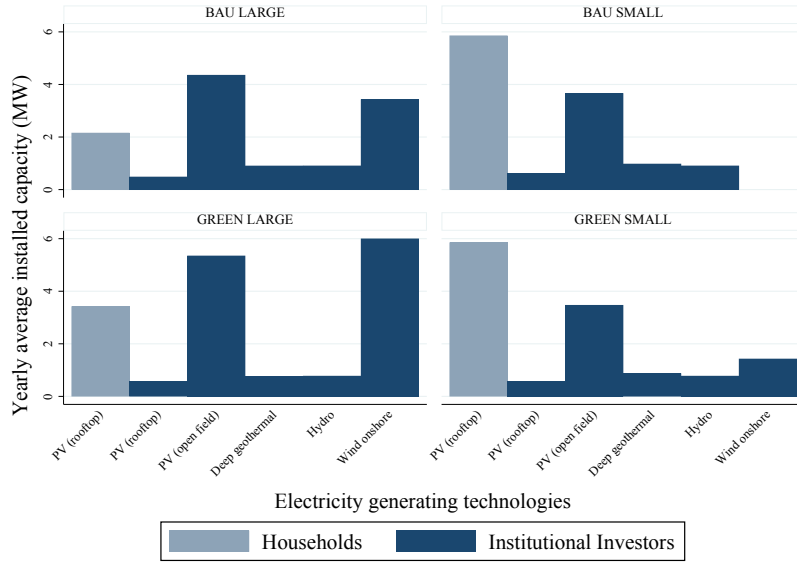
Table 2 depicts the comprehensive set of technologies and measures we consider in the analysis. It also shows that companies and other institutional investors invest in almost all type of technologies and measures except in heat pumps. Investments by private households take place in rooftop solar PV, solar thermal installations and heat pumps, on the generation side, and in district heating networks, renovations and batteries, on the energy infrastructure side.

The investment and operating costs for most power and heat generating technologies, as well as their distribution among sectors was obtained from Hirschl et al. (2010). The information for deep geothermal is from Hirschl et al. (2015). The renovations costs as well as their distribution among sectors is obtained from Hinz (2015), Loga et al. (2015) and IWU (2018). For each scenario we combine this information with the installed capacity by year, technology, investor type and district, which results in several cost vectors. We subsequently sum up over technologies to arrive at a vector by investor type, district and scenario. These vectors are the basis of the methodology outlined in Section 2.3.1.

**Table 2:** Technologies, measures and type of investor

Technology	Companies	Private households
PV (rooftop)	x	x
PV (open field)	x	
Solar thermal	x	x
Biomass	x	
Wind onshore	x	
Hydro	x	
Deep geothermal	x	
Geothermal heat pumps		x
District heating network	x	x
Renovations	x	x
Batteries	x	x
Power-to-Gas	x	
Gravity storage	x	

In the following, we describe the deployment figures obtained from Danner et al. (2019) (forthcoming). Figure 1 shows the average installed capacity for electricity generating technologies, classified by technology, type of investor and scenario. From the figure, it becomes clear that the largest differences in the yearly installed capacity arise from concentrating the efforts on small scale installations (scenarios BAU SMALL and GREEN SMALL) or focusing on large scale installations (scenarios BAU LARGE and GREEN LARGE). So, for instance, in the GREEN SMALL scenario the average installed capacity of rooftop solar by households is, with 6 MW, twice as large than in the GREEN LARGE scenario. The contrary and with even more pronounced differences, occurs for wind installations, where the average installed capacity in the GREEN LARGE is 6 MW

**Figure 1:** Installed capacity by scenario, yearly average

versus 1.2 under the GREEN SMALL scenario. Figure 8 in the Appendix shows a similar pattern for heat generating technologies.

Expressing these figures in relation to the number of inhabitants allows a comparison to current deployment in the whole of Bavaria. We see that for the GREEN LARGE scenario, the yearly PV and wind installations are equivalent to 25.7 kW per 1,000 inhabitants and 18.5 kW per 1,000 inhabitants, respectively. The newly installed capacity in kW per 1,000 inhabitants in Bavaria for the year 2017 (2018) was 50.9 (31.3) for PV and 24.2 (17) for wind (Agentur für Erneuerbare Energien 2019). Thus, putting the regional deployment figures into context shows that, although the regional energy transition in the Bavarian Oberland requires an important deployment of renewable technologies, it does not require an unrealistic development. Yet, it is important to mention that these deployment scenarios would not achieve a complete coverage of the energy demand by renewables by 2035, but would bring the coverage rate in electricity from 38% in 2015 to 51-62% in 2035. For heating, the coverage rate would increase from 26% in 2015 to 62-66% in 2035. Although the natural and technical potential would allow the region to meet its target by 2035, in the deployment simulations an annual technology specific “administrative installation cap” was set. The main rationale behind this cap was to account for the observed limited capacity of the public administration when it comes to granting the necessary licenses for the installation of renewable energies.

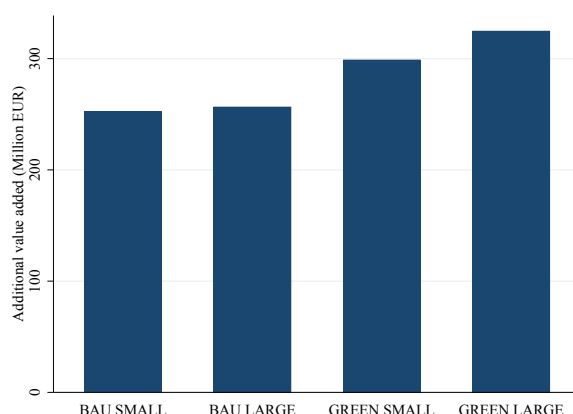
## 4 Results

In this section we present the results obtained by applying the methodology outlined in Section 2 to investigate the economic effects of a future energy transition in the Bavarian Oberland region. We start by presenting aggregated effects for the whole region and then dig deeper and show value added and employment effects for the individual districts and for individual sectors.

### 4.1 Effects on value added

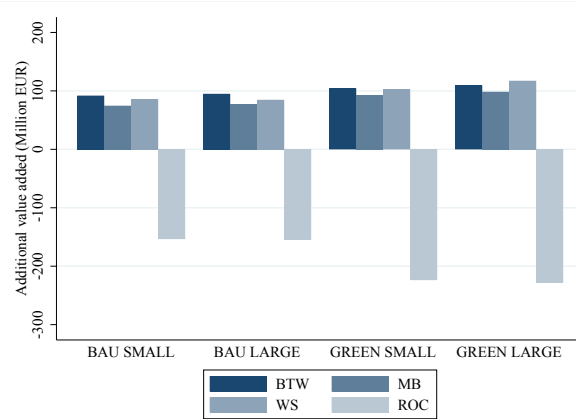
Investments in renewables generate an aggregated regional value added ranging from 252 to 325 Million EUR, depending on the scenario, as shown in Figure 2. Considering that the value added in 2014 amounted to 9.5 Billion EUR, the presented figures translate to an increase in value added of between 2.6% and 3.4%. In Figure 3 we see that all three districts benefit to a similar extent from RES investments in absolute terms. The overall effects for the whole of Germany (that is, including the Oberland region) are also positive, yet the rest of the country suffers from the crowding out of alternative investments and consumption, and from the Oberland region attracting factors of production which are then missing for production in the rest of Germany. The reason for the overall effects for Germany to be positive is that we allow for financial resources to be attracted from the rest of the world when considering crowding out effects in the investment phase. This approach leads to a lower investment crowding out in Germany than if we had restricted financial resources in the investment phase to come only from Germany.

**Figure 2:** Aggregated effects on value added, by scenario



*Notes:* The bars show the aggregate value added figure for the three districts in the Oberland region.

Looking at the sectoral effects in Figure 4, which shows exemplarily the results for the GREEN LARGE scenario, it is not surprising that the winners from the energy transition in the Oberland region are the sectors that are more closely related to the installation

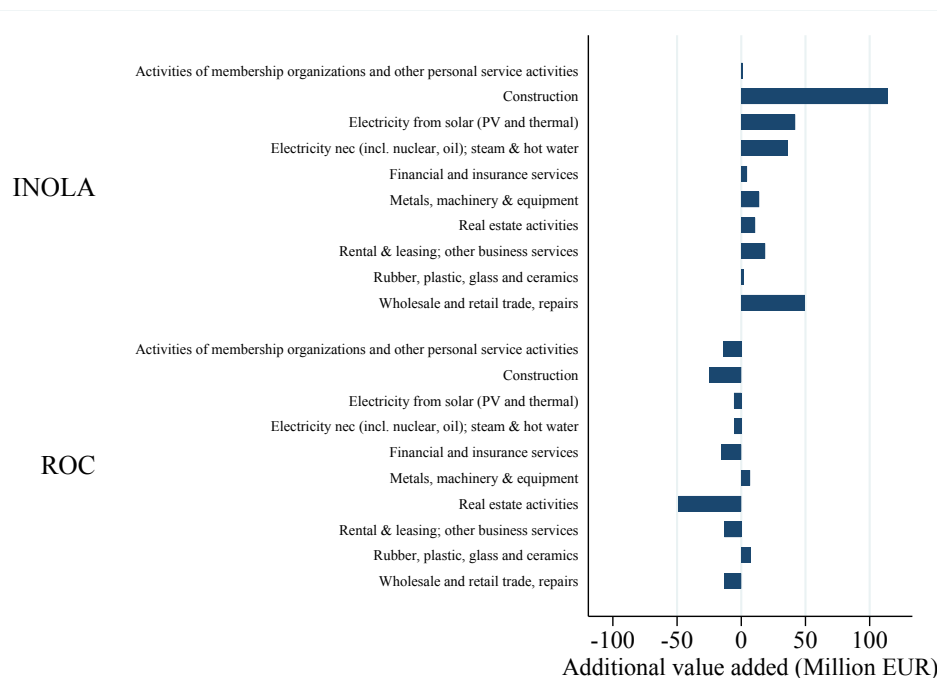
**Figure 3:** Effects on value added, by scenario and region

and operation of renewables as well as to renovations to increase the energy efficiency of buildings. Capturing about 30% of the additional value added, the *Construction* sector benefits the most across all scenarios, as can also be seen for the remaining scenarios depicted in Figures 12 to 14 in the Appendix. *Wholesale and repairs, Electricity from solar* and *Electricity nec; steam and hot water* are also among the sectors that benefit most across all scenarios.<sup>20</sup> Although we cannot verify the subsectors's share in the increase or decrease in a sector's value added, it can be argued that *steam and hot water* are the subsectors contributing most to the increase in value added in the *Electricity nec; steam and hot water* sector. Within the Oberland region there are no proper losers from the energy transition. The sector with the most negative change in value added is *Human health and social work activities* with a decrease of 0.5 Million EUR. To a certain extent, this can be explained by our assumption that factors of production are fully mobile within Germany, granting the Oberland region access to a large pool of factors. The consequence of the assumption is that sectors in the Oberland region increase their production at the expenses of sectors in the rest of the country and not at the expenses of other sectors within the region.

The careful reader might be missing conventional electricity sectors among the losers of the energy transition. In fact, in the rest of the country value added in the sectors *Electricity from coal* and *Electricity from gas* decreases, yet, only by about 5 Million Euro, corresponding to a decrease of approximately 0.02% of these sectors' value added in 2014. The almost insignificant loss for these two sectors is more reassuring than worrying, given the small size of the Oberland region compared to the rest of Germany. Since there are no coal power plants in the Oberland region, there is no *Electricity from coal* sector in any of the districts and, therefore, no value added losses.

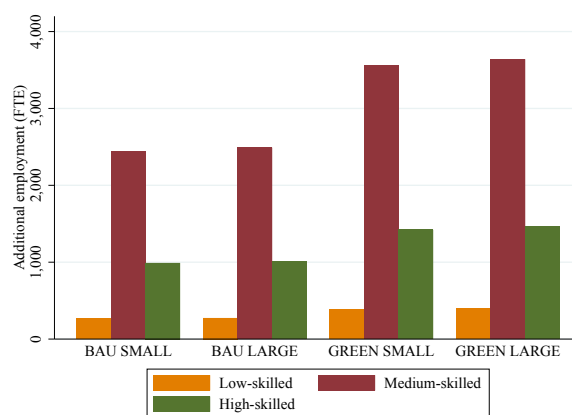
<sup>20</sup>nec: not elsewhere classified.



**Figure 4:** Effects on value added for selected sectors, GREEN LARGE scenario

*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

## 4.2 Effects on employment

**Figure 5:** Aggregated effects on categories of employment in the Oberland region, by scenario

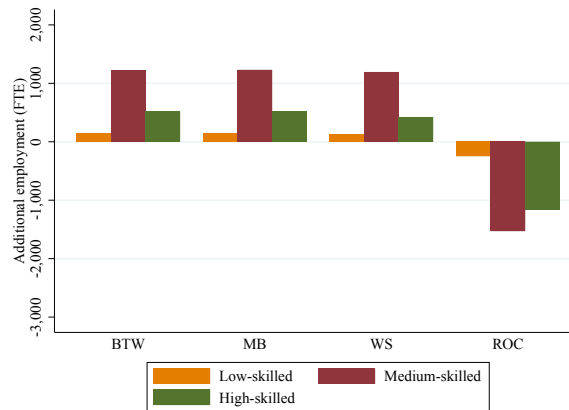
The employment effects of the energy transition in the Oberland region are shown in Figure 5. Most of the increase occurs in medium-skilled employment, making up about 66% of the additional full time equivalent (FTE) jobs.<sup>21</sup> Under the GREEN LARGE scenario, for instance, the considered investments in renewables create 3,640 medium-skilled

<sup>21</sup>Considering that in 2014 medium-skilled labor accounted for 52% of employment across all categories, this result implies that the increase in medium-skilled labor is more than proportional to the pre-energy transition shares.

jobs in the region, while the increase in high-skilled and low-skilled jobs is close to 1,460 and 400, respectively.<sup>22</sup> In relative terms the increase in medium-skilled employments lies between 3% and 4.5% with respect to the year 2014. For low-skilled and high-skilled employment, the percentage increase is 2-2.9% vs. 1.6-2.4%, respectively. This implies that, in contrast to the absolute changes, the relative increase in low-skilled employment is larger than in high-skilled employment.

Looking at the regional distribution of the employment effects, we see that it follows a pattern similar to the effects on value added (see Figure 6 and Figures 9 to 11 in Appendix A.3). The negative effects for the rest of the country in all three categories show that most of the employment effects occurring in the Oberland region are job reallocations from the rest of the country and, therefore, cannot be referred to as job creation. Note, however, that in light of the findings of Buchheim et al. (2019), the employment results under the mobile labor assumption can to some extent be understood as results for slack labor markets: when we interpret labor from the rest of the country as coming from an unemployment pool. It has to be noted though that in our model, these employees contributed to production in the rest of the country before the “shock”, so it is not an accurate representation of unemployment.

**Figure 6:** Effects on employment by category and region, GREEN LARGE scenario

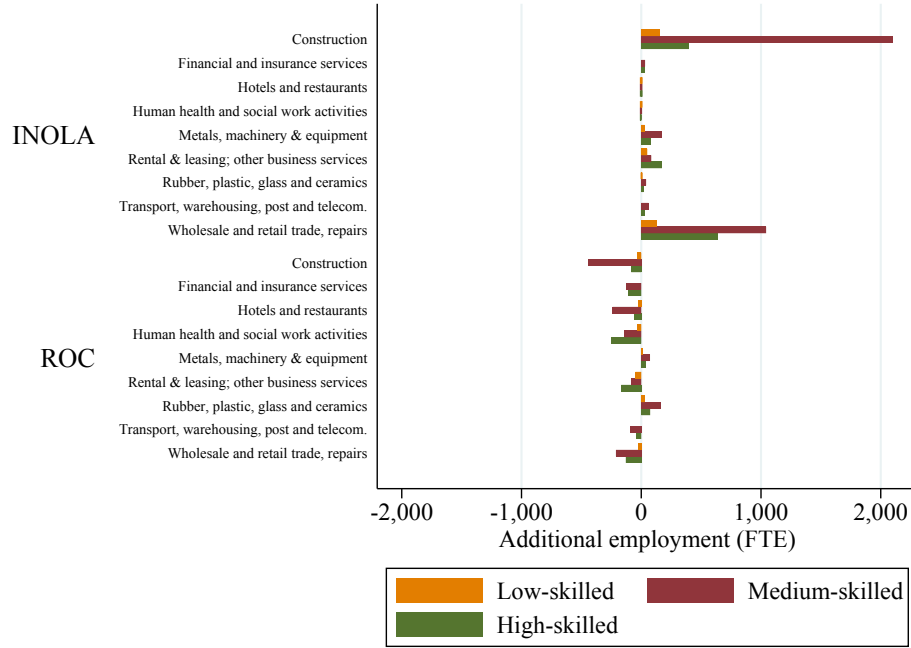


Breaking down the employment effects in the GREEN LARGE scenario by sector delivers the results in Figure 7.<sup>23</sup> Considering the results presented so far, it is not surprising that for medium-skilled labor the *Construction* sector exhibits the largest positive effects for the Oberland region and the largest negative effects for the rest of the country. *Electricity from solar* and *Electricity nec; steam and hot water* are among the sectors that benefit

<sup>22</sup>Note that, technically, we should rather refer to a reallocation of jobs instead of job creation, since we assume labor to be scarce. However, interpreting the results as job creation in the region is not wrong per se, but we need to keep in mind that this requires that jobs are “destroyed” somewhere else.

<sup>23</sup>A sector breakdown for the other scenarios can be found in Figures 15-17.

**Figure 7:** Aggregated effects on employment by category, selected sectors and aggregated region, GREEN LARGE scenario



*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

most in terms of value added, yet, due to their low labor intensity, the employment effects in these sectors are rather low.

## 5 Conclusions

In this investigation of the economic effects of an intended energy transition in the Bavarian Oberland region we contribute to the literature in several ways. First, we disaggregate the energy sector in the IO table to be able to consider the specificities of each technology's interlinkages with the rest of the economy. Second, we contribute to the literature on the economic effects of regional investments, in a broader sense, and more specifically, on the effects of regional investments towards a transformation of the energy system. The key contribution to this literature is the consideration of scarcities, which generate crowding out effects both in the investment and in the operation phase. A third contribution consists in expanding the approach developed by Fisher and Marshall (2011), Benz et al. (2014), and von Schickfus and Zimmer (2018) to improve its performance in a subnational context.

We show that following investments in a sector embedded in a framework where full employment and scarcity of financial resources is realistically assumed, value added and

employment in this and other sectors increase, but this comes at the expenses of other sectors and other regions. We further show that assuming full mobility of factors of production within Germany, gives the sectors in the Oberland region access to a very large pool of workers and capital, that is, that of the rest of the country. Thus, the negative effects on other sectors are almost fully “exported” to the region(s) where the investments do not take place. In our case the decline in value added and employment occurs almost exclusively in sectors of the rest of the country and not in our region of study. Moreover, we find that although employment in the Oberland region increases in all three categories (low, medium and high-skilled), the increase in medium-skilled employment is stronger than for the other two categories.

Thus, from the analysis of the employment effects of the intended energy transition in the Bavarian Oberland region we can also draw conclusions for the whole of Germany and for other countries with similar conditions. Irrespective of whether the energy transition occurs at the regional or the national level, our results show that fundamentally restructuring the energy system, as it is necessary to reduce greenhouse gas emissions in a serious manner, requires an intensified employment of medium-skilled labor. Thus, considering that already today Germany suffers from medium-skilled shortages, this can turn into a bottleneck for the transformation of the energy system. We could expect market forces to fix the shortages by increasing incentives (i.e., wages) in the demanded professions. Yet, the working of market forces could take time, which is not available when talking about mitigating climate change. The other, better option is to act proactively and increase the awareness for the importance of these professions and their attractiveness as part of climate and energy policy interventions.

It is important to take into account that our analysis of the economic effects of a regional energy transition is placed in a context where investments in renewable energies remain constant outside of the Oberland region. If, on the contrary, other regions pursue a similar goal or the energy transition at the national level is intensified, scarcities in the factors of production would inhibit the achievement of the goals and therefore limit the positive effects on the regional economy. Hence, further questions that arise in this context concern the consequences of a far-reaching regionalization of the energy transition goal, that is, when many regions intend to totally cover energy consumption by renewable energy generation. In particular, an interesting question would be whether this regionalization could give rise to a systems competition between the regions, seeking to attract capital (and labor) for the respective energy transitions.

Possible extensions of the methodology could consider alternatives to our assumption of full mobility of factors of production within Germany. On the one hand, the full mobility assumption is a plausible assumption, specially for the production factor capital. On the

other hand, although in theory it is possible that workers move freely, there might also be frictions binding workers to a specific region. A further development of our methodology could deal with restricting mobility partially, so that it is possible to attract workers from other regions, but to a limited extent. One possibility in this respect is to include neighboring districts in the analysis to allow mobility within that larger region, but not with the rest of Germany. Finally, modelling unemployment specific to sectors, regions and skill levels can be a useful addition in light of the findings of Buchheim et al. (2019) and the current economic crisis.

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## A Appendix

### A.1 Sectors

**Table 3:** Sector description and numbers

Sector number	Sector description
1	Agriculture, forestry and fishing
2	Mining and quarrying
3	Food, beverages, textiles, leather
4	Wood, paper, publishing, broadcasting, arts, entertainment, recreation
5	Coke and refined petroleum products
6	Chemicals and pharmaceuticals
7	Rubber, plastic and glass products and ceramics
8	Metals & metal products, machinery & equipment, and other products
9	Water supply, sewerage, waste management and remediation
10	Electricity from coal
11	Electricity from gas
12	Electricity from hydro
13	Electricity from wind
14	Electricity from biomass and waste
15	Electricity from solar (PV and thermal)
16	Electricity nec (incl. nuclear, oil); steam & hot water
17	Transmission of electricity
18	Distribution and trade of electricity
19	Manufacture of gas; distribution of gaseous fuels through mains
20	Construction
21	Wholesale and retail trade, repairs, including motor vehicles
22	Hotels and restaurants
23	Transport, warehousing, post and telecommunications
24	Financial and insurance services
25	Real estate activities
26	Rental & leasing; other business services
27	Computer programming and information service
28	Scientific research & development
29	Public administration & defense, social security
30	Education
31	Human health and social work activities
32	Activities of membership organizations and other personal service activities



**Table 4:** Available regional gross value added values

Aggregated sector	Corresponding CPA classifications	Sector description
A	1-3	Agriculture, forestry and fishing
B-E	5-39	Industry excluding construction
C	10-33	Manufacturing
B, D, E*	5-9, 35-39	Industry excluding construction and manufacturing. B: Mining and quarrying; D: Electricity, gas, steam and air conditioning supply; E: Water supply; sewerage, waste management and remediation activities
F	41-43	Construction
G-J	45-63	G: Trade, repair of motor vehicles; H: Transportation and storage; I: accommodation and food services; J: Information and communication
K-N	64-82	K: Financial and insurance activities; L: real estate activities; M: Professional, scientific and technical activities; N: Administrative and support service activities
O-T	84-98	O: Public administration and defense, social security; P: Education; Q: Health and social work; R: Arts, entertainment and recreation; S: Other service activities; T: Activities of households as employers

## A.2 Scenarios

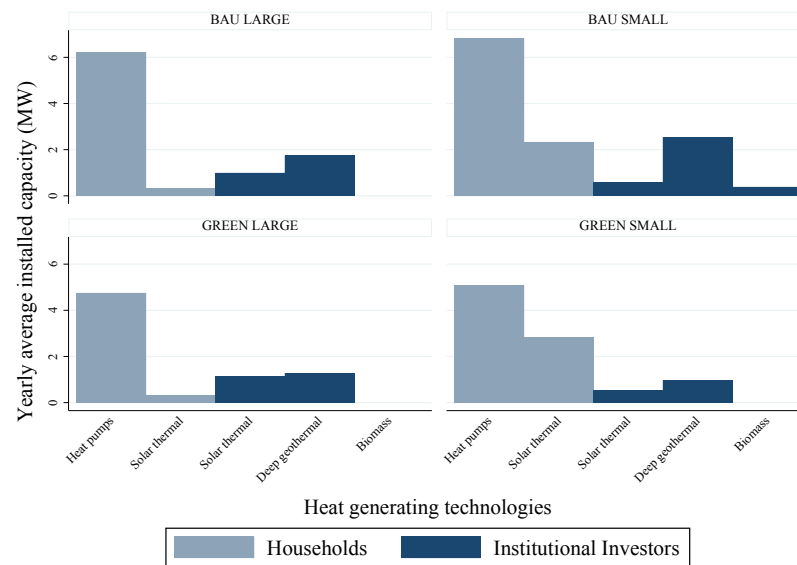
**Table 5:** Scenario description

Green scenario	Business as usual scenario
Low price path for fossil energy sources on the global market	High price path for fossil energy sources on the global market
Return to the historical interest rate level in Germany	Moderate recovery of interest rates in Germany
Strong increase of the Gross Domestic Product in Germany	Moderate increase of the Gross Domestic Product in Germany
Increasing globalisation, increasing trade relations with a global paradigm shift on sustainability	Increasing globalisation, increasing trade relations without common environmental and energy targets
Higher population (weak decrease), higher migration balance	Higher population (weak decrease), higher migration balance
Societal value orientation: trend towards a sustainable materialism	Societal value orientation: trend towards differentiation
Trend towards a decentralised energy production and storage	Trend towards a mixed structure in energy production and storage
Preference for technology-specific economic instruments for the energy sector (e.g., EEG)	Preference for technology-specific economic instruments for the energy sector (e.g., EEG)
Higher policy stability for the energy sector	Constant level of policy stability for the energy sector
Redistribution of the EU Common Agricultural Policy funds: More funding for environmental protection in agriculture	Continuation of the EU Common Agricultural Policy
Intensified environmental and resource protection in Germany	Constant level of activity in environmental policy in Germany
Comparatively low global greenhouse gas concentration (temperature increase 2046-2065 probably between 0.4°C and 1.6°C)	Medium level of global greenhouse gas concentration (temperature increase 2046-2065 probably between 0.9°C and 2°C)

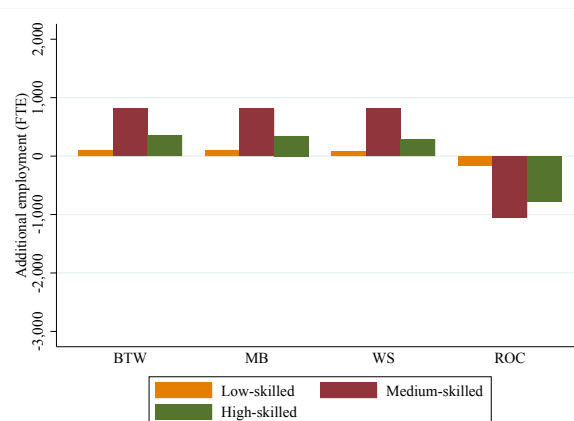
*Source:* Musch and Streit (2017)

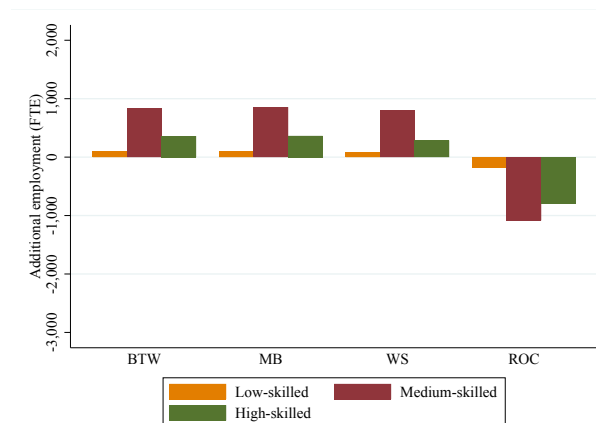
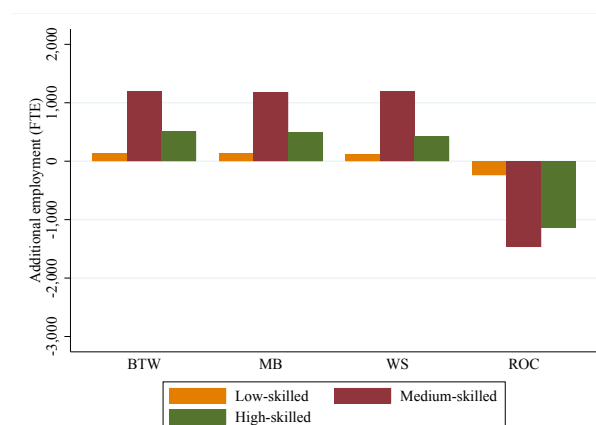
### A.3 Additional figures

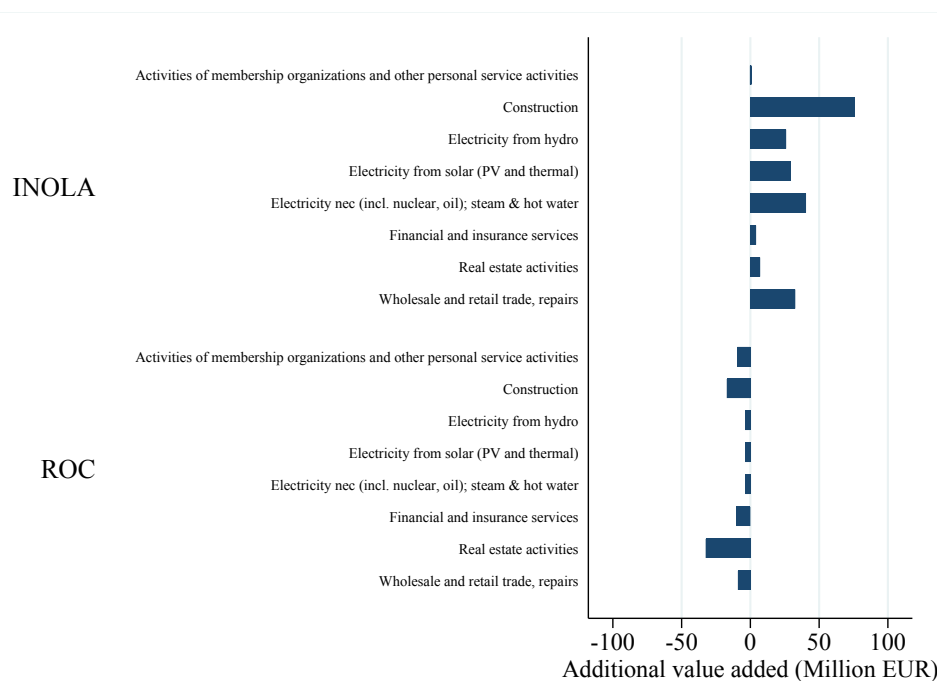
**Figure 8:** Installed capacity for heat generation by scenario, yearly average



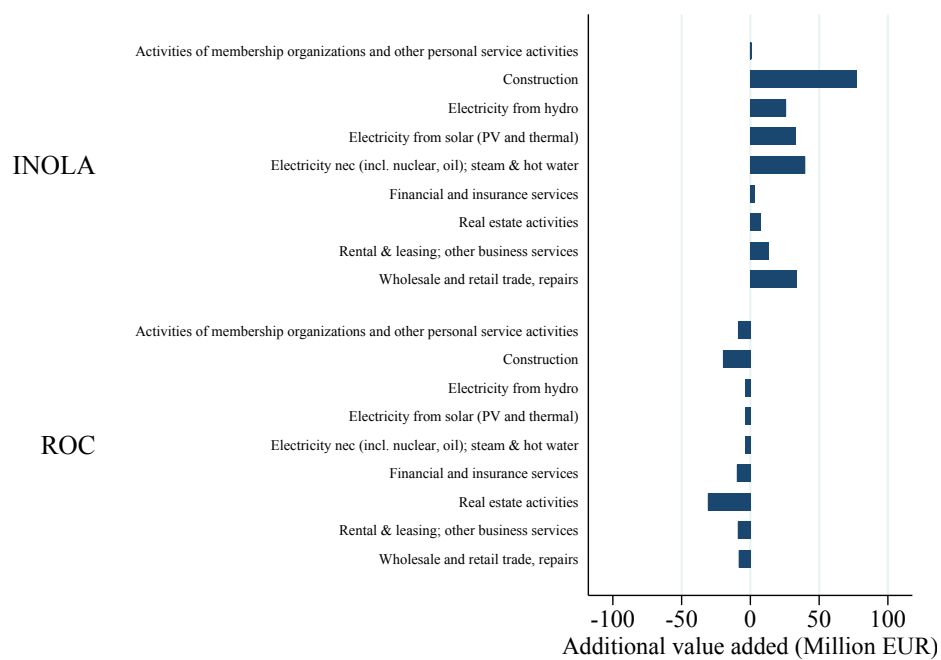
**Figure 9:** Effects on employment by category and region, BAU SMALL scenario



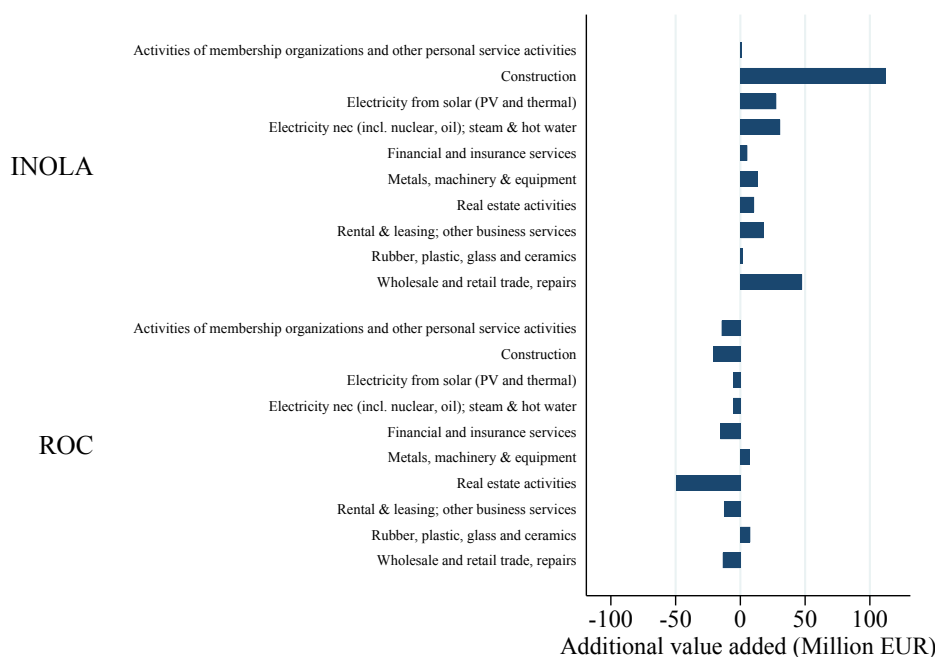
**Figure 10:** Effects on employment by category and region, BAU LARGE scenario**Figure 11:** Effects on employment by category and region, GREEN SMALL scenario

**Figure 12:** Effects on value added for selected sectors, BAU SMALL scenario

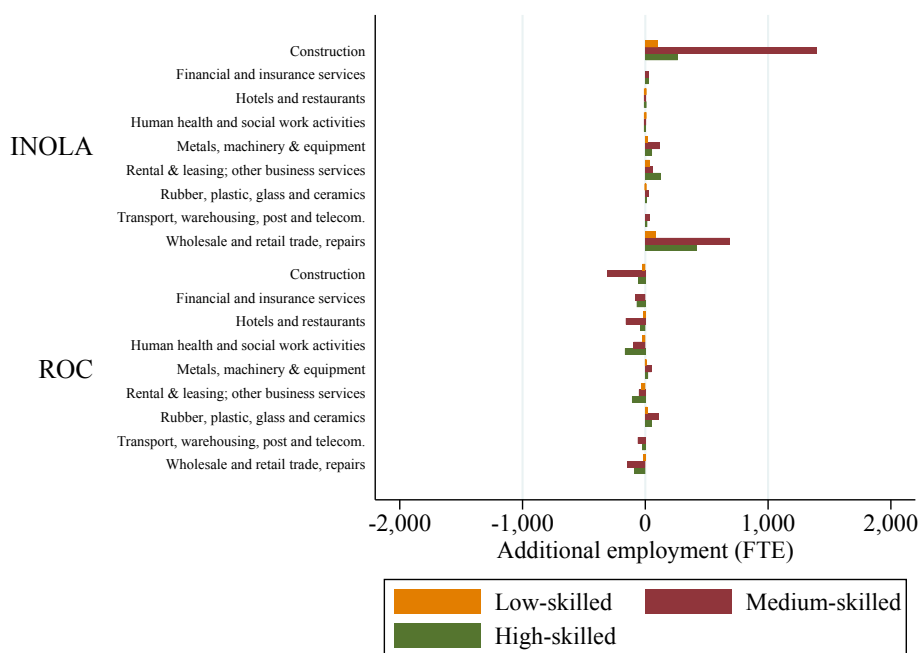
*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

**Figure 13:** Effects on value added for selected sectors, BAU LARGE scenario

*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

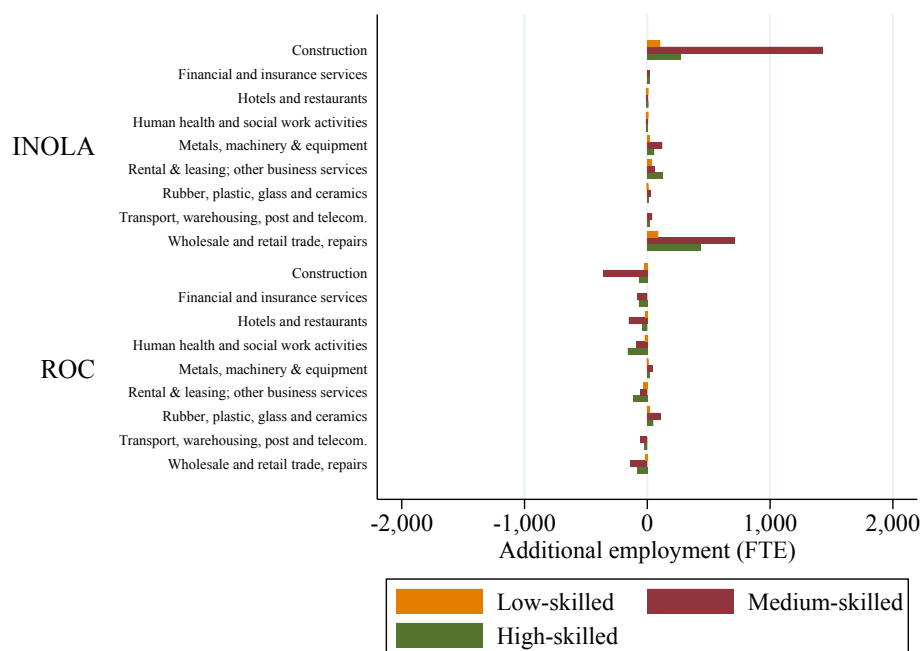
**Figure 14:** Effects on value added for selected sectors, GREEN SMALL scenario

*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

**Figure 15:** Aggregated effects on employment by category, selected sectors and aggregated region, BAU SMALL scenario

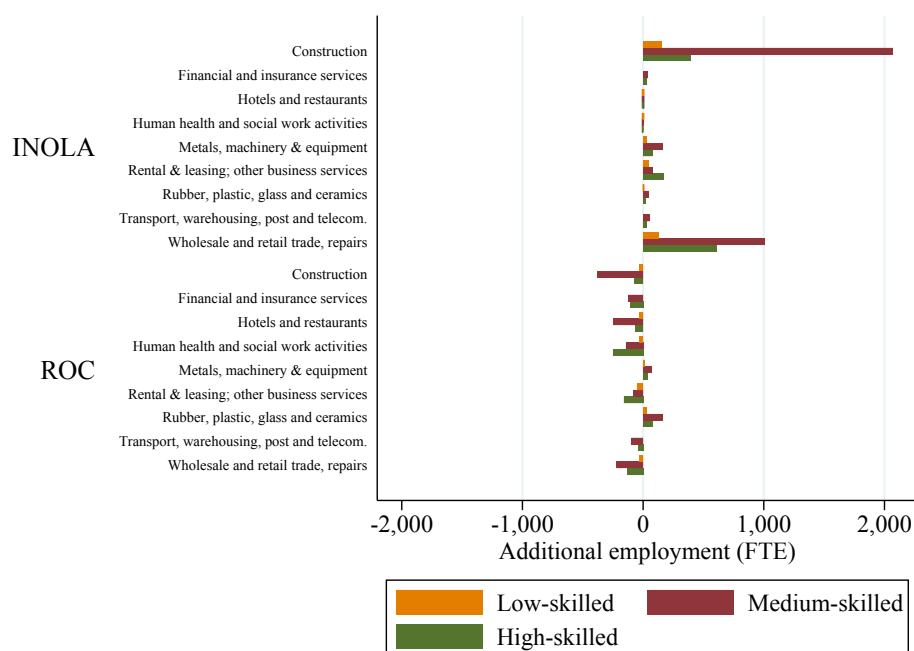
*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

**Figure 16:** Aggregated effects on employment by category, selected sectors and aggregated region, BAU LARGE scenario



*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.

**Figure 17:** Aggregated effects on employment by category, selected sectors and aggregated region, GREEN SMALL scenario



*Notes:* For a better visualization some sector descriptions have been shortened. See Appendix A.1 for the full sector descriptions.