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Local Economic Effects of Solar Panels and Onshore Wind Turbines: Evidence from German counties

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Abstract:
There is an abundance of literature on the economic effects of renewable energy stimulation at the national level, but the local effects of deployment have received relatively little academic attention. Against the backdrop of increases in local opposition against renewable energy plants, this thesis studies the local effects of solar and onshore wind energy capacity expansions in Germany. To this end, a panel regression was run using county level data over the period 2000-2016, correcting for county fixed effects, year fixed effects and county-specific trends, and controlling for capacity expansions of other renewables. I find effects of wind turbines on employment, but these are small and temporary (about 2.5 job-years per megawatt in the year preceding the start of energy production) and no effects on GDP. However, I find that wind capacity causes losses to the construction sector of about 0.41 jobs and €60,000 per megawatt. These seem to be the result mostly of temporary contractions in the years immediately following capacity expansions. The effects of solar capacity expansions are more difficult to establish. I find positive effects on GDP, jobs and the construction sector, but there is significant evidence that these arise due to reverse causality. As such, I find that instrumental variable models are preferred when measuring the effects of solar panel capacity.

Keywords: Renewables, GDP, Employment, Local Effects

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1. Introduction

Many countries have made significant strides towards transitioning from fossil-fueled electricity to renewable energy production in recent years. Yet, the extent of this transition differs tremendously even amongst the richest countries on the planet. There are countries that almost exclusively produce renewable electricity, such as Iceland, Norway and Uruguay (World Bank, 2019). Other countries have been catching up with this group, such as Sweden, Canada and Switzerland (all have around 60% renewables in their electricity mix). However, several equally rich countries with similar opportunities for renewables such as the Netherlands, the United States and Australia have been unable or unwilling to increase the share of renewables in their electricity mix, despite having ample financial muscle.

Indeed, the discussion around renewable usage is often a highly political one. There are significant costs and benefits to renewable electricity production. Although the environmental benefits of renewables are apparent, opponents at the national level often argue that large scale renewable energy production is simply more expensive than using fossil fuels, which leads to increases in electricity bills. Proponents however, argue that investments in renewable energy have a significant positive impact on the economy through creating jobs, and stimulating R&D. Indeed, extensive research on individual countries has found that such investments generally have positive effects on GDP and job numbers at the national level (see for example Markaki et al, 2013 or Caldés et al., 2009). Opposition against renewables, however, often stretches beyond this national level. Planned deployment of wind parks, hydro plants and solar panel parks have repeatedly met criticism at the local level amongst communities living in the vicinity of these plants. Even in countries like Germany, where the energy transition enjoys overwhelming support amongst the population, there are instances of the 'not in my back yard' phenomenon. Locals often support renewable energy in general, but may fear the negative effects local production may have on themselves and their communities.

Despite several studies pointing to a relation between economic outcomes and renewable plant acceptance, relatively few studies have aimed to establish the local economic effects of renewable energy production. Furthermore, most of those that did have only looked at the direct job effects, such as those connected to operation and maintenance (Cameron and van der Zwaan, 2015). However, deployment effects are conceivably more comprehensive. For example, wind and solar operators often lease their sites from local landowners, who get payments in return that they may spend in the community. Likewise, operators may buy inputs in the vicinity of plants, creating further local economic activity and jobs. Such effects may also be negative if investments in renewable energy are generally less lucrative than other projects, or if they suspend spending on consumption of local goods and services. Phenomena such as these make it likely that deployment effects stretch further than these ‘direct’ jobs.

To investigate the more general effect of deployment on the local economy, I employ a fixed-effect panel study of German counties (*Kreise*) between 2000 and 2016. Ideally, one would study the effects of all forms of renewable energy that are widely used in the country: biofuel, hydropower, solar and wind energy. However, hydropower and biofuel capacity are often highly concentrated which makes it difficult to establish effects in a cross-locality panel setting. Onshore wind power and especially solar power, on the other hand, are well-distributed around most developed countries, built in smaller capacities and also generally contribute a larger share of the electricity mix. The aim of this thesis is therefore to analyze the local economic effects of the deployment of two main sources of renewable electricity in Germany: solar and onshore wind energy.

The German setting is especially suitable for a number of reasons. Firstly, local information in Germany is well documented. Measures of economic variables, such as GDP and job numbers are available for low-level administrative districts. Moreover, the location of most of the country’s wind and solar energy plants is well documented and readily available. Both matters are indispensable for such a cross-locality endeavor. Secondly, it is widely known that the country is in the midst of a large-scale energy transition, which started in 2010 and is characterized by one of the most expansive renewable energy policies found around the world today. As such, there is significant variation in renewables deployment between districts as well as over time.

Two other studies have attempted to empirically estimate the effect of wind power through using cross-locality estimations on low-level administrative bodies (Brown et al., 2012; May and Nilsen, 2015). These authors study counties in the United States and Germany, respectively. Despite using the same units of analysis as May and Nilsen, I make several extensions to these analyses. Firstly (as noted), I extend the analysis to solar power. Second, I employ county-specific trends, which are arguably crucial to the precision and interpretation of the results, as counties within Germany differ strongly in their economic circumstances. Thirdly, I control for the expansion of other renewables (hydro power, biofuel and geothermal). Despite their limited geographical distribution, they are correlated with wind and solar capacity expansion and likely to affect local economies. Fourth, I extend the analyses of these papers to more recent years, and more than double the timeframe used by May and Nilsen. Finally, I use a more extensive set of parameters of local economic performance to better capture the integral effects of deployment on the local economy.

Despite the fact that a positive effect of wind capacity was expected, I cannot conclude that either of these have a strong or prolonged effect on local economies. In fact, wind energy has no significant effect on GDP, and a short-term negative effect of about 2.5 1-year jobs equivalents per megawatt in the year before production of electricity starts. Moreover, whilst specific positive effects were expected for the construction industry, especially during the construction phase, these are not found. Contrarily, I find industry losses of 0.41 jobs and €60,000 in value added. However, the size of these effects is relatively limited, and likely only economically significant when constructing large wind parks. These findings confirm those of May and Nilsen (2015) who find no effect on GDP, but contrast with the findings of Brown et al. (2012) who find positive effects on both GDP and overall jobs.

The effect of solar energy capacity is more difficult to establish. I find positive effects in my main regression using county and time fixed effects, as well as county specific trends. However, the data suggests that this effect is not causal and rather signals that more solar panels are built when local economic growth increases. To overcome this, I establish a regression using daily averages of county sun hours as an instrument for solar energy capacity, an instrument similar to those used by May and Nilsen (2015) and Brown et al. (2012). I also apply this strategy to the wind energy capacity analysis using daily average wind speeds as an instrument but find insignificant first-stage regressions for both.

The structure of the paper, then, will be as follows. First, section 2 gives a short overview of the developments surrounding renewable energy in Germany in recent years. Thereafter, section 3 presents an overview of the existing work surrounding economic effects of renewable energy. In this section, I pay particular attention to those works that focus on regional effects, which are more relevant to this paper. Section 4 portrays the nature and origin of the data employed for the empirical models of this paper that are described in section 5. Section 6 then outlines the main results of these regressions, and towards the end of this section I also discuss the instrumental variable analysis. Afterwards, in section 7, I discuss the implications of the estimations and make several suggestions for future researchers. Finally, section 8 concludes.

2. Renewable energy in Germany

In recent years, Germany has become one of the leading nations in the world with regards to renewable energy production. Although several countries boast larger shares of renewables in their electricity production, or have a larger installed capacity, the rise in renewables usage in Germany has been tremendous. Figure 1 (presented at the end of the document) shows the percentage of renewables in energy use for Germany as a whole compared to a handful of European countries between 1990 and 2017. It shows that the country has had a much larger increase in renewables usage than similar countries in Europe, which is especially remarkable after the year 2000. The upwards trend of renewable energy in Germany becomes even more clear when studying the share of renewables in electricity production, shown in figure 2, which lists the same countries between 1990 and 2015. This graph naturally shows a very similar pattern: the renewables share in electricity production stayed relatively flat between 1990 and 1999, after which it increased dramatically. However, one feature that is more pronounced in figure 2 is the large change in slope after 2010. This is the result of the country's exceptional push for sustainable energy generation that started in 2010. Known in German (and by now also in English) as the *Energiewende*, the national government passed legislation in 2010 to embark on an ambitious policy to increase renewables' share of electricity production to 80% by 2050 (Federal Ministry for Economic Affairs and Energy, 2015).

The green rationale for the *Energiewende* and the general reduction of greenhouse gases is generally appreciated by the German population. Surveys show that a large part of the German population supports renewable energy generation. A study conducted by the Institute for Advanced Sustainability Studies in 2017, for example, found that 88% of respondents approved of the *Energiewende* (IASS, 2017). Likewise, a survey by the Renewable Energies Agency of Germany found that 95% of respondents supported further expansion of the renewable energy network in the same year (Renewable Energies Agency, 2017). However, despite this overwhelming general support, local support for plant construction is significantly less, especially for wind energy (Reusswig et al. 2016, Langer et al. 2018).

Planned renewable energy projects in Germany are regularly slowed, or do not materialize due to local opposition. Reusswig et al. (2016), for example, describe an instance where local opposition prevented the construction of a wind park, despite the local government's support, transparent planning processes and a plebiscite vote which passed with 59% support for wind energy generation within the county. The literature into the acceptance of wind and large solar plants is substantive, and authors have pointed out the correlation between renewable plant acceptance and a variety of objective and geographical factors, such as visibility, sound, distance from one's property or plant size (Langer et al., 2017; Langer at al., 2018).

However, recent studies have pointed out that more abstract and procedural matters also have an important effect on acceptance by local communities in Germany. Such factors include modes of participation, such as whether locals have a financial interest in energy production (Langer et al., 2017; Langer et al., 2018; Liebe, Bartczak & Meyerhoff, 2017). Furthermore, an important predictor for acceptance of renewable energy deployment is distributive justice, which reflects how locals perceive the costs and benefits of deployment, and how these are distributed (Langer et al., 2016; Liebe, Bartczak & Meyerhoff, 2017; Sonnberger & Ruddat, 2017). Importantly, recent work on the acceptance of wind turbines in Switzerland and Germany has found that job creation and regional economic benefits are also strong influencers of local acceptance (Spiess et al., 2015; Sonnberger & Ruddat, 2017). In the face of dwindling local support for solar and wind farms, studying local economic effects of renewable energy is therefore a useful enterprise and the recent surge in deployment Germany provides for an ideal study object.

3. The Economic effects of renewable energy

3.1 Input-Output models

The recent literature on economic effects may be broadly defined into two categories (Lambert and Silva, 2013; Cameron and van der Zwaan, 2015) [1]. Firstly, there are those that use input-output (I-O) models to study the effects of investments and growth in the renewable energy sector. In general, these models use interdependencies between sectors to determine a multiplier for investments in a specific sector (Lambert and Silva, 2013). Indeed, by establishing quantitative relationships between industries, these authors estimate increases in output and jobs associated with expansions of investments, both within the industry as well as in other industries (Lambert and Silva, 2013; Cameron and van der Zwaan, 2015). There are a number of these studies available for developed countries, especially in Europe. Markaki et al. (2013), for example, create an I-O model for Greece and estimate that adopting EU guidelines on green energy production would lead to 108,000 extra jobs and GDP increases of €9.4 billion each year between 2010 and 2020. Caldés et al. (2009), specifically study solar energy production and find that compliance to the Spanish Renewable Energy plan would lead to over 100,000 equivalent full-time jobs of 1-year duration.

I-O models are relatively straightforward to apply to renewable energy and give a rather complete overview of the effects of investment. However, a number of important shortcomings arise when applying this method to regional settings. First, I-O models require extensive amounts of data (such as detailed expenditure and revenue figures). These data are often only available at the national level, rendering them unusable for many sub-country settings (Lambert and Silva, 2013) [2]. At the regional level, for example, revenue streams between wind energy operators and wind mill

[1] For readers interested in the origins of the more recent literature, a short overview of the first decades of research into the economic effects of renewable energy production is given in Appendix 1.

[2] Two notable exceptions are found in Kahouli and Martin (2018), who find large potential effects of investment in wind energy for a region in north-western France, and Slattery et al. (2013) who find positive effects on GDP and employment in Texas.

manufacturers may not be mapped, and as a result precise interdependencies are unknown. Secondly, it may be difficult to differentiate between the effects caused by investments in the production of renewable energy and *deployment*. Indeed, certain forms of renewable energy investment, such as R&D spending, may result in jobs that neither occur in deployment regions nor are directly related to national deployment if exports are sufficiently large. As such, I-O models are instrumental to understanding the overall economic impacts of renewable energy but provide relatively little information regarding the local effects of deployment.

3.2 Analytical models

Researchers interested in regional effects of deployment have therefore often resorted to other methods. As a result, there is a significant literature of more analytical studies, which fit better to regional cases (Cameron and van der Zwaan, 2015). Often, they revolve around surveys of renewable energy operators, or readily available figures supplied by actors within the industry to establish a 'job ratio', measured as an increase in jobs associated with an increase in capacity (usually in megawatts). A number of these studies focusing on solar power have been conducted in Spain, which has a significant renewable energy base, and is also one of the world leaders in wind energy generation. LLera et al. (2013), for example, find that solar panel deployment may increase local job availability by conducting a value-chain employment survey. Singh and Fehrs (2001) find these results for wind, solar and biomass energy in the United States. Industry reports also find increases in employment and GDP due to deployment of wind energy through surveys in Denmark (Danish Wind Industry Association, 2008), also in Spain (Asociación Empresarial Eólica, 2007, 2008 and 2018) and in the EU (European Wind Energy Association, 2009). On a more regional level, Moreno and López (2008), find that wind and solar energy production have significantly increased employment in the region of Asturias in northern Spain, as do Comings et al. (2014) for Montana.

However, while these analytical studies are more suited to regional settings than I-O models, they still present significant drawbacks. Firstly, they require extensive data gathering to establish job ratios. As a result, a significant number of authors have used job ratios found by other first-hand studies and transferred these figures to their own subjects of study (Cameron and van der Zwaan, 2015). However, jobs ratios can differ tremendously, both over time and between regions (Lambert and Silva, 2012). As such, Jenniches (2018) criticizes the transfer of employment ratios, even if they are calculated for relatively similar settings. Furthermore, several authors have pointed out that employment ratios may sometimes be overstated. Indeed, Brown et al. (2012) and Loveridge (2004) note that this may occur in country- or project-level case studies, because there is an incentive for project developers to create a favorable impression of their projects. Yet, even when data are gathered properly and employment ratios are valid, they often still fail to present the true effects of renewable energy deployment (Jenniches 2018; Lambert and Silva, 2012; Brown et al., 2012). That is, the effects of deployment likely spread beyond direct jobs.

3.3 Beyond analytical models

3.3.1 Indirect economic effects

In a review of the renewable energy literature, Cameron and van der Zwaan (2015) identify three different types of jobs created by renewable energy investments. First, there are the direct jobs: construction and maintenance jobs. Second, there are indirect jobs, which are generally related to input supply and support. These include, for example, jobs at local companies that supply tools for construction, jobs at local consultancy firms or administrative jobs in local governments. And finally, there are the induced jobs, which arise from general economic activity, such as local restaurant jobs or other local services jobs. Since the increase in jobs found by analytical studies often rely on surveys of energy companies or construction firms, they “ignore those jobs that are less directly associated with [the] industry” (Cameron and van der Zwaan, 2015, p. 161). Therefore, they may underreport the overall effect if there is a positive sum of indirect and induced jobs, or overreport where opportunity costs outweigh GDP or employment gains. This may occur, for example, when locals invest money that would otherwise be spent on consumption or invested in more profitable projects.

Apart from an increase in jobs, solar and onshore wind plants both generate direct cash flows to *Kreise*, which mainly happens in two ways. First, if plants (both solar and wind) are absentee-owned (such as by an energy company), they often purchase or lease land for them from local land-owners generating direct cashflows into the community (Brown et al., 2012; May and Nilsen, 2015). Since these landowners are likely to spend their money within the local community, this would have a positive effect on the local economy (Brown et al. 2012; Slattery et al., 2011). Second, if plants are locally owned, electricity production profits or subsidies will add to the income of locals, if the return to investment is higher than for other projects (Brown et al., 2012). As such, renewable energy deployment is expected to directly increase both job numbers and GDP at the local level.

3.3.2 Econometric ex-post models

Because analytical models fail to account for these effects, several authors have looked for alternative ways to reliably determine the economic effects of deployment. One promising area of research focuses on using econometric ex-post models. Where the geographical distribution of renewable energy plants is available, it is possible to ascertain the total effects of deployment on economic variables by constructing panel data on small administrative bodies. To the author's knowledge, only two studies have attempted such cross-locality studies to date. Brown et al. (2012) focus on counties within a large part of the contiguous United States between 2000 and 2008. Through using average local wind speeds as an instrumental variable (IV) to correct for possible endogeneity, they find a significant positive effect of wind energy production on county GDP (about $11,000 per MW) and jobs (0.5 per MW). May and Nilsen (2015) construct a panel of German districts (the same as used in this paper) and use a slightly more intricate IV (wind potential) to measure the effect of wind power deployment. However, in contrast to Brown et al., they find no significant effects. Partly, this may be because they use different dependent variables. Brown et al. employ absolute changes in county-level GDP and jobs, while May and Nilsen employ percentage change in GDP per capita and fail to study job effects. However, it is also feasible that the economic effects of deployment actually differ between the United States and Germany like the differences between employment ratios.

3.4 Aim of the thesis

The aim of this thesis, therefore, is to extend on the work by Brown et al. (2012) and May and Nilsen (2015), and to establish whether renewable energy deployment has a significant effect on local economies by employing a panel regression of German counties between 2000 and 2016. The merit of this thesis, then, is four-fold. First, whereas both May and Nilsen and Brown et al. focus solely on wind energy, I extend the analysis to also include solar energy deployment. Because solar panels and wind mills are fundamentally different in nature (solar panel plants, for example, are generally smaller and the electricity is more likely to be consumed locally), these may be expected to have different economic effects. Secondly, I extend on the analysis by May and Nilsen by extending the timeframe. Whereas these authors studied 2002-2009, I study the years 2000-2016. As such, I more than double the number of years, which allows me to increase precision of the results. This extension also allows for the inclusion of both the aftermath of the financial crisis, as well as the *Energiewende* and the significant expansions in deployment reflected in figures 1 and 2. Thirdly, I employ the total number of jobs within a county, alongside county GDP figures. Moreover, because deployment is expected to affect the construction sector, I also test for the effects on construction jobs and value added by the sector. Fourth, I use a different econometric analysis by specifically allowing for county fixed effects and county specific trends, which arguably increases the precision of the results.

4. Data and Study Population

4.1 Study population

To this end, I employ data on the counties of Germany which are agglomerations of several municipalities. There are two variations of these districts: 294 are classified as rural and 107 as urban. Although the number of municipalities changed considerably over the sample period, the number and geographical dimensions of the *Kreise* remained rather stable. Only two (Hanover and Aachen) changed; both absorbed another. To account for this, these districts and those they absorbed were dropped from the analysis. Moreover, the three German city states (Hamburg, Berlin and Bremen) were also excluded from the analysis, because they are both *Kreise* and states at the same time, and are therefore too different in size and political structure to allow for proper comparison. This brings the total amount of initially considered districts to 397. The year 2000 was chosen as the starting year of the panel analysis, because GDP and job figures are not available at the county level before this year. Reliable and precise data for most variables (especially the dependent variables) are available until 2016. As such, the time span of the analysis becomes 2000-2016, and includes both the major economic crisis of 2007 and the subsequent European economic malaise, and several years of the *Energiewende*. During this period, however, not all districts deployed wind turbines, or had any installed capacity. This reduced the final number of considered districts to 339 for the final regressions, with a total of 5742 observations.

4.2 Independent variable data: Renewable energy deployment

The data for wind power capacity as well as solar power deployment was taken from the Open Power System Data project. This initiative is a collaboration between several German and Swiss universities as well as large power providers in Europe that aims to map electricity production within a number of European countries, including France, the UK and Germany. As a part of this project, it has collected extensive data on renewable energy plants within Germany and published these online. The database lists the first day of energy production for all of these plants, as well as their capacity. In total, it lists around 1.6 million solar power plants, including domestic panels, that together accounted for 40.26 GW, or about 99% of capacity as reported by the German government, at the end of the studied period in 2016 (Federal Ministry for Economic Affairs and Energy, 2019; Open Power System Data 2019a).

Although the Open Power System Data includes data for offshore wind capacity, I specifically study only the effects of onshore turbines. This is the result of two considerations. Firstly, it is difficult to assign offshore wind mills capacity to counties, as many of these wind mills are relatively far out at sea. Therefore, assigning offshore turbines to onshore counties would likely result in imprecise estimations of local capacity. Second, the aim of this thesis is to specifically study the effects of onshore wind mills. The effects of offshore turbines are likely to differ significantly from those onshore. Lease payments, for example, are not paid for offshore capacity and offshore turbines are almost exclusively absentee-owned. As such, including offshore wind turbines would likely lead to precise estimates for neither form of energy production.

The number of onshore wind power plants, then, is understandably much smaller than the number of solar plants at 23,733, but they provide more electricity: 43.75 GW, or about 97% of capacity reported by the government (Federal Ministry for Economic Affairs and Energy, 2019; Open Power System Data, 2019b). The similarity between the total energy reported by the Open Power System Data and those reported by the German government for both solar and wind capacity suggests that these data are indeed a credible source for the analysis in this paper.

Importantly, the data also include a spatial measure; all power production sites are listed by their postal code. Because postal codes do not span across districts, one can then construct the yearly change in renewable energy capacity within them. Finally, I constructed the cumulative sum of these yearly changes in capacity to produce a score of both solar and wind capacity energy production capacity, for each available year and *Kreis*. As noted, all districts have at least some solar power capacity, while wind capacity figures are positive for 339 of the considered districts.

Figures 3 and 4 give an overview of the distribution of wind and solar capacity throughout the country by listing the installed solar and wind capacity for each *Kreis* in different years. The left panes depict the situation at the outset of the studied period in 2000, whilst the middle depicts 2009, the year before the Energiewende officially started, and conveniently in the middle of the timeframe. Finally, the panes on the right depicts the distribution at the end of the period in 2016. Several remarkable observations arise from these figures. Firstly, the expansions of both solar and wind energy capacity have been phenomenal. With regards to solar energy, the least-endowed county in 2016 had about four times the amount of deployment (8MW) than the most well-endowed *Kreis* had in 2000 (2MW), whilst that with the highest capacity in 2016 had more than 200 times this amount (440MW). Overall, the total capacity of solar power in Germany increased by a multiple of around 550 during the timeframe studied by this thesis. The increases in wind energy, too, have been remarkable. Two counties in the north of the country (Dithmarschen and Nordfriesland) were by 2016 installed with almost as much capacity (3.9 GW) as the entire country in 2000 (4.2 GW). Overall, the total onshore wind power capacity was expanded almost by a factor of 11.

Second, wind and solar power generation are not distributed equally over the country. Relatively little renewable energy was produced in the center of the country, especially in the states of Thuringia, Hesse and Rhineland-Palatinate. Wind power generation mostly took place in the windy north of the country over the entire timeframe. The northern states Mecklenburg-Vorpommern and especially Schleswig-Holstein generated tremendous amounts, while the districts in the southern states of Baden-Württemberg and Bavaria produced very little. These sunnier states, however, were relatively early at adopting solar panels, and continue to contribute a significant share of solar power in the country.

Of particular importance to the empirics of this paper are the growth patterns laid out by figures 3-5. The expansions of solar and wind capacity followed significantly different geographical trends. That is, the relatively local expansion of wind electricity in the north was not mirrored by a similarly concentrated expansion of solar energy in the south. Especially the proliferation of solar capacity in the north-east of the country is remarkable, because it transformed from the region with the lowest installed capacity to a major powerhouse of solar energy production. Together, then, these figures show that there was significant variation in installed capacity of both solar and wind capacity, both between municipalities and over time.

4.3 Dependent variable data: Jobs and economic activity measures

To study the effects of these increases in solar and wind capacity then, I employ a total of four different dependent variables. Since the effects of deployment are generally thought to affect jobs and GDP, I first estimate the effect on overall employment by using the total number of jobs with each county. Specifically, I take the number of people whose job is located within the county, rather than the number of working people living within country borders. To operationalize overall economic effects, I use Gross Regional Product (GRP), which measures economic activity for counties in the same way GDP does for countries. This is the same variable as used by May and Nilsen (2015). Both of these measures are readily available from the German *Regionaldatenbank* (Regional data bank), which compiles the data collected by the country's regional statistical bureaus (Regionaldatenbank 2019a; Regionaldatenbank 2019b). The data are available between 2000 and 2016, which limits the analysis to these years.

These variables are used to answer the main research question in this paper. However, a more thorough understanding of the effect of such deployment may be gained by looking at the specific sectors of the economy most likely to be affected by them. In this case, it is likely that the construction sector is the most strongly affected, as jobs and economic activity surrounding deployment are generally thought to arise partly through construction and maintenance of plants. As such, I would ideally employ two further variables analogous to those used for the overall effects: construction jobs and construction sector GRP. The number of construction jobs is readily available from the regional data bank, from which I again extract the number of people whose (construction) job is located with the county (Regionaldatenbank 2019a). These data are also available between 2000 and 2016. Sectoral GDP figures, however, are not calculated at the district level. As such, I employ the Gross Value Added (GVA) of the construction sector, which is also available between 2000 and 2016. Again, this figure was taken from the regional data bank (Regionaldatenbank 2019b).

Akin to figures 3 and 4, figures 5 and 6 shows the regional trends of the two general dependent variables: GDP and jobs. In these figures, both variables are shown in per capita numbers to give a better overview of the economic situation, rather than overall figures which are more likely to be a representation of population numbers. Again, there are several interesting observations here. Firstly, as expected, the employment and GDP per capita figures are highly correlated, and employment is highest there were the GDP per capita is also highest: in the cities. Second, within states, there is significant variation between districts, which becomes partly clear by the fact that there are many districts bordering each other with very different GDP and job figures. This observation enforces the notion that municipality fixed effects should be accounted for, rather than state fixed effects as done by May and Nilsen (2015).

Third, the distribution of the variables does not vary strongly over time. Indeed, the districts with high per capita job and GDP numbers at the outset were generally those with high figures at the end of the timeframe as well. And fourth, the absolute growth in GDP per capita was significantly higher in richer districts. Munich, for example, which is one of the richest counties, saw an increase of about €21,000, whilst the GDP per capita in the least wealthy district (Südwestpfalz) increased by only €4,700. Overall, however, there was a relative convergence between the counties (growth *rates* for poorer counties were generally higher than for richer counties, which is especially apparent in former East Germany). The differences in absolute and relative trends suggest that the parallel trend assumption vital to difference-in-difference regression may not hold. Therefore, correcting for municipality-specific trends seems to be necessary and is likely to affect the results of the regression.

A quick comparison of the capacity figures and Figures 5 and 6 then, provides some important insights into the spread of solar and wind energy. Especially in the first half of the timeframe, most solar capacity was installed in the richer parts of the country (the south and the west) and very little in the poorer districts formerly belonging to East Germany. This provides some evidence for potential reverse causality; it is likely that richer countries were able or willing to build more solar panels before the start of the *Energiewende*. However, this pattern changed over the second half of the timeframe, when large capacities were added especially in former East Germany. With regards to wind capacity, this region also has significant installed capacity. However, the distribution of wind capacity appears to be less dependent on economic activity, and more on geography. That is, wind capacity is generally located in the north of the country, where there is more wind, but capacity is similarly distributed among the richer west and poorer east in that part of the country.

5. Empirical Strategy

5.1 Models

The multitude of dependent variables implies, of course, that I employ several estimation regressions. In general, because of the similarity in dependent variables, the basis of each regression is very similar. In their simplest form, each regression would therefore be structured as the following:

$$Y = \beta_0 + \beta_1 * (Wind\ power\ capacity) + \beta_2 * (Solar\ power\ capacity) + \ \varepsilon$$

Or:

$$Y_{k,t} = \beta_0 + \beta_w * W_{k,t} + \beta_s * S_{k,t} + \varepsilon_{k,t} \qquad (1)$$

Where k denotes municipality, and t denotes the year. Y denotes the dependent variable (which differs by hypothesis) and W and S denote the main independent variables: the installed capacity wind and solar energy, respectively.

To find a causal effect, however, requires further immersion. It is likely that there are significant confounding variables, such as local governmental policies or geographic factors. For example, figure 3 shows that more solar panels are located in the sunny region of Bavaria, which has also historically had higher growth figures. β_s, as estimated by regression 1, is therefore very unlikely causal. The same goes for β_w,; many wind turbines are in the north of the country where there is more wind, and this region has historically had lower growth than other regions.

Brown et al. (2012) try to account for such differences by employing state fixed effects in their analysis of wind power in the United States. Moreover, they argue that both GDP growth and renewable energy deployment are likely dependent on other factors within counties, and therefore correct for a large variety of social and economic characteristics, such as sectoral job shares, initial GDP per capita and how educated the population is. Finally, they find that there may be a reverse causality problem because economic growth may affect renewables deployment either positively (because richer counties may have more economic sway to build turbines), or negatively (if renewables are built in poorer counties to improve economic performance). To overcome this problem, they use average county wind speeds at the outset as an instrument for wind power deployment. As such, they construct an equation akin to the following:

First stage:

$$\hat{X} = \beta_0 + \beta_1 * (Z) + State\ fixed\ effects + Controls + u$$

Second stage:

$$Y = \beta_0 + \beta_1 * \left(\hat{X}\right) + State\ fixed\ effects + Controls + \varepsilon$$

Where $\hat{X}$ is the predicted wind power capacity a result of the first stage regression on average county wind speeds (Z), and Y is a differenced version of either jobs or GDP.

However, despite the virtues of an IV analysis, I find that the methodology employed by Brown et al. (2012) may be improved in several respects. First, many of the variables corrected for by Brown et al. (2012) are related to geographical location or economic variables at the outset, such as initial GDP per capita. These effects may easily be corrected for by using municipality fixed effects, which also has the added value of correcting for other time-invariant variables that are unobserved or otherwise not considered.[3]

[3] Of course, accounting for district fixed effects removes the higher-level state fixed effects from the regression.

Furthermore, it is likely that there are other variables associated with increases in solar and wind capacity, even when correcting for county fixed effects. Most importantly, expansions of wind and solar capacity are often part of a more general clean electricity policy implemented by districts. Therefore, they may be associated with increases in other renewable energy sources, such as hydro power, biofuel and geothermal energy. As noted, because of the limited dispersion of these energy plants it is difficult to assess their effects individually, but they may affect the coefficients on solar and wind deployment. Therefore, I control for the presence of additional renewable capacity: the sum of the capacities of geothermal, biofuel and hydro energy. These are calculated in a similar manner as the solar and wind capacity variables using the Open Power Systems Project data. This yields the following equation structure:

$$Y_{k,t} = \beta_0 + \beta_w * W_{k,t} + \beta_s * S_{k,t} + \beta_R * R_{k,t} + \sum_{m=Ahrweiler}^{Zwickau} (\beta_m * M_{mk}) + \varepsilon_{k,t} \qquad (2)$$

Where M_m denotes a vector of dummies for each municipality m, and β_m represents the vector of coefficients for these district fixed effects. R denotes the installed capacity of additional renewables.

Second, most of the deployment in Germany was brought about in recent years (since roughly 2010 as can be seen in figure 1 and 2), which was also a period characterized by relatively stable economic growth for the country as a whole. This however, was unlikely solely an effect of the increase in deployment, but rather of general national and international economic trends, such as currency fluctuations and ECB policy. Of course, such increases in national GDP and challenges facing the economy of the entire country affect the GDP growth within districts as well. As such, even when correcting for time-invariant confounders by using *Kreis* fixed effects, the estimates of the deployment coefficients may be severely biased. However, such exogenous variables that affect all districts may be relatively easily accounted for by including year fixed effects. Adding this to the *Kreis* fixed effects regression yields the following estimation:

$$Y_{k,t} = \beta_0 + \beta_w * W_{k,t} + \beta_s * S_{k,t} + \beta_R * R_{k,t} + \sum_{m=Ahrweiler}^{Zwickau} (\beta_m * M_{mk}) \qquad (3)$$

$$+ \sum_{j=2001}^{2016} (\beta_j * T_{jt}) + \varepsilon_{k,t}$$

Analogously to the district fixed effects, T_j here represents a vector of dummies for each year j, and β_j represents the vector of coefficients for these time fixed effects.

Using time and county fixed effects effectively creates a difference-in-difference regression. It is widely known, however, that such regressions rely heavily on an assumption of equal trends. That is, the growth paths of the dependent variables in each *Kreis* should be similar. This is unlikely to hold, due to the diverse nature of the districts. However, in such a setting with multiple time periods and a multitude of districts this may be accounted for by allowing for district-specific trends. This is done by creating interaction variables between the period variable (years) and dummies for all groups (the districts), which correct for overall district-specific trends in the dependent variable. Controlling for these, then, allows for the measurement of a deviation from this trend, and we thus more accurately measure the causal effect of renewables deployment. As such, the main regressions in this paper will take the following form:

$$Y = \beta_0 + \beta_w * (Wind\ power\ capacity) + \beta_s * (Solar\ power\ capacity)$$

$$+\beta_R * (Additional\ renewable\ capacity) + \text{Kreis}\ Fixed\ effects + Time\ fixed\ effects$$

$$+\text{Kreis}\ specific\ trends + \varepsilon$$

Or:

$$Y_{k,t} = \beta_0 + \beta_w * W_{k,t} + \beta_s * S_{k,t} + +\beta_R * R_{k,t} + \sum_{m=Ahrweiler}^{Zwickau} (\beta_m * M_{mk}) \qquad (4)$$

$$+ \sum_{j=2001}^{2016} (\beta_j * T_{jt}) + \sum_{m=Ahrweiler}^{Zwickau} \gamma_m (M_{mk} * t) + \varepsilon_{k,t}$$

Where γ_m represents the vector of coefficients for each municipality-time interaction.

5.2 Expectation of results

The main coefficients of interest, of course, are β_w and β_s, which measure the effects of wind and solar capacity expansions, respectively. The interpretation of these coefficients, then, differs by dependent variable but is relatively straightforward. For the model with overall jobs, for example, it shows how many extra jobs per MW are created as a result of wind capacity expansion. Such conclusions, of course, hold analogously for β_s, or when employing other dependent variables. β_s for example, for the model using GDP, represents how much GDP increases as a result of a 1 megawatt increase in solar capacity.

The literature suggests that the effect of solar and wind capacity on both economic activity and employment are positive if the sum of indirect and induced effects is not both negative and larger than the increases caused by deployment. That is, the effect of wind and solar capacity is expected to be positive, because the number of indirect and induced jobs is expected to be positive. However, they may be negative if renewables plants push away other business that are more productive or employ more people. In general, I expect that the effects on the construction sector may be more pronounced, especially during the construction of plants when direct jobs are created.

6. Results

6.1 Naive regressions

The results of the simplest regressions are shown in table 1, which includes all dependent variables. This table shows significant coefficients on both solar and wind capacity for almost all of the regressions. Overall, the coefficients of solar energy are highly positive, whilst those on wind power are highly negative (except that on construction jobs, which is insignificant). This confirms the observation in figures 3-6, namely that wind power is concentrated in the poorer north and much of the solar capacity in the wealthier south.

Table 1. Regression results using only solar and wind capacity on the 339 counties.

Model	1	2	3	4
Dependent Variable	GRP (Million €)	GVA Construction Sector (Million €)	Overall Jobs	Construction Jobs
Solar Power Capacity	8.215***	0.797***	56.28***	6.621***
	(1.469)	(0.0403)	(18.29)	(0.791)
Wind Power Capacity	-4.968***	-0.0961***	-50.55***	0.295
	(0.752)	(0.0206)	(9.359)	(0.405)
Constant	6,056***	225.0***	101,193***	5,939***
	(3.044)	(1,381)	(59.74)	(110.9)
County fixed effects	No	No	No	No
Time fixed effects	No	No	No	No
County-specific trends	No	No	No	No
Observations	5,742	5,742	5,742	5,742
R-squared	0.004	0.031	0.002	0.005
Mean of dependent variable	5842.8	234.6	94957	5758

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Adding district fixed effects and other renewables (table 2), however, does not change the results markedly: the coefficients on the solar capacity remain positive, whilst those on the wind energy remain generally negative (except that on GDP). When the time fixed effects are added in table 3, however, there are several significant changes. Firstly, the effects of solar capacity on the general economy are strongly reduced, and the overall effects on GDP becomes insignificant. This effect is also apparent to a lesser extent for the construction sector. Secondly, the coefficients of wind capacity on the overall economy increased in absolute value. The coefficient on construction GVA also slightly increases, whilst the coefficient on construction jobs become smaller. This hints at the possibility that models without time fixed effects actually underreport the effect of wind capacity on the overall local economy (at least in Germany). This may be of some importance to the findings of Brown et al. (2012) who do not employ time fixed effects, although it is impossible to say whether similar patterns would hold in the United States.

Table 2. Regression results with county fixed effects and controlling for other renewables.

Model	1	2	3	4
Dependent Variable	GRP (Million €)	GVA Construction Sector (Million €)	Overall Jobs	Construction Jobs
Solar Power Capacity	8.071***	0.631***	42.13***	3.439***
	(0.701)	(0.0464)	(3.871)	(0.623)
Wind Power Capacity	-0.386	-0.0563***	-4.925**	-1.729***
	(0.357)	(0.0169)	(2.080)	(0.508)
Other Renewable Capacity	5.837**	0.152	7.589	-12.35***
	(2.375)	(0.103)	(14.01)	(3.484)
Constant	5,006***	210.4***	89,415***	6,031***
	(33.53)	(1.805)	(238.7)	(42.86)
County fixed effects	Yes	Yes	Yes	Yes
Time fixed effects	No	No	No	No
County-specific trends	No	No	No	No
Observations	5,742	5,742	5,742	5,742
R-squared	0.217	0.446	0.175	0.079
Mean of dependent variable	5842.8	234.6	94957	5758
Number of counties	339	339	339	339

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.2 Adjusted models: including *Kreis* specific trends

The results of these regressions, again, change markedly when constructing the most rigorous analysis: those including *Kreis* specific trends. The results of these are listed in table 4. Overall, as expected, the effects seem to be concentrated in the construction sector. Indeed, each MW of solar capacity increases the amount of construction jobs within a district by roughly 3 (out of a total job increase of 6.6), and the GVA of the sector by €137,000. The coefficients for wind capacity, however, are somewhat surprising. Whereas wind power, then, was expected to increase economic activity (akin to Brown et al., 2012), it seems to have a negative effect on the construction sector in Germany. Indeed, every MW installed seems to lead to a decrease of around 0.41 construction jobs and around €60,000 of value added by the manufacturing sector.

Table 3. Regression results with county and time fixed effects and controlling for other renewables

Model	1	2	3	4
Dependent Variable	GRP (Million €)	GVA Construction Sector (Million €)	Overall Jobs	Construction Jobs
Solar Power Capacity	1.571	0.353***	14.83**	3.146***
	(0.953)	(0.0609)	(6.000)	(0.722)
Wind Power Capacity	-1.318***	-0.0672***	-7.275***	-1.009**
	(0.375)	(0.0179)	(2.338)	(0.415)
Other Renewable Capacity	-0.353	0.207*	-9.063	-5.996**
	(1.692)	(0.109)	(14.34)	(2.914)
Constant	4,525***	229.5***	89,314***	6,990***
	(60.84)	(2.408)	(306.4)	(81.49)
County fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
County-specific trends	No	No	No	No
Observations	5,742	5,742	5,742	5,742
R-squared	0.371	0.560	0.266	0.319
Mean of dependent variable	5842.8	234.6	94957	5758
Number of counties	339	339	339	339

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.3 Robustness of results

As a next step, I test for the timing of the effects of both solar and wind energy capacity using lags and leads of the dependent variable. The rationale behind this is two-fold. Firstly, through assessing whether the correlation between capacity and the dependent variables precede deployment, one can test whether there is a possibility of reverse causality. For example, if there is a correlation between deployment in year *t* and economic activity in year *t-4*, this may indicate that the coefficients in table 4 are representative of an increase in deployment caused by economic improvements, rather than the other way around. Secondly, this allows me to test for the temporal nature of the effects found in table 4. In other words, when they arise specifically and if they fade

Table 4. Regression results with fixed effects, county trends and controlling for other renewables

Model	1	2	3	4
Dependent Variable	GRP (Million €)	GVA Construction Sector (Million €)	Overall Jobs	Construction Jobs
Solar Power Capacity	0.168	0.137***	6.153**	2.966***
	(0.476)	(0.0419)	(3.040)	(0.540)
Wind Power Capacity	-0.200	-0.0597***	-2.246	-0.406**
	(0.207)	(0.0145)	(1.363)	(0.204)
Other Renewable Capacity	1.469	0.324**	13.89*	3.395**
	(0.972)	(0.161)	(7.860)	(1.380)
Constant	-92,050	-4,052	-953,325***	-185,293***
	(56,429)	(2,931)	(303,960)	(27,840)
County fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
County-specific trends	Yes	Yes	Yes	Yes
Observations	5,742	5,742	5,742	5,742
R-squared	0.916	0.843	0.886	0.759
Mean of dependent variable	5842.8	234.6	94957	5758
Number of counties	339	339	339	339

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

over time. The resulting event study figures are represented by Figures 8.1-8.4 and 9.1-9.4. The figures are split up by independent variables first: 8.1-8.4 present the coefficients on wind capacity, whilst Figures 9.1-9.4 list those on for solar capacity. Secondly, they are split up by dependent variable: 8.1 and 9.1 list the effects on GDP, 8.2 and 9.2 on total jobs, 8.3 and 9.3 on value added in the construction sector and 8.4 and 9.4 on construction jobs.

6.4 Wind capacity

Most notably, wind power deployment does not seem to have an effect on overall GDP. Indeed, the coefficients on all lags and leads are insignificant (Figure 8.1) which confirms the insignificance of the coefficient in table 4. The effect on overall jobs, then, is surprising. Figure 8.2 shows that a negative effect arises a year before energy production starts of about 2.5 1-year jobs equivalent. The timing of this effects is expected. Indeed, wind plant planning, construction and site development often start about a year before the wind turbines produce electricity. The direction of the coefficient, however, is the opposite of what was expected. Indeed, especially during this phase one would expect positive effects on job numbers as construction of wind turbines requires laborers. The most likely explanation for this is that the employment gains do not outweigh the opportunity costs of building wind turbines in the short run, which therefore leads to negative estimates. However, table 4 suggests that this short-run contraction fades in the medium run.

Overall, there are negative effects on wind capacity on the construction sector. Like overall employment, the number of construction jobs and the sectoral value are depressed around the time production starts. Importantly, however, these effects commence at the 0-year point. This observation that construction jobs decrease after construction is finished provides some evidence for the validity of the analysis, because it is in accordance with the notion that the construction sector should be relatively well-off during the construction process. Yet, it was expected that the construction sector would show expansion during the construction period. Again, this is probably because even within the construction sector, employment gains do not outweigh the opportunity costs.

6.5 Solar capacity

Table 4 suggests that solar capacity has no overall effect on the economy, but a positive effect on the construction sector and overall jobs. However, the event study figures of 9.1-9.4 suggest that the interpretation of the coefficients in table 4 is not straightforward. That is, they show that the coefficients in the analyses with lagged dependent variables are significantly different from zero. This phenomenon holds similarly for all dependent variables: there are positive coefficients that start around *t-4* or *t-3*, which are generally preceded by negative coefficients for GDP and overall jobs. If the effects of solar capacity were causal, however, one would expect the coefficients on all lags (except for *t-1*) to be insignificant, especially for the construction sector. Indeed, it is not likely that solar panel construction has an effect on growth 3 or 4 years before they come into production, because it generally takes less than a year for a solar park to be constructed, and much less time for domestic panels to be installed.

The fact that these coefficients are significantly different from zero, then, indicates that the effects in table 4 are perhaps not a result of deployment, but rather of a different phenomenon. One possible explanation is that land- and homeowners are more inclined to install solar panels in times of economic booms. Indeed, this seems likely, because solar panels have large up-front costs that people may be more willing to incur in times of higher economic growth within the community. It is therefore impossible to reject that the coefficients in table 4 are the result of other elements than deployment. Thus, I conclude that, even after correcting for *Kreis* and time fixed effects, *Kreis* specific trends and other renewable capacities, it is impossible to precisely estimate the effects of solar panels on the local economy. As such, I now turn to an instrumental variable regression to attempt to overcome this issue.

6.6 Instrumental Variable regression

As noted, both Brown et al. (2012) and May and Nilsen (2015) apply an instrumental variable to study the effects of wind power deployment, partly because they are concerned about this reverse causality. Even though my analysis indicates little reverse causality for the wind energy analysis, it is worthwhile to also apply this instrumental variable analysis to wind capacity in a similar way. More specifically, Brown et al. (2012) use a direct measure of wind speed, using a five-point scale. May and Nilsen (2015) use a more complicated measure called 'wind potential', which also includes other local factors such as wind gustiness, topography and other geographical features, but which is not publicly available. They argue that this satisfies both IV criteria. Firstly, both works show that their instruments induce significant variation in wind mill placement, satisfying the relevance criterion. Second, they argue that using wind speeds removes the possibility of reverse causality, since weather patterns are virtually unaffected by processes happening 'on the ground', such as GDP growth and jobs creation. Moreover, they note that windiness does not influence GDP or jobs through other channels than increasing wind power capacity. A thorough analysis of the validity of this exclusion restriction is beyond the scope of this thesis, but it seems likely that the effect of wind speed on concurrent economic performance is small, especially when measuring growth using differenced GDP and job measures.

As such, I employ two similar instruments, one each for wind and solar energy. Weather patterns are not readily available at the *Kreis* level, and thus both instruments were constructed by the author using weather stations locations and data provided by the German Meteorological Office (2019a and 2019b). First, I located the wind-measuring stations and divided them amongst the *Kreise*. Then, I used the average daily wind speeds at 10 meters above ground-level to create a measure of average yearly wind speeds by Kreis between 1995 and 2010[4]. By taking the mean of these observations, I thus created a measure of prevailing wind speeds to be used as an instrument. Similarly, then, I employed a weather instrument for solar panels: the daily average of sun hours over the period 1995-2010. Analogously to the wind energy instrument, the weather stations measuring sun hours were located and divided among *Kreise*, to create a measure of the prevailing sun hours per *Kreis*. [5] The resulting distributions are mapped in figure 7.

I estimate the regressions separately for both instrumental variables. The equations then become the following:

First stage:

$$X_{k,t} = \beta_0 + \beta_Z * \left(Z_{k,t}\right) + \sum_{l=Bavaria}^{Thuringia} (\beta_L * L_{lk}) \; + \beta_c * C_{k,t} + u_{k,t} \qquad (5)$$

Where X is either installed wind capacity or solar capacity, and Z is the corresponding instrument (either average wind speeds or average daily sun hours). L_l denotes a vector of dummies for each state l, and β_L represents the vector of coefficient for these dummies. C denotes a vector of controls, including the sectoral shares of employment and GDP per capita at the start of the time frame. β_c, then, represents the vector of coefficients associated with these variables.

Second stage:

$$Y_{k,t} = \beta_0 + \beta_X * \left(\hat{X}_{k,t}\right) + \sum_{l=Bavaria}^{Thuringia} (\beta_L * L_{lk}) \; + \beta_c * C_{k,t} + \varepsilon_{k,t} \qquad (6)$$

Where Y represents the first differences of GDP, jobs, construction GVA or construction jobs, depending on the model. Table 5 shows the results of the first-stage regression individually and when both endogenous variables are entered into a single regression. Most of the coefficients are insignificant, except for the coefficient of sun hours on solar capacity. However, this correlation is not strong enough to be exploited for IV regression. Overall, it impossible for both instruments

[4] Where multiple wind-speed weather stations were located in a *Kreis*, I used the simple mean of the observations.
[5] Again, if multiple stations were present in a *Kreis*, the simple mean of observations was used.

Table 5. Results of first-stage regressions using Sun Hours and Wind Speeds as IVs.

Model	1	2	3	4
Instrumented Variable	Wind Power Capacity in MW	Solar Power Capacity in MW	Wind Power Capacity in MW	Solar Power Capacity in MW
Average Wind Speed	40.205	-	18.88	1.06
	(25.06)		(23.94)	(6.62)
Average Sun Hours	-	31.32	36.51	45.52*
		(52.80)	(54.79)	(25.53)
Constant	1300.57***	1874.31***	2103.74***	983.60***
	(473.29)	(424.00)	(620.28)	(273.12)
Land fixed effects	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	3,621	4,420	3,235	3,235
Mean of Dependent Variable	42.79	82.69	49.17	87.11

Note: Controls are the sectoral job shares and initial GDP per capita
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

to be used for IV regressions. This is a surprising finding, especially in the light of the validity of a similar instrument used by May and Nilsen (2015). There are two possible explanations for this. Firstly, I use the average wind speeds at 10 meters above the ground. Wind turbines are much taller than this, averaging more than 100 meters in height in many places. It is plausible then, that wind speeds at 10m do not correlate strongly enough with prevailing winds at higher elevations. Wind speeds at altitudes around this height may therefore constitute are better IV, but accurate measurements for winds at such heights are not publicly available. Second, it may suggest that not only average wind speeds, but also other (geographical) factors heavily influence placement of wind turbines in Germany. It is likely that other factors, such as gustiness and relative proximity to markets may affect wind turbine placement and efficiency. Likewise, the absence of a strong correlation between average sun hours and solar panels is remarkable, but not entirely unexpected. Although placing solar panels in districts with higher daily sun hours is likely to be more efficient in terms of energy production, a significant number of solar panels are built by local entrepreneurs and domestic home owners. Other factors like prevailing economic circumstances (as suggested by figure 9.1-9.4) and local policy are therefore more likely to affect solar panel distribution than sun hours.

However, the failure of the sun hours variable to produce significant variation in solar capacity deployment has important implications for this paper. Indeed, it does not allow me to test the validity of the results found for solar capacity deployment. I therefore conclude that it is possible that the coefficients on the solar capacity variables in table 4 are not causal and that a difference-in-difference model is not suited for studying such effects. I therefore refrain from making predictions about the possible effects of solar energy on the local economy.

7. Discussion

7.1 Effects of wind energy deployment

The results of the analysis partially confirm the findings of May and Nilsen (2015), who find no effect of wind turbines on local GDP. The absence of evidence for such an increase using two different econometric approaches and datasets increases the confidence in these results. However, this is not to say that wind turbines have no local economic effects. Indeed, the short-term decrease in employment suggest that there are significant opportunity costs associated with wind turbine construction. One example of such opportunity costs occurs where turbines are absentee-owned. In this case, the land that local landowners lease to operators of these could perhaps have been used for more productive processes such as intensive farming.

Brown et al (2012) note that it is unlikely that landowners would accept this, but leasing land to operators may have significant benefits. Firstly, leasing land to a third-party requires relatively little effort and investment from landowners, especially because wind operators have ample experience with handling such contracts and typically take care of site development. For landowners with little time or experience, it may therefore be attractive to lease their land. Secondly, green-minded landowners may prefer to have a windmill on their land over extensive farming or polluting factories, both of which may use the land more productively. Furthermore, areas that are designated for wind mill placement may not be used productively in the year immediately before production starts due to site development.

The opportunity costs, and therefore the short-run losses, may be higher for locally-owned turbines. Indeed, much like green-minded land-owners, green-minded locals may prefer to invest in non-polluting turbines with lower returns than more lucrative projects with significant environmental impact. Furthermore, if locals save or borrow money to invest in wind mills, they cannot spend it on goods and services which may provide ample employment. In the bigger picture, however, the effects of wind turbines are likely limited. The loss of about 2.5 1-year job over a short time period is very small compared to the average number of jobs per county (which averages at around 95,000). Therefore, the employment effects of wind turbines are likely only relevant when constructing very large wind parks. All in all, because of an absence of long-term effects on overall employment and relatively small short-run effects, I conclude that it is unlikely that wind energy deployment has a significant positive or long-lasting effect on local aggregate economic outcomes.

However, table 4 and figures 9.3 and 9.4 indicate that there may be consequences of turbine deployment for the local construction sector. Overall, I find that there are losses of about 0.41 jobs and €60,000 value added in the construction sector, which seem to be concentrated in the years immediately following construction. These effects are likely due to significant opportunity costs specific to the construction sector. In the context of this study, however, I again find that these effects are not very large. The average gross value added by the construction sector per county averaged around €234 million and the number of construction jobs about 5,758, meaning the effects of deployment are relatively small. As such, it is likely that significant aggregate effects on the county-level construction sector only arise when constructing large-scale wind parks.

It is possible, then, that these construction sector opportunity costs are higher for locally-owned wind mills. Indeed, whereas overall opportunity costs could be incurred by decreasing land productivity, this is likely not reflected in jobs and GVA of the construction sector. Therefore, since large wind operators are not expected to invest in other construction projects within a county, most opportunity costs are likely to arise from locally-owned wind mills. More specific research therefore, could focus on the differences between the (magnitude of) effects arising from absentee- and locally-owned wind mills.

7.2 Limitations of the wind capacity analysis

The causal interpretation of the coefficients found in the analysis, then, depends on whether several assumptions of the difference-in-difference models are met. The first assumption is the previously mentioned equal trends assumption. Allowing for differential trends allows for the relaxation of this assumption. The diverse economic nature of German counties, characterized for example by the former East-West divide, means that it is unlikely that parallel trends hold. Indeed, the large difference between the estimates with and without controlling for differential trends suggest that this should be controlled for. However, this does not come without a cost. Indeed, it is known that allowing for these trends may lead to imprecise results by decreasing variation and therefore increasing standard errors. As such, the effects of wind capacity may be more pronounced than sketched by the analysis in this paper.

Another caveat that is common to difference-in-difference regression is that the timing of treatment may be correlated with variables not controlled for in the analysis. In the context of this paper, this means that wind deployment may not be correlated with other things that happen at the same time and also affect the dependent variables. Several of these are already corrected for: it is likely that increases in wind capacity happen at the same time as increases in solar and other renewable energy capacity. Moreover, national policy changes are filtered out by the time fixed effects. However, future research may investigate further into the possibility of confounding variables persisting despite the application of fixed effects and county-specific trends.

7.3 Solar energy deployment

The solar capacity analysis shows that significant reverse causality may persist between economic outcomes and panel deployment even when constructing a thorough difference-in-difference analysis. As such, I refrain from conclusions regarding the local effects of solar power deployment in Germany. I find that researchers interested in the economic effects of solar power should aim to find instrumental variables. The analysis in this paper, however, suggests that sun hours (even though data are widely available) do not constitute a valid instrumental variable in Germany. That is not to say that they would not constitute a valid instrument in other countries.

Indeed, the fact that solar hours do not strongly predict solar capacity distribution in Germany does not indicate that there is a similarly weak correlation in other countries where sun hours differ more between regions, or where panels are more specifically placed in areas with more sun. Indeed, this is underlined by the significant prediction power of wind capacity on turbine placement found by Brown et al. (2012) who study a much larger geographical area with bigger differences in wind speeds. Perhaps in such large areas sun hours also constitute better predictors of solar panel distribution. Researchers should also keep the nature of solar panel distribution in mind. In some countries where large solar parks are common, using sun hours may yield significant variation. However, in other countries where domestic panels are more common, researchers may be likelier to succeed when using other instruments.

7.4 Implications for future research

As noted throughout this paper, there is relatively little academic work on the local effects of renewable energy production. Studying such economic effects may be important for overcoming local opposition against plants. However, it is known that job effects may differ strongly between and within countries (Lambert and Silva, 2012; Jenniches 2018). The differences between the findings of Brown et al. (2012) on the one hand, and this thesis on the other, are a testimony to this. Indeed, the results in this paper do not imply that the findings of Brown et al. are necessarily incorrect. The American setting and rationale behind wind turbine construction are rather different from those in Germany. Many wind turbines in the region studied by Brown et al. are located in very remote areas with extremely low population densities. If there are relatively few other possibilities for business in such areas, it is plausible that wind mills have large effects, as opportunity costs are low. Such settings are relatively rare in Germany. As such, the effects found in this paper may not easily be transferred to other settings, and the scope of research on this topic should arguably be expanded. It is therefore important to understand what the academic and methodological implications of this thesis are.

The methodology of this study was consciously chosen to be different from earlier work, and therefore provides some pointers for future research. Firstly, it is important to look beyond GDP effects. Although local GDP figures give a general view of the economy within districts, the effect of renewables deployment may be subtler than this. For example, akin to May and Nilsen (2015), I do not find significant effects of wind energy deployment on overall GDP, but I do find effects on employment and the construction industry, albeit small effects. Future researchers may wish to also specifically study other sectors, such as the agricultural sector, which could also be affected by wind or solar energy production if land leased by operators is generally cultivable.

Second, when studying cross-locality effects, it is essential to control for both district and time fixed effects, but also district-specific trends. It is likely that districts, also in other countries, are often on different average growth paths, which must be corrected for to get reliable estimates. In the analysis of this paper adding the fixed effects and trends greatly affected the coefficients, which means that researchers should be wary of results found by models not including these. Generally, future research may also study more uniform regions or countries. Germany is a country which is characterized by economic disparities and it may be worthwhile to uncover how wind turbines affect local variables in more homogenous settings.

Third, the analysis in this thesis suggests that reverse causality maybe not be a huge concern to researchers aiming to study the effects of wind power. Employing district fixed effects, time fixed effects and district specific trends would likely suffice for removing most of the reverse causality and confounding variables biases, a least in Germany. As such, constructing intricate instrumental variables may not be necessary when studying the effects of wind turbines. This depends, however, on the nature of deployment; if turbines are generally locally-owned, the analysis may be more susceptible to reverse causality bias.

Finally, the aim of this thesis was to empirically establish the effects of onshore wind and solar energy expansions on the local economy. However, in such a setting, the precise channels through which this happens are difficult to pinpoint. Although it is likely that the observed negative effects on the construction sector are the result of opportunity costs, it is unclear how they arise. For example, it is difficult to disentangle the supposed effect of a decrease in land productivity from other effects that may occur. Therefore, future research may investigate specifically how deployment affects local economies, rather than to what extent. Case studies of local deployment expansions, or life-cycle analyses of turbines, for example, may provide such information.

8. Conclusion

Despite significant research into the effects of renewable energy at the national level, the local effects of the deployment remain relatively unexplored. There are several papers that study regional settings, but most of these fail to look beyond direct job effects associated with construction and maintenance. However, some authors have noted that it is likely that the economic effects of deployment are more comprehensive. It has been pointed out for example, that wind energy operators often lease land from local landowners which leads to direct money transfers into local communities (Brown et al., 2012). These local effects are especially relevant because recent research has found that economic considerations are crucial for renewable plant acceptance by local communities (Sonnberger and Ruddat, 2017; Spiess et al., 2015). Two earlier studies have therefore aimed to establish the local effects of wind turbines by constructing cross-county analyses in the United States and Germany (Brown et al., 2012 and May and Nilsen, 2015). This thesis has sought to make several contributions to this literature through extending these analyses in a number of ways.

First and foremost, I extend on the wind turbine analysis by also studying the effects of solar panels. Secondly, although I study the same panel as May and Nilsen (2015) by investigating German municipalities, I more than double the period by studying the years 2000-2016. Studying these years ensures that there is significant variation in solar and wind capacity between municipalities as well as over time because of the *Energiewende*. Third, I extend on the dependent variables employed during the analysis. More specifically, the literature suggests that effects would be largest in the construction sector. As such, I look at the overall economic effects (GDP and total number of jobs), as well the effects on this sector (Gross Value Added by the construction sector and number of construction jobs). Fourth, I use a different methodological specification by employing a difference-in-difference analysis including county-specific trends. I find that for both analyses the outcomes change significantly when failing to account for such trends and researchers should be wary of models that fail to include these.

The difference-in-difference analysis of solar energy capacity initially pointed to effects on local construction sectors. However, careful observation of the event study figures revealed that these effects are perhaps not causal. Indeed, contemporary deployment is strongly correlated with construction sector performance up to four years ago, even after correcting for fixed effects and trends. Since solar parks and domestic panels are generally constructed within less than a year, these coefficients are more likely to reflect that people are more inclined to install solar panels in years of economic success. I therefore conclude that a difference-in-difference analysis is likely not suitable for estimations of local effects of solar capacity. As such, I constructed an instrumental variable analysis using an instrument (sun hours) similar to those used for wind capacity analyses (wind speeds). This instrument did not yield a significant first-stage regression, which makes it difficult to establish the validity of the solar capacity results. However, usage of a different instrument in Germany, or a similar instrument in other countries, may yield a satisfactory first stage, which would allow for better causal estimation.

The difference-in-difference estimation of onshore wind deployment, then, was deemed to be more representative of a causal relationship. However, the effects of wind energy deployment on local economies were found to be relatively limited. Overall, no effects were found on GDP levels, although short-term employment losses of about 2.5 1-year jobs per MW were observed during the year before energy production started. The effects of wind deployment on the construction sector, then, were found to be negative. Overall, the deployment of 1 MW of wind capacity leads to a loss of GVA of about €60,000 and 0.41 1-year, which is concentrated in the immediate years following the start of energy production. However, in the bigger picture, these effects are relatively minor (the construction sector averages a GVA per county of about €234 million and 5,758 jobs). Therefore, I tentatively conclude that the effects of onshore wind turbines are likely only economically significant when considering large-scale wind parks.

These effects stand in contrast to those found by the 'direct jobs' literature. Generally, these studies find positive effects of wind energy deployment, because they estimate directly how many construction and maintenance jobs are created due to deployment. It may therefore have been expected that studying effects in a more integral way would lead to higher estimations of job and GDP increases. The findings in this paper, however, indicate otherwise. Of course, construction and maintenance require labor, but these effects are not apparent in this analysis. One explanation for this is that investments in wind turbines are associated with significant opportunity costs. This would be the case, for example, if a wind energy operator leases land from a local landowner which could otherwise be used as productively. Likewise, if a turbine is locally-owned, the necessary funds may otherwise have been invested in other projects or spent on goods and services within the community. However, the generalizability of these results (especially to other countries) may be limited as job effects are generally thought to differ between regions. Much more research is needed into this topic, especially where local opposition to deployment is high. All in all, this paper finds that direct job effects paint only a part of a more complicated picture, and more comprehensive analysis is necessary to unearth the true effect of renewables deployment on local economies.

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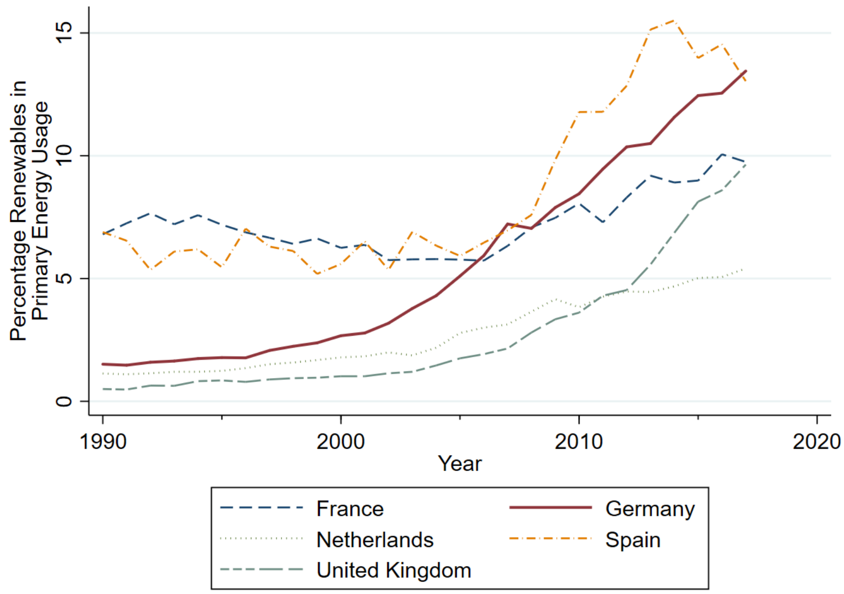
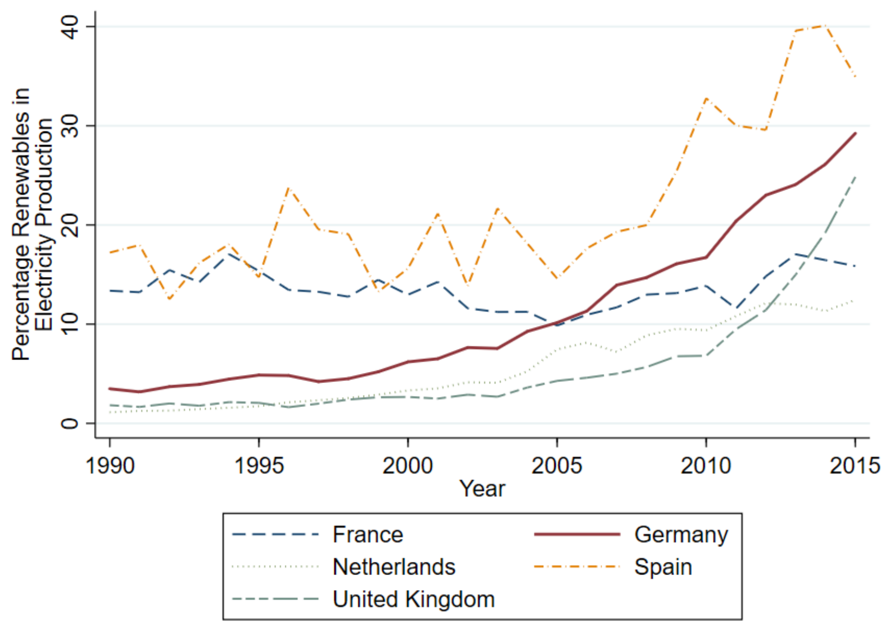
10. Figures

Figure 1. Percentage Renewables in Primary Energy Usage in several European countries



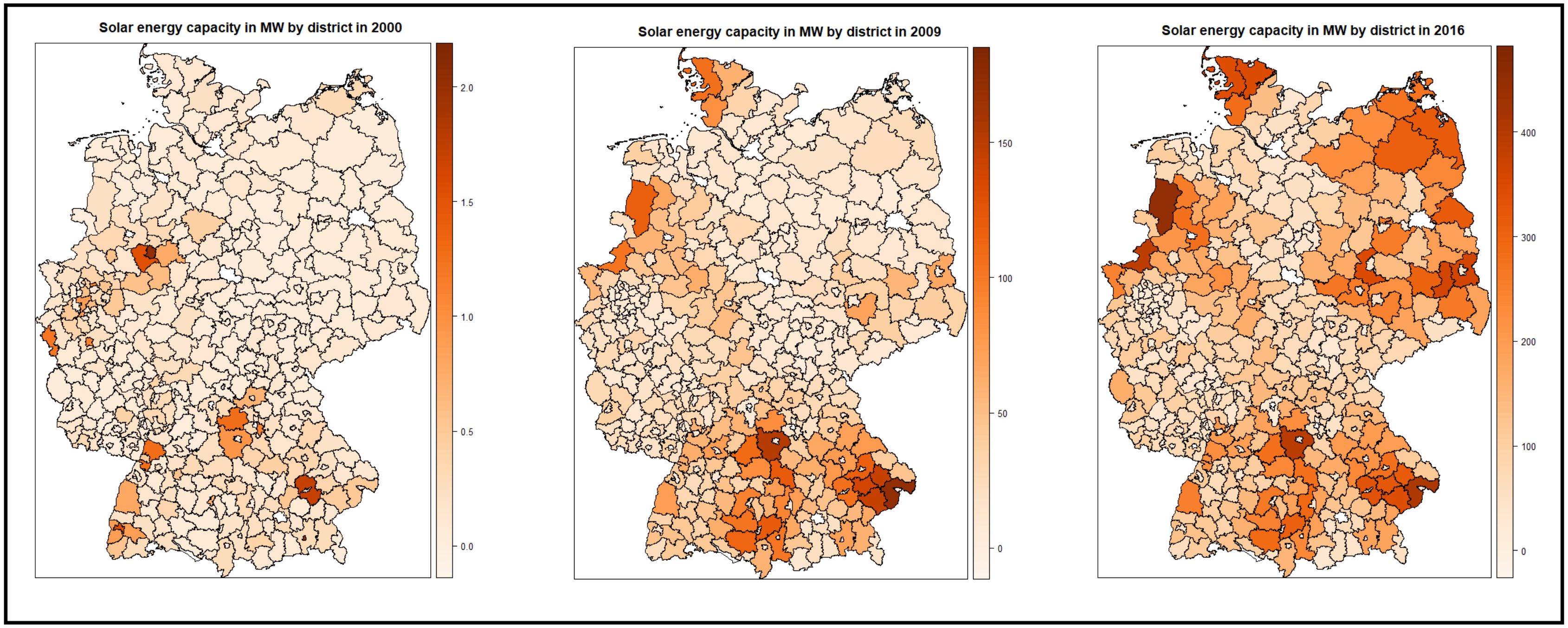
Source: OECD (2019)

Figure 2. Percentage Renewables in Electricity Production in several European countries



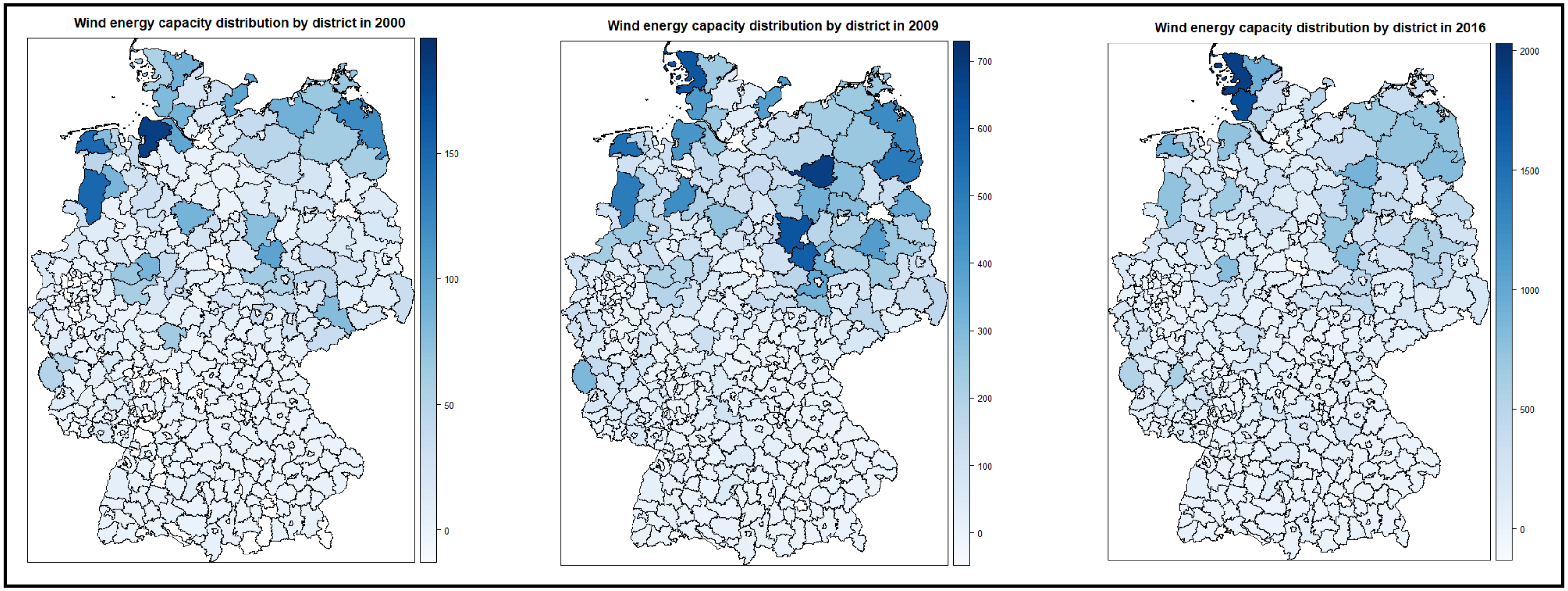
Source: World Bank (2019)

Figure 3. Solar energy capacity in MW by district in 2000, 2009 and 2016



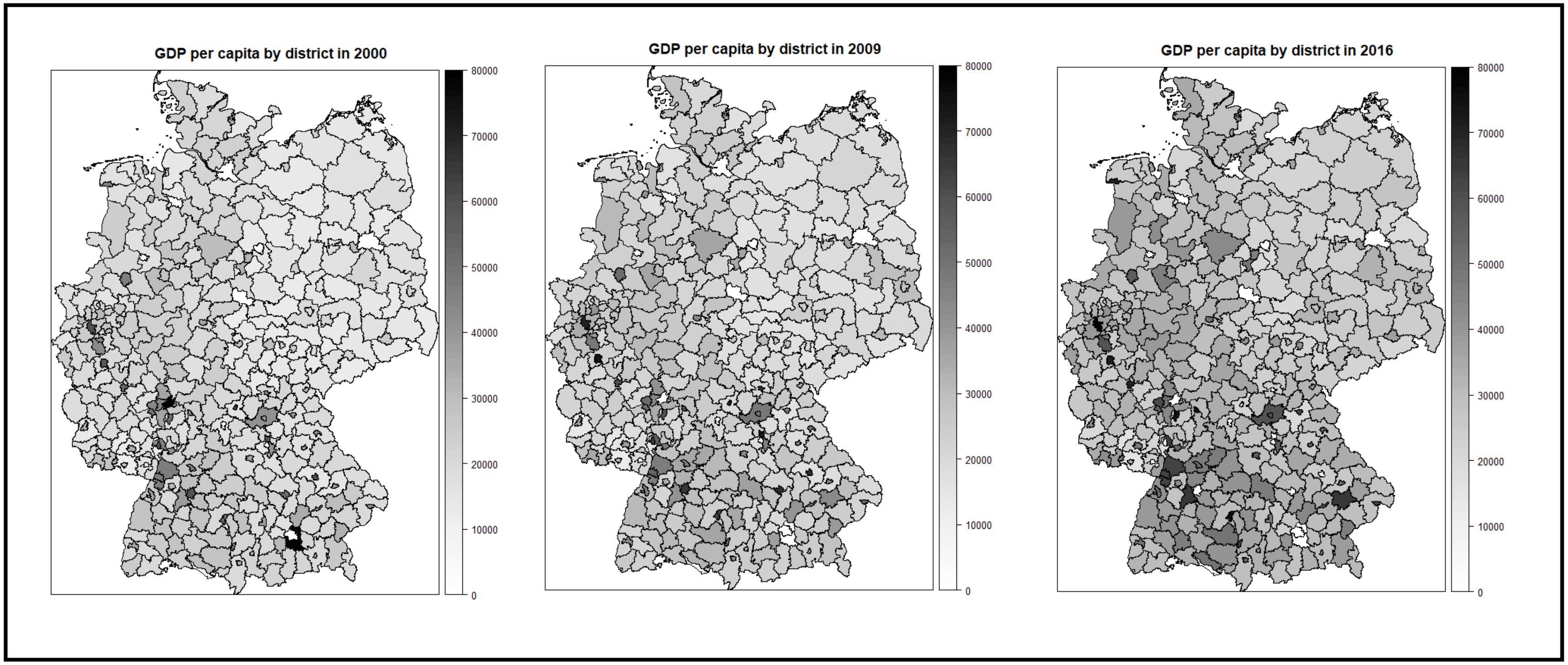
Note: The scales differ between the maps. This is done so regional growth patterns may be observed.

Figure 4. Wind energy capacity in MW by district in 2000, 2009 and 2016



Note: The scales differ between the maps. This is done so regional growth patterns may be observed.

Figure 5. GDP per capita in Euros by district in 2000, 2009 and 2016



Note: The scale up to 80,000 was consciously chosen for clarity. However, there are some districts (notably Frankfurt, Munich and Wolfsburg) that were generally above this over the period. These districts are colored in white.

Figure 6. Jobs per capita by district in 2000, 2009 and 2016

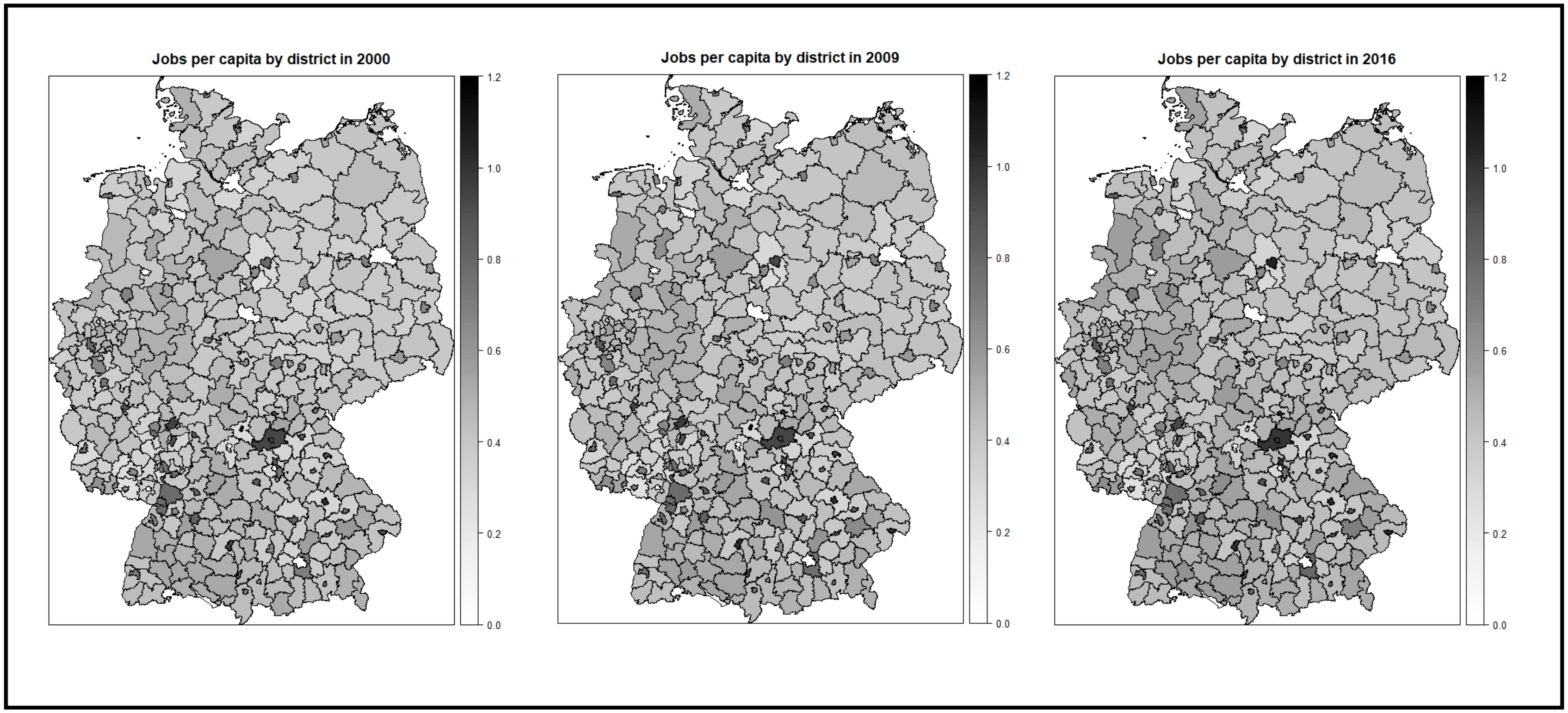
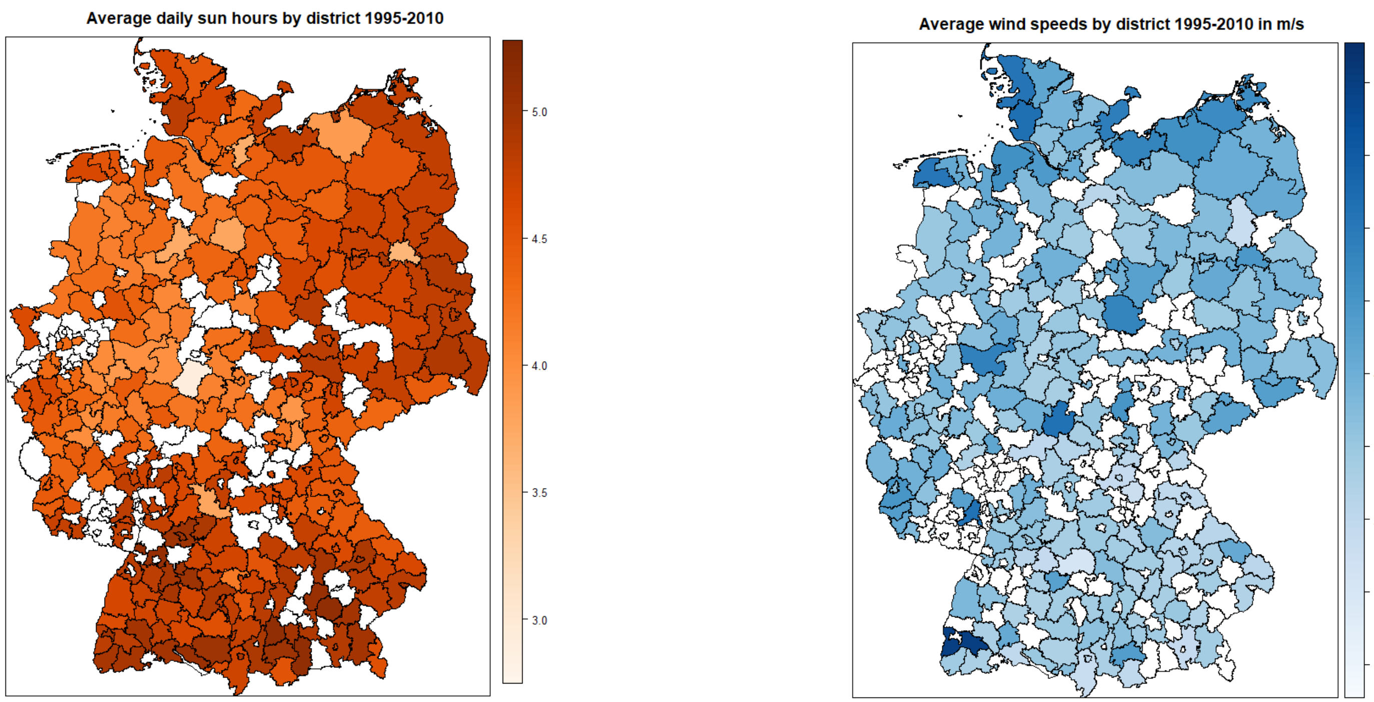
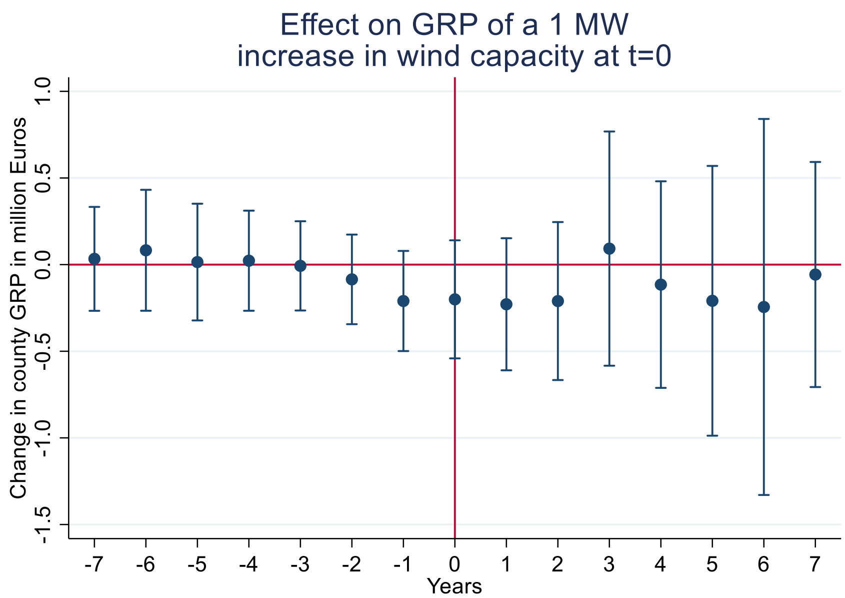


Figure 7. Distribution of average daily sun hours and wind speed by district



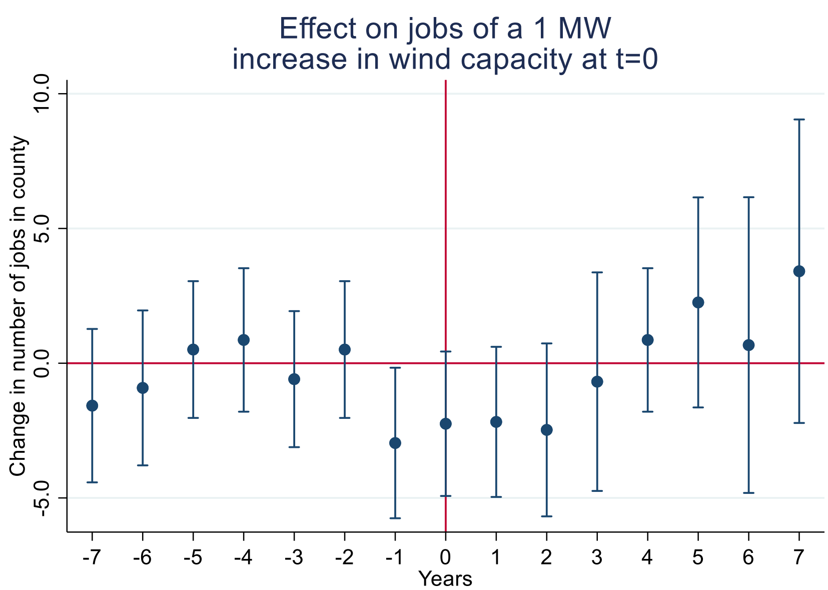
Note: The districts with missing data are colored white in both panes

Figure 8.1. The temporal effects of wind capacity on county GRP.



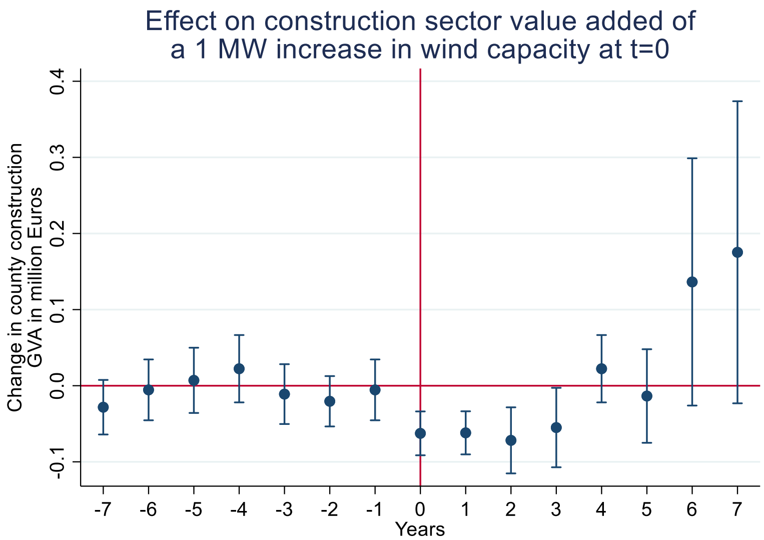
Note: The bars represent 95% confidence intervals.

Figure 8.2. The temporal effects of wind capacity on county jobs.



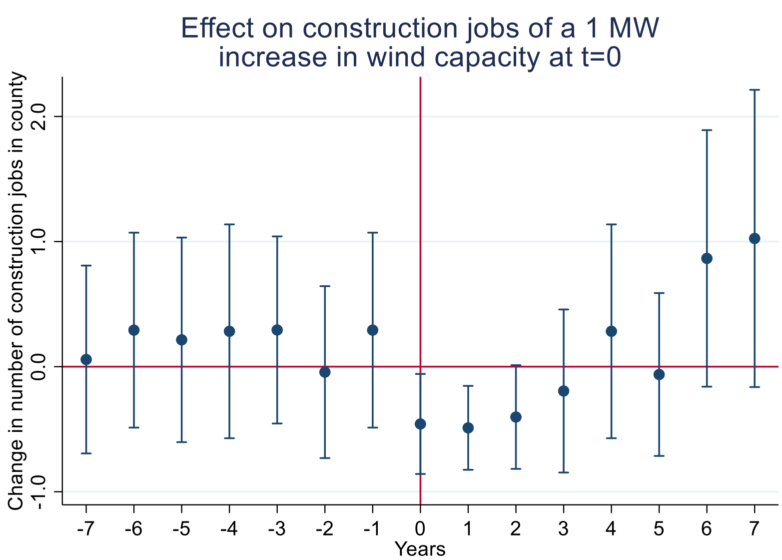
Note: The bars represent 95% confidence intervals.

Figure 8.3. The temporal effects of wind capacity on county construction GVA.



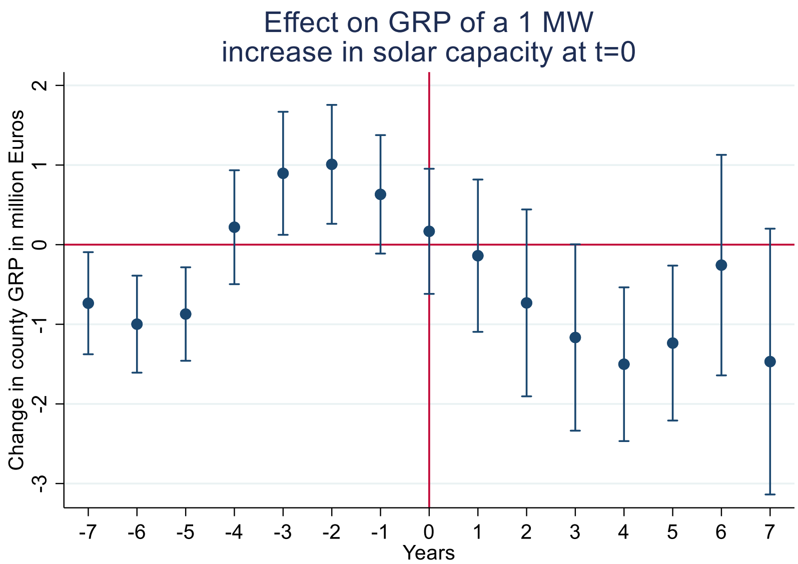
Note: The bars represent 95% confidence intervals.

Figure 8.4. The temporal effects of wind capacity on county construction jobs.



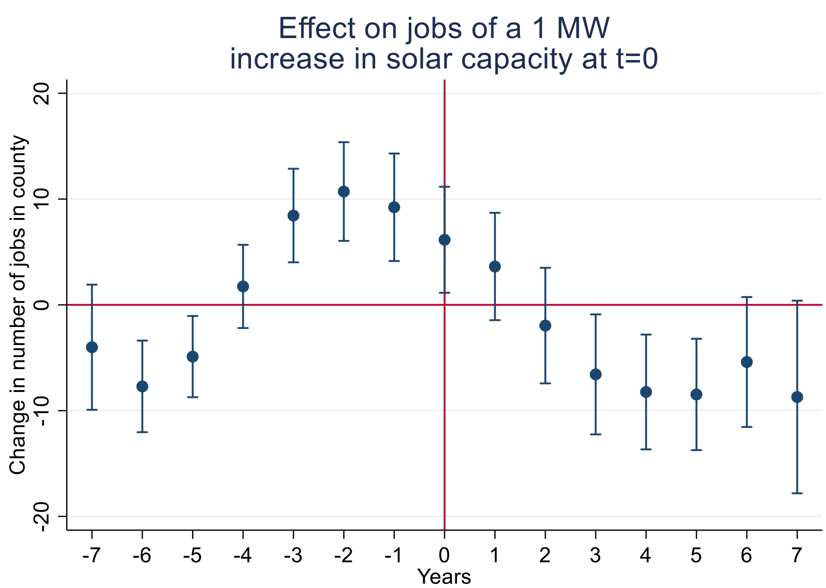
Note: The bars represent 95% confidence intervals.

Figure 9.1: The temporal effects of solar capacity on county GRP.



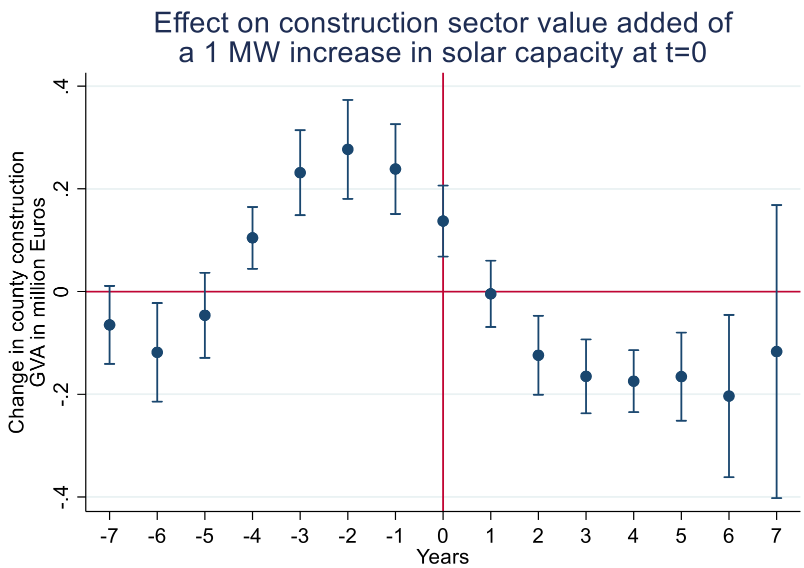
Note: The bars represent 95% confidence intervals.

Figure 9.2: The temporal effects of solar capacity on county jobs.



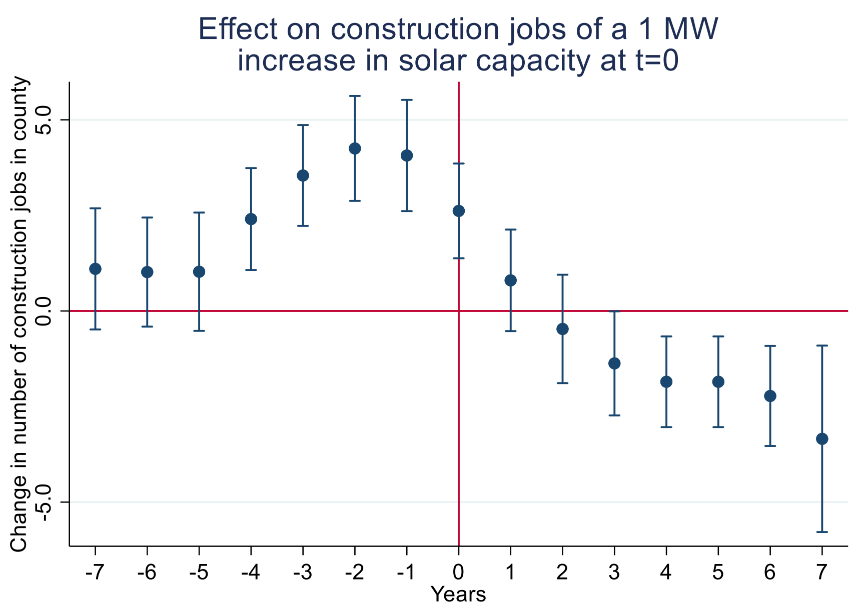
Note: The bars represent 95% confidence intervals.

Figure 9.3: The temporal effects of solar capacity on county construction GVA.



Note: The bars represent 95% confidence intervals.

Figure 9.4: The temporal effects of solar capacity on county construction jobs.



Note: The bars represent 95% confidence intervals.

Appendix 1

Early studies on the economic effects of renewable energy

The scientific debate around the economic effects of renewable energy sources before the turn of the century was characterized by several shifts in focus. The earliest studies concerning the link between renewable energy and the economy originated in the 1970s and early 1980s. Often, these papers aimed to study the potential of renewable energy sources as a means to limit developed countries' reliability on oil from the Middle East. Naturally, then, the units of analysis were often entire countries. Indeed, off the back of the oil crises of the 1970s, several studies into the potential of wind, solar, hydro and bio mass energy were published for individual countries, often under the auspice of their federal government.

Although these studies typically emphasized the need for energy independence from volatile oil-producing countries, they generally found a potential (positive) economic effects of renewable energy through decreasing long-term energy prices. Sørensen (1975), for example, notes that solar power and wind energy could be favorable for long term growth in Denmark, because their resources and equipment are less prone to monopolization (such as by foreign countries) [6]. A study of Canada by Robinson et al. (1983) finds that the country could make a viable transition to 80% renewable energy by 2025 through decreasing the marginal costs of energy production. Johansson and Steen (1977) study Sweden, and find that, although increasing reliance on renewable energy would increase energy prices, this increase would not be significantly higher than those caused by oil price hikes.

Over the course of the following decade, however, the global narrative around renewable energy changed significantly. Whilst reliance on oil imports from the Middle East remained an important concern to countries around the world (as they remain today), the 1980s were characterized by an increase of environmental concerns. Pressure from NGOs, interest groups, scientists and individual

[6] He also notes that renewable energy deployment would lead to immediate job creation due to plant construction, which could help the then-struggling Danish construction sector, which is of particular significance to this thesis.

governments culminated in the Earth Summit of 1992, which saw the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) that represented a strong push for sustainable development. As such, both international and domestic pressure pushed countries around the globe to decrease fossil fuel emissions, especially in Western Europe.

In many countries, governments set up integral approaches to reduce emissions, such as through subsidizing home and office insulation, increasing fuel taxes and setting emission standards for passenger vehicles. Since energy generation was (and remains) a large source of greenhouse gas emissions in many countries, almost everywhere have these integral approaches included a push green energy production. This new narrative towards renewable energy production became mirrored in the academic literature during the 1990s.

During this period, many works focused on the potential growth effects of renewable energy production (often job growth), rather than the feasibility of using renewables as a divestiture away from using oil from volatile countries. Meidav and Pigott (1994), for example, study the projected impact of geothermal energy expansion on the economy and predict that it would create about 700,000 jobs in the United States alone between 1995 and 2010. Løvseth (1995) conducts a similar exercise for Norway and notes that renewable energy (especially wind) would create jobs, especially in areas that otherwise have scarce employment opportunities. Perhaps due to the nature of energy legislation or data availability, these projects again typically focused on larger entities like entire countries or American states.

While these single-case studies are obviously instrumental towards our understanding of the large-scale economic effects of renewable energy (including R&D jobs), they fail to describe local effects of *deployment*. There are two, however, notable papers from this period focused on local effects. Sifford and Beale (1993) find significant short-term employment gains of geothermal energy production development within a single county in Oregon. Similarly, Hanley and Nerin (1999) conduct a case study on the effects of exploitation in a remote community in Scotland and find significant employment effects. However, although the nature of these studies makes them better suitable for making predictions about local economic effects, they fail to establish cross-county correlations which makes it difficult to establish the external validity of these results.