Discussion Paper No. 17-067

Does the Stick Make the Carrot More Attractive? State Mandates and Uptake of Renewable Heating Technologies

Martin Achtnicht, Robert Germeshausen,
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Zentrum für Europäische
Wirtschaftsforschung GmbH

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Abstract

In this paper, we investigate the effect of the state-level renewable heating mandate for existing homes in Baden-Wuerttemberg, Germany's third largest federal state. The mandate requires homeowners to supply at least 10 % of their heat demand with renewable energy when they replace their existing heating system. To assess the impact of the renewable heating standard on the uptake of renewable heating systems, we use unique data on a federal government subsidy scheme and exploit geographic differences in state laws over time. We find no evidence of an effect of the mandate even after restricting distance to the state border and refining the data set through matching on population and building characteristics. These findings are unchanged, when we allow effects to vary across space or over time. While energy efficiency and renewable standards are often criticized for not being cost-effective, our results challenge the widespread view that a standard is nevertheless successful in achieving its policy goal.

Keywords: Technology diffusion; Building regulations; Subsidies; Renewable energy sources.

JEL-Classification: Q4, Q48, O33, Q58, H23

*Leibniz Institute of Ecological Urban and Regional Development (IOER), Weberplatz 1, 01217 Dresden, Germany, Email: m.achtnicht@ioer.de.

†Centre for European Economic Research (ZEW), P.O. Box 10 34 43, 68034 Mannheim, Germany, & University of Münster, Center of Applied Economics Research Münster (CAWM), Am Stadtgraben 9, 48143 Münster, Germany, Email: germeshausen@zew.de.

‡Corresponding author. Centre for European Economic Research (ZEW), P.O. Box 10 34 43, 68034 Mannheim, Germany, Email: vongraevenitz@zew.de.

1 Introduction

This paper studies the effect of a state-level renewable energy heating mandate for the existing residential building stock in Baden-Wuerttemberg, Germany's third largest federal state. The state law mandates a certain minimum amount of renewable energy sources when a heating system is replaced. While such renewable standards at the micro level may be appealing to policymakers, it is an open empirical question how they perform in practice. To assess the impact of Baden-Wuerttemberg's mandate on uptake of renewable heating systems, we use unique data on a federal government subsidy scheme and exploit geographic differences in state laws.

In Germany, as in other developed countries, residential space and water heating is one of the most energy-intensive activities. Space and water heating accounts for 83 % of the energy consumed in German households, representing 22 % of the country's total final energy consumption (BMWi, 2017). Most of the domestic heating comes from natural gas and oil, both associated with the release of carbon dioxide. But the share of renewable heat is steadily growing. In 2015, solar systems, heat pumps, and biomass-fired installations together supplied 16 % of space heating and some 13 % of hot water in residential buildings (AGEB, 2016).

The development of renewable energy sources is often attributed to Germany's energy and climate policy. Germany has embarked on an ambitious energy transition, aiming to decarbonize the economy by 2050. A massive increase in energy efficiency and renewable energy is planned to achieve the necessary reductions in carbon emissions. Primary energy consumption of buildings is targeted to drop by 80 % by 2050, relative to 2008 levels. Progress towards this goal has been made as a reduction of some 16 % was achieved by 2015 (BMWi, 2016). The policy tools employed include a number of different programs aimed at subsidizing investments in energy efficiency and renewable heating through access to cheap credit or direct subsidies in addition to requirements in building regulations. However, it is difficult to evaluate the contribution of a single policy instrument to the adoption of renewable heating technologies because the counterfactual world without the instrument cannot be observed.

In this paper, we make use of differences in state regulations for buildings for identification. Since 2010, the federal state of Baden-Wuerttemberg, located in the southwest of Germany, requires homeowners who replace their existing heating system to supply at least 10 % of their heat demand with renewable energy. No other federal state has such a law in place. There is also a national law mandating renewable energy for heating, but this applies only to new buildings. To estimate the causal effect of the state-level mandate for existing buildings, we follow an approach similar to Holmes (1998) and Keele and Titiunik (2015, 2016). We compare the uptake of renewable heating systems in German municipalities on either side of the Baden-Wuerttemberg border before and after the introduction of the policy. Then municipalities outside Baden-Wuerttemberg act as a control group. This approach enables us to control for unobserved confounding factors that may affect both the state's introduction of environmental regulations and household adoption of green technologies. Natural resources and sunshine hours are just two examples of such potential confounders, which are unlikely to vary significantly across municipalities that are geographically close. To further reduce heterogeneity between treatment and control municipalities, we match on observable characteristics of the population and the building stock.

The analysis is based on data on subsidy applications for the Market Incentive Program (MAP), the second largest government scheme in Germany, combined with demographic and housing data at the municipal level. The program was initiated in late 1999 and is administered by the Federal Office of Economics and Export Control (BAFA). It provides subsidies for investments into heating with renewable energy sources, primarily for households. Since its introduction, the program has funded more than 1.5 million applications (BAFA, 2015). Our data contain information on all granted subsidy applications in the period from 2007 until 2014. As there is no large-scale microdata available on the uptake of renewable heating systems, we use the MAP applications as a measure of uptake. If the renewable standard for existing homes increases the usage of renewable heating technologies in Baden-Wuerttemberg, we should observe a larger increase in subsidy applications there than on the other side of the border.

Our main results show no evidence of a significant effect of the introduction of the state mandate on applications for the MAP. After restricting distance to the border and using matching, we find a small, insignificant effect of around 1 additional application per 1000 eligible buildings. The basic finding does not change after we test for spatially- and time-varying treatment effects in robustness checks. Thus, our empirical results suggest that the stick (renewable energy mandate) does not make the carrot (subsidy scheme) more attractive.

Our paper contributes to the literature on the effectiveness of building regulations to make homes greener. Jacobsen and Kotchen (2013) use monthly utility billing data for households in one Floridian city to evaluate the effect of Florida's building code change in 2002 on energy consumption. They find electricity savings of 4 % and natural gas savings of 6 % per year in homes built after the code change. In a follow-up study, Kotchen (forthcoming) analyzes data over a longer time span and shows that the electricity savings diminish over time while the building code effect on natural gas consumption endures. Levinson (2016) evaluates the energy savings from building energy codes in California. He employs three different approaches using detailed data from California and U.S. households to control for home and occupant characteristics, time trends, and people's self-selection into newer, more efficient houses. His results suggest a significant gap between projected and realized savings. In a recent working paper, Novan et al. (2017) find that houses built just after the adoption of California's building code use 13 % less energy for cooling than similar houses built just before. Their analysis relies on data of hourly household electricity consumption from houses in Sacramento. To our knowledge, we are the first to provide empirical evidence on the impact of building codes requiring renewable heating energy for existing homes. Instead of (fossil) energy savings, we consider the number of renewable installations caused by a state-level mandate. We are also the first to use a border research design in the context of building energy policy.

The paper also contributes to the relatively sparse empirical literature on the determinants of renewable heating adoption. Mills and Schleich (2009), relying on cross-sectional variation from a German survey, find that the adoption of solar thermal systems is more likely in newer houses and in regions with more sunshine hours and less heating degree days. Michelsen and Madlener (2012) use data from a questionnaire distributed to a random sample of MAP subsidy recipients and analyze the choice between oil or gas condensing boilers with solar thermal support, heat pumps, and wood pellet boilers. They show that the determinants differ across owners of new and existing homes and types of heating. And there are a few studies that use stated preference data to investigate what drives homeowners to adopt energy retrofits, including the use of renewable heating (e.g., Scarpa and Willis, 2010; Achtnicht, 2011; Alberini et al., 2013). Exploiting the panel dimension of our revealed preferences data set, we take advantage of the within-municipality over-time variation in the number of granted MAP subsidies to identify the effect of a state mandate on the adoption of renewable heating systems.

The remainder of the paper is organized as follows. Section 2 describes the regulatory background in Germany. Section 3 provides an overview of the data sets used in this study. Section 4 explains our empirical strategy. Section 5 presents the econometric models and results, together with additional robustness checks. Section 6 discusses our findings, and Section 7 concludes.

2 The regulatory background

This paper studies the effect of a state regulation mandating a share of renewable energy in space heating on uptake of renewable heating technologies. The measure of uptake is based on the use of a federal subsidy scheme as no large scale microdata is available on installations of renewable heating technology. This section briefly describes the state mandate and the federal context into which it enters as well as the design of the federal subsidy scheme.

2.1 Residential buildings and building energy regulation in Germany

In Germany, there are 18.5 million residential buildings, and 83 % thereof are single-family and two-family houses (ARGE, 2016). These houses are almost entirely solid buildings with walls made of bricks, concrete blocks, etc. and roofs covered with clay tiles. Building a new house in Germany is very expensive compared to other countries because of the strict building regulation that include energy codes. In response to the 1970s oil crisis, the German government enacted the first ordinance on thermal insulation of buildings in 1977, with the goal of reducing energy consumption. This ordinance was amended twice, in 1984 and 1995. In addition, since 1978, there has been an ordinance that imposed energy efficiency requirements on newly installed and existing heating systems. Both these ordinances were combined and replaced by the Energy Savings Ordinance (EnEV) in 2002. EnEV is still in place and regulates the annual primary energy requirement of newly constructed and renovated buildings that are regularly heated or cooled. Several amendments of EnEV have ratcheted up the energy performance standards for buildings since its introduction.

Roughly two-thirds of Germany's residential buildings were built before 1979, usually not meeting the requirements of the first ordinance on thermal insulation at the time of construction. However, between 1985 and 2013, almost all residential buildings have been partially energy retrofitted. Most energy efficiency measures implemented by homeowners related to heating systems (71 %), windows (51 %), and roofs (44 %). Today, the median energy use intensity of Germany's residential buildings is estimated to be 142 kWh per square meter of useful floor space per year, and 152 kWh for single- and two-family houses only (all figures are from ARGE, 2016).

2.2 State mandate on renewable heating technology

Baden-Wuerttemberg was the first federal state in Germany to introduce a law mandating the use of renewable heating technologies (EWaermeG) referred to hereafter as the "state mandate on renewable heating technology". It entered into force on 1 January 2008. The purpose of the law is to increase the use of renewable energies for heat supply in Baden-Wuerttemberg and to increase deployment of renewable heating technologies. The state of Baden-Wuerttemberg has set a goal that the share of renewable energy in space heating should be 16 % by 2020. The law considers solar energy, geothermal energy, and biomass energy (including biogas and bio-oil) as renewable. Heat pumps utilizing environmental heat (including waste heat) are also considered as renewable if they meet an efficiency standard prescribed by the law. The law applies to all residential buildings with only a few exemptions.[1] New buildings (with planning application from 1 April 2008) are required to supply at least 20 % of the building's annual heat demand with renewable energies. In addition, from 1 January 2010 onwards older buildings where the heating system is replaced (i.e. replacement of the furnace or boiler) are required to supply at least 10 % of their annual heat demand with renewable energies. This paper sets out to assess the impact of the mandate for the existing building stock.

To comply with the law's requirements, homeowners may install (1) a solar system with a collector size of 0.04 m^2 per square meter of living space, (2) a heat pump that supplies the total heat demand of the house (with no more than two dwellings), (3) a heating system that supplies the total heat demand and where 20 % of the required fuel is provided by biogas or bio-oil (10 % in older buildings), or (4) a highly efficient wood (pellets) burning heating system or stove that heats at least 25 % of the living space or has a water heat exchanger. Alternatively, homeowners of new buildings can comply

[1] Residential buildings that are occupied for less than four months over the period 1 October to 30 April, and that have a total living space of less than 50 square meters are exempt from the law.

with the law by exceeding the energy efficiency required by the German Energy Saving Ordinance (EnEV) by 30 %. Similar regulations exist for older buildings and their components, with the required efficiency level decreases with the age of the building. Alternatively, the law allows for the use of a highly efficient micro combined heat and power (CHP) system, local and district heating coming from cogeneration or renewables, or a photovoltaic system if this excludes the use of solar energy for heating purposes. Homeowners can be fined up to 100,000 euro for failing to comply with the law.

One year after the Baden-Wuerttemberg mandate, on 1 January 2009, a federal law on the use of renewable energy for heating (EEWaermeG) entered into force. The federal law aims to increase the share of renewable energy sources in Germany's heating energy consumption to 14 % by 2020. The requirements are very similar to those of Baden-Wuerttemberg's state law. This also includes the use of similar compensating measures such as exceeding the energy efficiency requirements of EnEV and using heat from CHP units. But in contrast to the state law, the federal law applies to all new buildings (i.e. with planning application from 1 January 2009), not only those with residential use, while the existing building stock is not subject to the federal regulation. In consequence only the existing building stock in Baden-Wuerttemberg is subject to a renewable energy mandate when retrofitted.

2.3 The Market Incentive Program

The Market Incentive Program (MAP) was initiated in late 1999 and provides subsidies for investments in heating with renewable energy sources. The goal of the program is to reduce dependence on fossil fuels and lower greenhouse gas emissions. A parallel aim is to increase the rate at which renewable energy sources penetrate the market and to lower the cost associated with their use. Since its inception in 1999, the program has granted subsidies for more than 1.5 million applications (BMWi, 2015).

The program primarily offers subsidies for households but also in a more limited fashion to small businesses and municipal institutions. The main technologies promoted are solar thermal collectors, biomass, and heat pumps. The program has been adapted several times both in terms of technologies promoted, efficiency requirements for the individual technologies, subsidy rates, and in terms of eligibility of applicants. Both existing and newly constructed homes were eligible for subsidies until 2010, after which only owners of homes constructed before 2009 could apply for the investment subsidy. The size of the subsidies varies by technology and scale of the installed capacity. The application procedure currently consists of submitting an application form within 6 months of the initial operation of the heating system. Before 2007, this was a two-stage process with applicants first submitting a funding application before making the investment, and then after installing the technology, submitting a certificate that it had been put to use in order to receive the subsidy. This procedure was simplified to reduce the administrative burden of the application procedure and because many applications were approved in the first stage, but the applicants never submitted documentation that the investment had been carried out.

A time line describing the main changes in the program can be seen in Figure 1. The data available for the analysis begins with the introduction of the new application procedure in 2007 and runs until 2014. Within that period several changes have occurred, in particular with regard to limiting the eligibility to buildings constructed prior to January 2009. There were also several (minor) adjustments in the size of the subsidies, as illustrated in Figure 2.

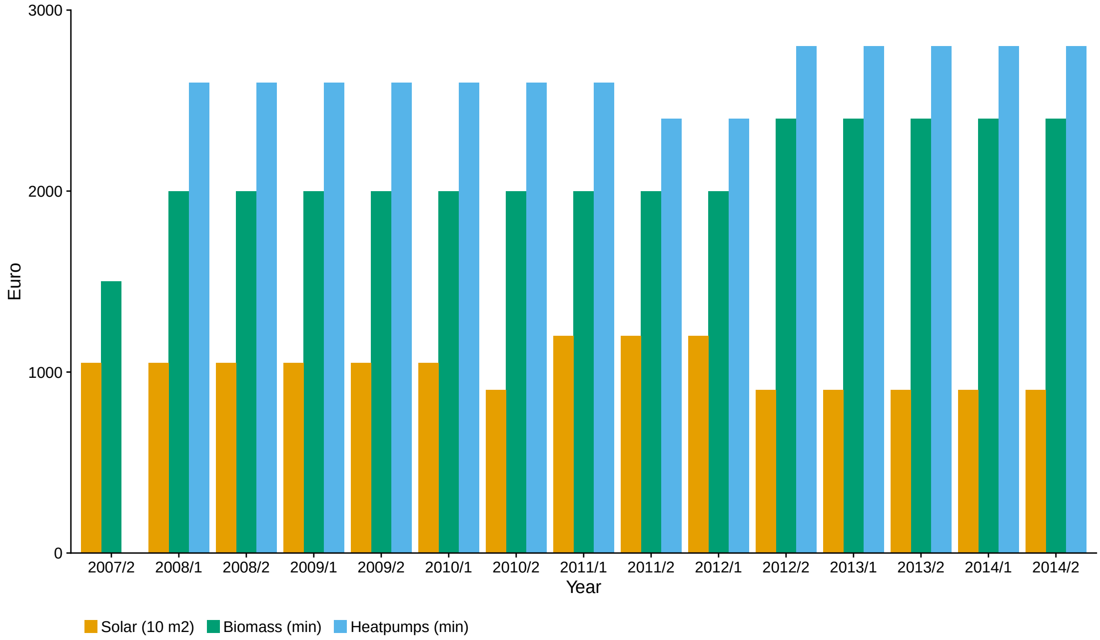
Figure 1: Time line, MAP

1999	Introduction: heat pumps, biomass and solar are eligible
2001	Heat pumps ineligible; subsidies for solar reduced; hand-fed biomass ineligible
2003	Subsidy for solar increased; hand-fed biomass eligible again
2004	Subsidies for solar reduced
2005	All subsidies reduced, Oct 2005: Out of funding
2006	Oct 2006: Out of funding
2007	Application spillover from 2006. From March 2007: Application procedure changes
2008	EWaermeG (new buildings, BW); Heat pumps become eligible; bonus/innovation premia introduced
2009	EEWaermeG (new buildings, federal);
2010	EWaermeG (existing buildings, BW); May: Out of funding; July: New construction ineligible
2011	Solar subsidy is increased until end of 2011
2012	Change in subsidy size
2014	

Data available (2007-2014)
Regulation effective

Notes: Based on evaluations of the MAP over the years.

Figure 2: Subsidies by technology, examples



Notes: Based on subsidy guidelines for the MAP over the years. The examples are calculated for a solar thermal collector of 10 sqm providing both hot water and heating. For the biomass example, the subsidy was the minimum paid for a pellet furnace, and for the heat pumps the example concerns minimum payment for a brine-to-water or water-to-water pump for an existing building with one residential unit of size 130 sqm and a heat pump with less than 10 kW capacity.

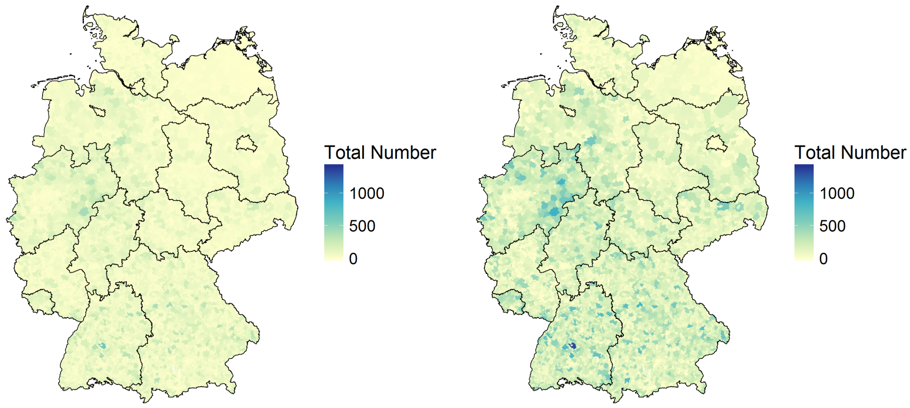
3 Data

We use a variety of data sources in the analysis. The main source is the data on the subsidy applications for the MAP. We complement this data set with information from the German Building Census and the INKAR data set describing the sociodemographic characteristics of German municipalities.

3.1 MAP subsidy applications

The main data set covers the population of granted subsidy applications for the Market Incentive Programme (MAP) in the period from 2007 until 2014. It contains information on the individual installation in terms of the type of technology, the size of the installation, whether a bonus was given for a particularly energy efficient home. It contains less information on the recipient, where only the type (household, community service (e.g. school, church, etc.), small business, or other) and the postal code where the installation is located is consistently recorded. There is substantial variation across space in the uptake of the MAP as can be seen in Figure 3. Until 2013 solar thermal collectors consistently made up the vast majority of the installations funded through the MAP. The number of biomass installations has been steadily increasing over time and became the most commonly funded technology in 2013 consistent with the relative and absolute decline in the size of grants offered for solar thermal collectors in late 2012.

Figure 3: Installations with MAP subsidies, 2008 (left) and 2014 (right)



Notes: Based on own computations. The map on the left shows the cumulative occurrence of subsidized installations at the postal code level in 2008. The map on the right shows the same information 6 years later in 2014. The darker areas are areas with more occurrences.

To what extent are MAP applications representative of the overall investment activity in renewable heating technologies? Aggregate data on total installations erected per year have been compared with the number of funded installations in evaluation reports on the MAP on a regular basis. In 2007 and 2008 this comparison reveals that more than three quarters of the new biomass, heat pump, and solar thermal installations were supported by the MAP (Langniß et al., 2010). After the program changed so that only installations in buildings constructed prior to 2009 were eligible for funding, this figure dropped by two thirds to around 20 to 25 % of all installations for the period from 2011 to 2013 (Stuible et al., 2014). The change in eligibility also coincides with a persistent decline of 75 % in the total number of funded MAP applications between 2009 and 2010 suggesting that a significant part of the installations funded in the past were installed in connection with construction of new homes. It therefore seems likely that the coverage of the MAP data for installations in the building stock constructed before 2009 remains high.

We aggregated the data to the municipal level based on the municipality codes, which we received by merging the postal code in the MAP data with a list of yearly assignments of postal codes to municipality codes from Acxiom.

3.2 German Building Census of 2011

The German building census provides a snapshot of the key characteristics of the building stock by use, year of construction, ownership rates, occupancy, etc. on the 9th of May 2011. All buildings used (in part) for residential purposes were included in the census and it therefore provides a fairly accurate picture of the structure of residential buildings in municipalities in the time period of our study.[2]

3.3 INKAR

The German Federal Institute for Research on Building, Urban Affairs and Spatial Development provides a data base of indicators on sociodemographic characteristics available for download from *www.inkar.de* (Indicators and maps of spatial and urban development). This data consists of time series on a wide variety of indicators, e.g. unemployment, tax revenues, age distribution of the population, type of housing, etc. The finest spatial scale at which the information is available is at the level of the 4,567 municipalities or municipal associations (Gemeindeverbände). We assigned the data to the municipal level based on an identifier assigning individual municipalities to municipal associations.

3.4 Shapefiles

We use shapefiles for the spatial analysis provided by the Service Centre of the Federal Government for Geo-Information and Geodesy (DLZ) and the Central Office for Geo-Topography (ZSGT) of the federal states. These shape files can be downloaded from *www.geodatenzentrum.de* and also contain information on the population in municipalities. Based on the size of the municipality, we calculated population density measures. Furthermore, for illustration purposes (see e.g. Figure 3) we used the freely available postal code shapefile from *www.suche-postleitzahl.org*, which compiles data from Open Streetmap.

4 Empirical strategy

There are several challenges to identification in our context and given the data available to us. Specifically, the change in eligibility requirements for the subsidy scheme coincides with the introduction of the state regulation on renewable energy in space heating. Another concern arises from the existence of other factors, that might simultaneously drive the decision to adopt stringent environmental regulation at the political level and investment decisions at the household level. We discuss each of these in turn in this section.

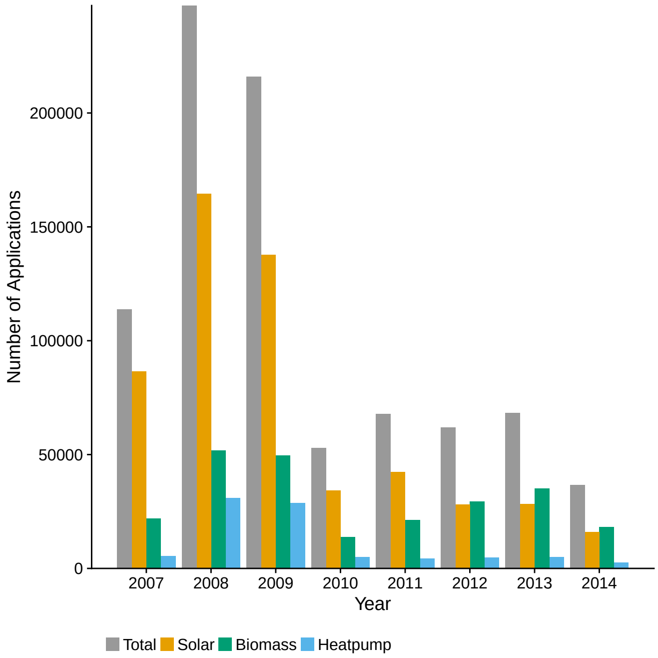
4.1 Change in the Market Incentive Program

After the introduction of the federal law mandating use of renewable energy sources in heating for new construction (new buildings with a heating system first installed after 1. January 2009), it was decided in 2010 to remove the subsidies for renewable heating

[2]The previous building census took place in 1987. We made no attempt to interpolate values between the two waves, nor to use the prior wave for our analysis as this would be likely to be noisier in terms of describing the period 2007-2014 than simply using the most recent wave.

technologies for this category of homes. As a result, uptake of the MAP dropped substantially between 2009 and 2010, as shown in Figure 4.[3] Unfortunately, the data contained in the MAP applications does not include information on the age of the building in which an installation is made for the years prior to the change in eligibility. Nevertheless, the figure suggests that a substantial share of subsidies went to newly constructed homes prior to the change.

Figure 4: Number of granted applications per year, 2007-2014



Notes: Based on own computations. The figure shows the number of granted applications per year in total and for each of the three technologies individually: Solar thermal collectors, biomass and heat pumps.

The change in eligibility was the same across all German states. The impact on uptake of the MAP, however, is likely to vary across states and municipalities due to differences in the housing structure and construction activities. To account for this, we construct our outcome variable as the number of granted subsidies *per eligible building* in a municipality. The number of eligible buildings is constructed based on the building census data, which fortunately counts the number of buildings constructed in different time periods including the period "2009 or later".[4] Nevertheless, it remains important to control for differences in building structure as the propensity to apply for a subsidy and the retrofitting rate is likely to differ across building vintages.

[3] In addition, there was a period of several months before July 2010 during which no applications were approved as the MAP was temporarily out of funding. This explains the decline in 2010 relative to the following years.

[4] To obtain year specific numbers of new buildings, we assumed a uniform distribution of construction years within each time category.

4.2 Geographic identification of treatment effects

There are a number of factors which may simultaneously drive the decision to adopt ambitious environmental regulation at the state level and the decision to invest in renewable energy technologies at the household level and thereby affect the trend in uptake of renewable heating technologies. At least three possible sources of correlation between investment in renewable technologies and environmentally ambitious building regulations come to mind.

First, political beliefs may induce households to vote for an environmentally ambitious government and simultaneously drive private investments in renewable technology. This would lead to correlation in investments and regulation without the former being driven by the latter in a causal sense. A second explanation for correlation between regulation and investments relates to the natural resources available: It could be the case that the location and landscape of Baden-Wuerttemberg makes it relatively cheap to use renewable energy, e.g. through the number of sunshine hours or easy availability of biomass. When renewable energy sources are cheap, it also becomes more likely that regulation is imposed as the cost of such regulation is low. Such a scenario would again make the adoption of regulation and investments in renewable energy sources correlated without the existence of a causal relationship. Finally, a similar argument arises from potential learning-by-doing effects among the skilled workers who install heating systems. The environmentally friendly attitudes in the state may lead to increased knowledge and experience with renewable heating technologies (and related funding schemes) among skilled workers. In the presence of learning-by-doing effects this would imply lower costs of installing renewable heating systems in Baden-Wuerttemberg and hence lower costs of introducing the state level regulation.

Our research design builds on ideas pioneered by Holmes (1998) and discussed in detail by Keele and Titiunik (2015, 2016). It accounts for these threats to identification by limiting the analysis to municipalities close to the state border and excluding municipalities further away. We thus base the analysis on the geographic differences in regulations between the state of Baden-Wuerttemberg and the three neighboring states: the Rhineland-Palatinate, Hesse, and Bavaria. In our research design we treat the differences in regulation as being "random" in the sense that the border location is exogenous to the households in the municipalities. This implies that households have not sorted across the border in response to the introduction of the state level regulation. This assumption allows us to use municipalities on the other side of the state border as controls and compare outcomes in treated municipalities, i.e. those located within Baden-Wuerttemberg, with municipalities outside.

Specifically, we limit the analysis to the subsample of municipalities within 25 and 50 km of the state border as shown in Figure 5. By comparing treatment and control municipalities that are close to each other in space, we effectively control for observable and unobservable characteristics driving correlations between investment in renewable technologies and regulation such as those described above. For municipalities close to each other in space, the pool of skilled workers available is not likely to vary discreetly at the border. Neither are the natural resources or the sunshine hours. In addition to relying on proximity to the federal state border to control for (un)observable differences, we refine our research design by also using matching on observable characteristics. Following the potential outcomes framework by Rubin (1974), our research design relies on the assumption of "Conditional Local Geographic Treatment Ignorability", as specified by Keele and Titiunik (2016), which formally states that:

$$Y_{i1}, Y_{i0} \perp\!\!\!\perp T_i | X_i, d_i < D,$$

i.e. the potential outcomes of individual i (Y_{i1} with treatment and Y_{i0} without) are independent of treatment T_i conditional on predetermined or pre-treatment covariates X_i and on being in close neighborhood to the border, with d_i being the (shortest) distance to the border and D a specified maximum distance to the border (in our case 25 or 50 km).

4.3 Matching on observables

We use genetic matching as developed by Diamond and Sekhon (2013) to match our treatment and control municipalities.[5] We match on municipality characteristics in 2008 including the share of single- and two-family homes, income tax revenues, unemployment levels, and share of population aged 65 and older from the INKAR data base. In addition, we also use information on share of owner-occupied homes and the age structure of buildings from the building census data. Although this census is available only for 2011, i.e. after the state law came into effect, the share of owner-occupied housing is unlikely to change substantially over such a short period of time and the year of construction for buildings is given. Finally, we include information on population density at the municipal level. The genetic matching algorithm combines propensity score matching and Mahalanobis matching. We estimate a propensity score using a generalized additive model with a logistic distribution to allow sufficient flexibility in the functional form.[6] More information about the propensity score estimation can be found in the appendix along with the QQ-plots comparing treatment and control municipalities along the observable dimensions. To strengthen our border research design, we match exactly on border segments to ensure that control and treatment units are not too far apart in terms of geography. To this purpose we divide the border into three segments as defined by the neighboring states and assign each municipality to the nearest border segment.

We match 1:1 with replacement and enhance balance in observable characteristics between the treated and control municipalities by using a caliper of 1.5. This results in the loss of a number of treated municipalities as there were no good matches available

[5] We use the implementation in the MatchIt software package for R.

[6] The longitude and latitude of the municipality centroids do not enter the propensity score, but we do include them in the matching algorithm in an attempt to reduce geographic distance between treated and control municipalities.

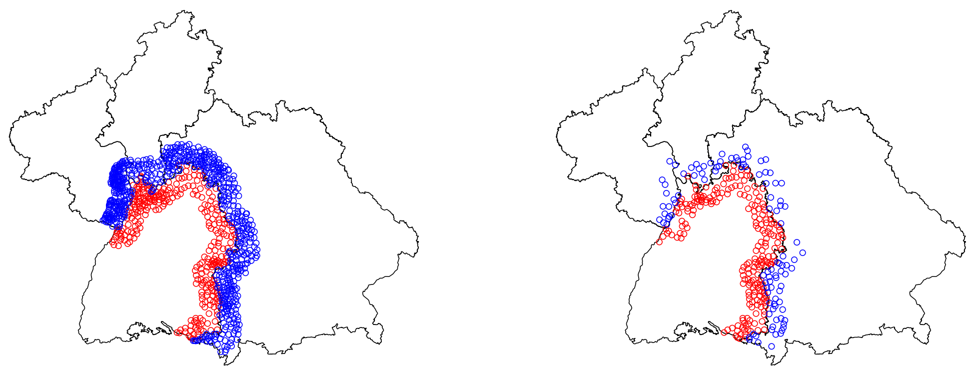
among the potential control municipalities. In particular, some of the more urbanized municipalities in northern Baden-Wuerttemberg are dropped. Table 1 shows the number of observations in each data set with and without matching.

Table 1: Number of observations in the treatment and control group

Design	25 km		50 km		All four states	
	Control	Treated	Control	Treated	Control	Treated
All	620	311	1,223	621	4,758	1,101
Matched	104	225	187	496	277	890
Unmatched	516	86	1,036	125	4,481	211

Notes: The table shows the number of municipalities in treatment and control group and the outcome of matching in the two border designs: 25 km from the border or 50 km from the border or all municipalities. Additionally we show the details of the sample using all municipalities in the 4 states sharing the border.

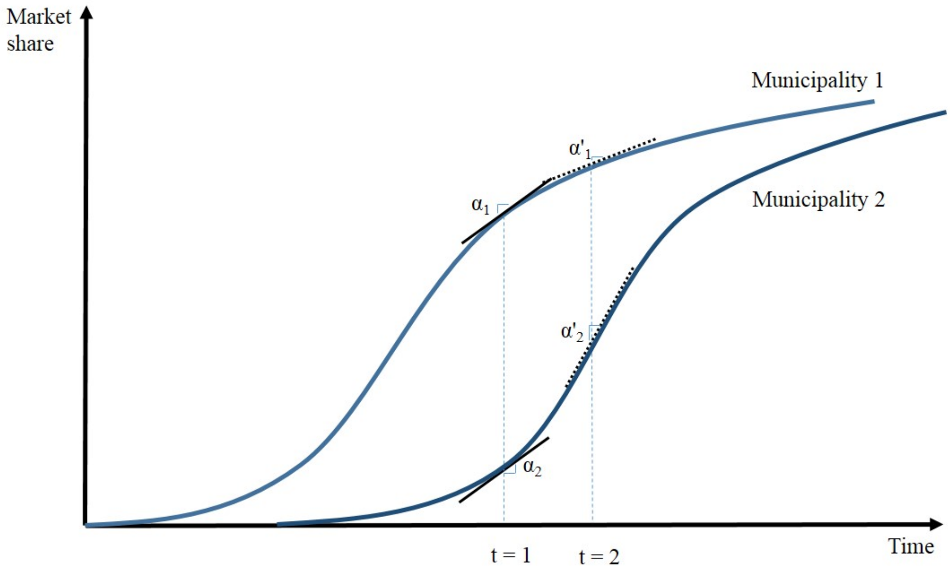
Figure 5: Treatment and control municipalities within 25 km of the border, unmatched (left) and matched (right)



Notes: Based on own computations. The figure shows the treatment municipalities in Baden-Wuerttemberg (*red*) and the control municipalities in the other three states (*blue*) within 25 km of the border. On the left hand side, all municipalities within 25 km are shown. On the right hand side, the matched treatment and control municipalities are shown.

Typically, difference-in-differences applications do not have to worry too much about matching the levels of pre-treatment outcomes. The primary focus therefore lies on common pre-treatment trends in the treatment and control groups to support the assumption that trends would continue to be parallel in the future in the absence of treatment. However, as we are examining the diffusion of new technology, common trends prior to treatment are not sufficient to predict common future trends in the absence of treatment. This is due to the S-curve which typically characterizes such diffusion processes (see e.g. Griliches, 1957, Geroski, 2000, Young, 2009) and is depicted in Figure 6. The figure shows how two municipalities at different points on the S-curve may have parallel trends at a moment in time, but very different trends in the future due to the state of their relative diffusion processes. The ideal comparison is therefore between a treatment and control unit which are at the same point on the S-curve prior to treatment.

Figure 6: The S-curve and the common trends assumption



Notes: The S-curve describes the rate of adoption of the new technology. Two municipalities, 1 and 2, each have their own S-curve. Municipality 1 is further along in the diffusion process than municipality 2. At time t = 1, the adoption rate (the slope) is the same across municipalities, i.e. $\alpha_{1,t=1} = \alpha_{2,t=1}$, but the expected future slope varies considerably between the two municipalities: $\alpha'_2 > \alpha'_1$.

Our research design goes a long way towards reducing the heterogeneity in the data. Table 2 shows the distribution of the *cumulative* number of applications per 100 eligible buildings for the years 2007-2009 before the state regulation was introduced. We pool applications across technologies as they are substitutes for the purpose of the analysis. The first two rows describe Baden-Wuerttemberg as compared to the rest of Germany. As we move down in the table, the comparison becomes more narrow. The second group described is Baden-Wuerttemberg in comparison to the three neighboring states. The third group narrows the comparison to municipalities within 50 km of the shared border and the final group describes municipalities within 25 km of the border. The final two rows in the three last categories describe the matched data sets. Comparing municipalities in Baden-Wuerttemberg to those in all other states clearly shows that diffusion is more advanced in Baden-Wuerttemberg with higher number of granted applications across the entire distribution. As we narrow the comparison to municipalities closer to the border these differences decline. Nevertheless, the 10th and 25th quantile of municipalities in Baden-Wuerttemberg consistently have more granted applications than their counterparts on the other side of the border. With matching on observables these differences decline and the distributions are much more similar.

Table 3 is structured similarly to Table 2 but shows the average number of granted applications *per year* for the pre-treatment period from 2007 to 2009. It is again clear that municipalities in Baden-Wuerttemberg submitted more successful applications per year for funding than municipalities in most other German states. The 10th percentile across all municipalities in Baden-Wuerttemberg is 0.6 granted applications per 100 eligible buildings whereas even the 25th percentile in the rest of Germany as well as in the neighboring states is zero. Reducing the distance band around the border again goes some way towards reducing this heterogeneity. Once we introduce matching, the heterogeneity in annual applications before treatment is further reduced and annual applications granted are very similar across treatment and control municipalities.

Table 2: Distribution of granted applications (cumulated), 2007-2009

Group	N	Mean	SD	p10	p25	p50	p75	p90
Treated all	1,103	2.028	0.958	1.623	2.471	3.338	4.133	5.117
Control all	10,227	1.034	1.522	0.000	0.000	0.843	2.976	5.084
Treated all (Border)	1,103	2.028	0.958	1.623	2.471	3.338	4.133	5.117
Control all (Border)	4,974	1.505	1.858	0.000	0.000	2.258	4.464	6.186
Treated - Matched (Border)	890	2.118	0.913	1.868	2.662	3.425	4.193	5.145
Control - Matched (Border)	889	1.964	1.070	1.235	2.064	3.062	4.756	6.288
Treated (50 km)	622	1.967	0.960	1.424	2.451	3.295	4.131	5.011
Control (50 km)	1,279	1.786	1.682	0.000	0.000	2.901	4.814	6.416
Treated - Matched (50 km)	496	2.071	0.870	1.948	2.659	3.429	4.286	5.083
Control - Matched (50 km)	497	2.051	1.193	1.812	2.502	3.223	4.756	6.295
Treated (25 km)	311	1.951	0.924	1.413	2.391	3.249	4.155	5.023
Control (25 km)	644	1.742	1.608	0.000	0.000	0.548	2.318	4.589
Treated - Matched (25 km)	225	2.134	0.876	2.006	2.724	3.514	4.367	5.125
Control - Matched (25 km)	225	2.093	0.953	2.014	2.486	3.678	4.984	6.116

Notes: Based on own computations. The table shows the distribution of the cumulative number of granted funding applications per 100 eligible buildings in the municipality for different subsets of the data. The first two rows show the complete data set. The next 4 rows describe the data set limited to the state of Baden-Wuerttemberg and its three direct neighbors ("border"). The following 4 rows describe the data set limited to municipalities within 50 km on both sides of the state border. Finally, the last 4 rows describe the data set reduced to municipalities within 25 km on both sides of the state border. For the matched data sets the observations are weighted appropriately as we use matching with replacement.

Turning to examine the age distribution of the buildings in the control and treatment municipalities, matching again seems to improve the similarity across the two groups. Figure 7 shows the construction years of the buildings in treatment and control municipalities in the 25 km border design.[7] Slight discrepancies remain in the sense that the treated municipalities have a slightly older building stock. To the extent that older buildings are more likely to be retrofitted with a new heating installation, this difference could make it more likely that we find a positive impact on the uptake when the state mandate is introduced.

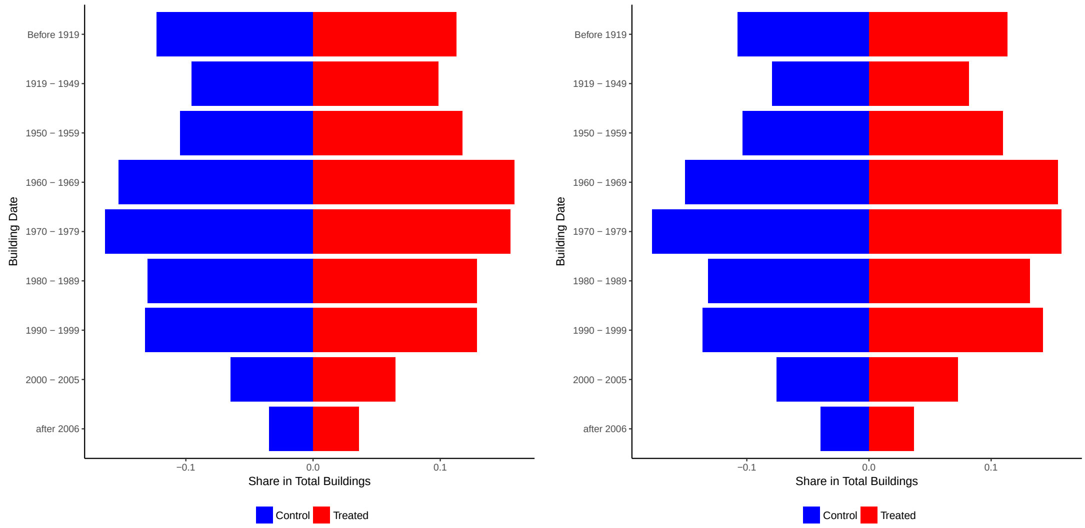
[7] For illustration purposes and as an additional robustness check, the categories presented in Figure 7 differ from those categories that we have used in the matching procedure. Balance on the categories used for matching is shown in the QQ-Plots in the appendix.

Table 3: Distribution of granted applications annually, 2007-2009

Group	N	Mean	SD	p10	p25	p50	p75	p90
Treated all	1,103	1.788	1.001	0.617	1.091	1.688	2.408	3.043
Control all	10,227	0.960	1.509	0.000	0.000	0.345	1.478	2.734
Treated all (Border)	1,103	1.788	1.001	0.617	1.091	1.688	2.408	3.043
Control all (Border)	4,974	1.414	1.866	0.000	0.000	0.994	2.225	3.466
Treated - Matched (Border)	890	1.106	0.909	0.218	0.446	0.832	1.547	2.452
Control - Matched (Border)	889	1.033	1.079	0.068	0.262	0.642	1.539	2.412
Treated (50 km)	622	1.747	0.990	0.553	1.056	1.671	2.368	3.017
Control (50 km)	1,279	1.672	1.701	0.000	0.000	1.413	2.493	3.693
Treated - Matched (50 km)	496	1.084	0.888	0.222	0.438	0.811	1.529	2.407
Control - Matched (50 km)	497	1.104	1.128	0.149	0.328	0.741	1.588	2.438
Treated (25 km)	311	1.746	0.965	0.629	1.0419	1.644	2.340	3.039
Control (25 km)	644	1.742	1.608	0.000	0.607	1.506	2.508	3.603
Treated - Matched (25 km)	225	1.112	0.908	0.234	0.443	0.814	1.580	2.477
Control - Matched (25 km)	225	1.138	1.039	0.196	0.376	0.781	1.606	2.560

Notes: Based on own computations. The table shows the distribution of the average annual number of granted funding applications per 100 eligible buildings in the municipality for different subsets of the data. The first two rows show the complete data set. The next 4 rows describe the data set limited to the state of Baden-Wuerttemberg and its three direct neighbors ("border"). The following 4 rows describe the data set limited to municipalities within 50 km on both sides of the state border. Finally, the last 4 rows describe the data set reduced to municipalities within 25 km on both sides of the state border. For the matched data sets the observations are weighted appropriately as we use matching with replacement.

Figure 7: Building vintages: Treatment and control municipalities within 25 km of the border



Notes: Based on own computations. The figure shows the building vintage in the treatment municipalities in Baden-Wuerttemberg (*red*) and the control municipalities in the other three states (*blue*) within 25 km of the border. On the left hand side, the distribution is shown for all municipalities within 25 km of the border. On the right hand side, distribution for the matched treatment and control municipalities are shown where the latter are weighted using the weights from the matching procedure.

5 Econometric model and results

We estimate a difference-in-differences model. Our model relates the annual number of granted applications per eligible building, y_{ijt}, to the introduction of the state law, T_{it}, and includes municipality level fixed effects, μ_i, time fixed effects, δ_t, and an error term clustered at the 25 km border segment level, ϵ_{ij}, to account for spatial and time correlation in the error term:

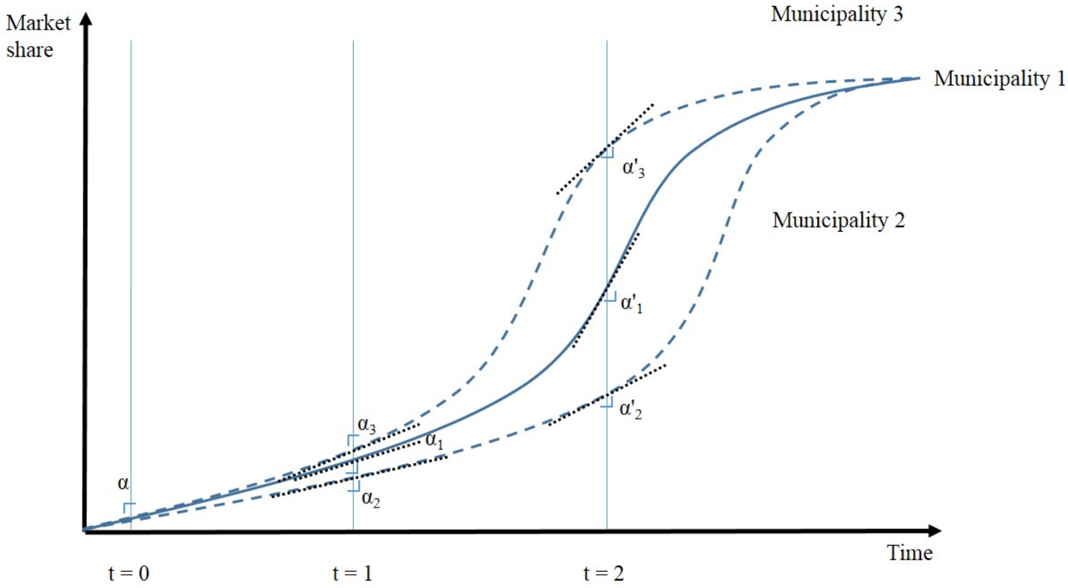
$$y_{ijt} = \beta\, T_{it} + \mu_i + \delta_t + \epsilon_{ijt}$$

Identification relies on the variation over time within municipalities. Any remaining confounding factors would need to change over time and affect households on the Baden-Wuerttemberg side of the border differently than households on the other side of the border in the three neighboring states.

As our dependent variable is the annual number of granted applications per eligible building in a municipality, the treatment effect estimated in β is the change in the slope of the S-curve for the municipality. With the standard assumption that the diffusion of technology follows the S-curve, it becomes clear that expected treatment effects could evolve both positively and negatively over time depending on the location of the individual municipality on its S-curve, as illustrated in Figure 8. For municipalities to the right of the point at which their S-curve becomes concave, the change in slope over time as the number of installations increases is negative. For municipalities on the convex part of the S-curve to the left, the slope is increasing over time. The reasoning behind the existence of the market incentive program and the mandate in renewable energies is consistent with an expectation that most if not all municipalities are currently on the convex part of the S-curve where market penetration is still very low. Both the state mandate on renewable energy technology in heating and the federal subsidy scheme aim to increase penetration of renewable technologies. As a result, we would expect a positive treatment effect when the mandate is introduced and a positive evolution over time consistent with a location on the lower, convex part of the S-curve.

Table 4 presents the results of our main regression for each of the border designs and, for comparison, the analysis based on all municipalities in the four states sharing the border. While the point estimates are mostly positive suggesting a small effect of 1 additional application per 1000 eligible buildings, they are insignificant. The only exception is the negative and significant coefficient recovered in the 5th column for the unmatched data including municipalities far from the common border. This estimate suffers from all the problems outlined above as we justify our refined border research design. The preferred results thereby consistently show no evidence of a significant effect of the introduction of the state mandate on applications for the MAP. The R^2 is generally fairly high suggesting that the model does a fair job of explaining the variation in the data.

Figure 8: The S-curve and the effect of the EWaermeG



Notes: The S-curve describes the rate of adoption of the new technology. Three municipalities (1, 2 and 3) are originally following the same S-curve and are located at time t = 0 at the same point on this curve. At time t = 1, the EWaermeG is introduced for municipalities 2 and 3. It is assumed that Municipality 2 is negatively and Municipality 3 is positively affected by the introduction of the state mandate. Thus, the adoption rate (the slope) of Municipality 3 is larger than and for Municipality 2 lower than the slope for Municipality 1 that lies outside of Baden-Wuerttemberg (control municipality), i.e. $\alpha_{3,t=1} > \alpha_{1,t=1} > \alpha_{2,t=1}$. However, this figure also illustrates the importance of comparisons over time as the initial positive effect can reverse over time, e.g. $\alpha_{3,t=2} < \alpha_{1,t=2}$.

5.1 Robustness checks

As illustrated in Figure 8 we would expect effects to differ over time given the shape of the S-curve. Therefore, we investigate whether treatment effects change over time by interacting the treatment variable with year indicators after 2010. The results are summarized in Table 5. The results are consistent with the time averaged treatment effects and in most cases, we do not find statistically significant treatment effect.

Treatment identification based on geographic differences in regulation is vulnerable to the existence of compound treatments when other factors vary discreetly at the border and over time, given that we are able to eliminate time constant differences in our difference-in-differences model. This concern is particularly warranted when the border is administrative such as is the case here. To assess this issue, we follow Keele and Titiunik (2015, 2016) and use a geographic discontinuity design to estimate local treatment effects at points along the border based on kernel estimation.[8] In the presence of compound treatment effects, heterogeneity along the border could provide hints as to what other factors might be at play.

For the estimation of local treatment effects we first define 21 points along the border at intervals of 50 km. We then for each point define the relevant neighbors as being

[8] We use the R package "rdrobust" developed by Calonico, Cattaneo and Titiunik (2015) for the analysis.

Table 4: Results, average treatment effects on the treated

	25 km		50 km		All four states	
	Unmatched	Matched	Unmatched	Matched	Unmatched	Matched
Treatment	0.0003	0.0011	−0.0001	0.0015	−0.0020***	0.0012
	(0.0006)	(0.0007)	(0.0004)	(0.0009)	(0.0003)	(0.0013)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7,456	2,632	14,784	5,464	47,096	9,336
R^2	0.478	0.758	0.432	0.749	0.295	0.745

Notes: The table shows the results of the main regression for two versions of the border design (25 km, 50 km) and all municipalities in the four states. For each data set we carried out the analysis for the unmatched and the matched data sets. The regressions based on the matched data sets use weights as matching was done with replacement. The standard errors (in parenthesis) are clustered in groups defined by 25 km segments of the border.

those neighbors within 50 km of the point. In order to have enough observations for the analysis of each point based on kernel estimation, it was not feasible to carry out the local analysis with the matched data set.[9] We reformulate our estimating equation in terms of first differences and collapse the data into pre- and post-treatment periods to facilitate estimation using kernel regression while still accounting for municipality fixed effects:

$$y_{ik,post} - y_{ik,pre} = \beta_k T_{i,post} + \delta_k + e_{ik},$$

where $T_{i,post}$ is a binary variable that is equal to one for municipalities in Baden-Wuerttemberg, and δ_k is a border point fixed effect that allows for different time trends along the border points.

The results are shown in Table 6. We report the p-values based on the robust bias-corrected standard errors adjusted due to multiple hypothesis testing by using the Bonferroni correction and the false discovery rate (FDR), respectively. While the point estimates vary somewhat along the border, they are in no case significantly different from zero at the conventional level, though two points (3, 18) come close. In other words, the robustness check does not contradict our main findings that the state mandate had no significant impact on applications for the market incentive program.

[9] In setting the bandwidth to 50 km we are effectively undersmoothing as the datadriven bandwidth choice would have set a higher bandwidth in all but four of the cases examined.

Table 5: Results, average treatment effects on the treated over time

	25 km		50 km		All four states	
	Unmatched	Matched	Unmatched	Matched	Unmatched	Matched
Treatment	0.0002	0.0010	−0.0002	0.0009	−0.0019***	0.0006
	(0.0006)	(0.0009)	(0.0005)	(0.0010)	(0.0003)	(0.0013)
Treat. x 2011	−0.0002	−0.0003	−0.0001	0.0003	0.0002	0.0003
	(0.0004)	(0.0008)	(0.0003)	(0.0006)	(0.0002)	(0.0006)
Treat. x 2012	0.0002	0.00002	0.0002	0.0009*	−0.0002	0.0006
	(0.0004)	(0.00062)	(0.0003)	(0.0005)	(0.0002)	(0.0004)
Treat. x 2013	0.0004	0.0005	0.0003	0.0017***	−0.0002	0.0015***
	(0.0004)	(0.0006)	(0.0003)	(0.0006)	(0.0002)	(0.0003)
Treat. x 2014	−0.0000	0.0002	−0.00003	0.0004	−0.0006***	0.0003
	(0.0003)	(0.0005)	(0.00024)	(0.0006)	(0.0002)	(0.0005)
FE:						
Municipality	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7,456	2,632	14,784	5,464	4,7096	9,336
R^2	0.477	0.758	0.432	0.749	0.295	0.745

Notes: The table shows the results of the main regression for two versions of the border design (25 km, 50 km) and all municipalities in the four states. For each data set we carried out the analysis for the unmatched and the matched data sets. The regressions based on the matched data sets use weights as matching was done with replacement. The standard errors (in parenthesis) are clustered in groups defined by 25 km segments of the border.

Table 6: Results, local treatment effects

Border points(k)	β_k	Z-statistic	p-value (Bonferroni)	p-value (FDR)	Obs (Tr. obs)
1	0.006	1.02	1.00	0.60	416 (129)
2	−0.007	−0.42	1.00	0.82	457 (78)
3	0.014	2.79	0.11	0.10	373 (92)
4	−0.009	−0.99	1.00	0.60	294 (149)
5	−0.010	−1.66	1.00	0.34	254 (144)
6	0.013	1.29	1.00	0.52	269 (82)
7	−0.013	−1.64	1.00	0.34	272 (38)
8	0.000	0.05	1.00	0.96	265 (46)
9	−0.003	−0.21	1.00	0.87	239 (66)
10	−0.018	−0.64	1.00	0.82	238 (48)
11	0.023	1.18	1.00	0.56	216 (77)
12	−0.010	−0.95	1.00	0.60	213 (91)
13	−0.006	−0.34	1.00	0.82	215 (78)
14	0.008	0.56	1.00	0.82	250 (84)
15	0.004	0.33	1.00	0.82	257 (84)
16	0.005	0.54	1.00	0.82	279 (107)
17	0.004	0.44	1.00	0.82	296 (180)
18	0.017	2.59	0.20	0.10	273 (107)
19	0.030	1.59	1.00	0.34	232 (77)
20	−0.018	−1.80	1.00	0.34	170 (66)
21	−0.021	−1.86	1.00	0.34	111 (76)

Notes: The table shows the results of the local regressions at specific border points. The first column shows the point estimate, the second column the z-statistic. The third and fourth columns contain the p-values where we have corrected for multiple hypothesis testing in two ways: The conservative Bonferroni correction and the "False Discovery Rate" (FDR). Finally, the fifth column contains the total number of municipalities within 50 km of the k^{th} border point with the number of treated municipalities in parenthesis.

6 Discussion

It could be argued that our estimates are a lower bound on the effect of the state mandate. It is likely that the policy environment or the general sentiments in Baden-Wuerttemberg would lead to more awareness among skilled workers installing heating systems about the opportunities for funding from the MAP. By limiting our analysis to municipalities near the border, we are looking at areas in which skilled workers are likely to have customers on both sides of the border and in some cases themselves are located outside of Baden-Wuerttemberg. It could be that the introduction of the state mandate through the proximity to Baden-Wuerttemberg has raised awareness of funding schemes for renewable heating technologies on both sides of the border. If the only or major effect of the regulation were to increase salience of the funding opportunities, this would be unlikely to vary discreetly at the border and such salience effects are not identified in our paper. We should however be able to capture effects net of salience effects which in this case seem to be insignificant.

What factors might explain the absence of a significant effect on applications for subsidies for investments mandated by the state law? One explanation lies in the alternative measures allowing homeowners to comply with the regulation without installing renewable heating technologies. Anecdotal evidence suggests that many homeowners applied higher standards of insulation than required by the building regulations in order to avoid having to invest in renewable heating (UM, 2011). Another easy to implement measure to comply with the law is to change the fuel used without installing a renewable heating technology. For instance, it would be possible to use a mix of standard gas and biogas to heat in a conventional gas heating system.[10]

An alternative explanation could lie in the increased cost of retrofitting due to mandated investments in more expensive technology. As in the seminal paper by Rust (1987), an increase in the replacement cost of a heating system would lead to a later replacement, all else equal. It may be that the time window we observe is too small to capture an effect. Unfortunately, there is no reliable data available on the retrofitting rate at the state level, so it is not possible to tell whether retrofitting activity has declined. If retrofitting costs have increased in response to the state mandate however, it should also capitalize into house prices making older homes that are more likely to require retrofitting sell at a lower price after the new policy was decided in 2008.

7 Conclusion

Today, many countries in cold and temperate climate zones, including Germany, have implemented energy codes for new and existing residential buildings. Energy conservation

[10]However, gas heating systems are less common in the south of Germany, where most homes are heated with oil. Only 31 % of the homes in Baden-Wuerttemberg are equipped with a gas (self-contained) central heating, compared to 47 % across Germany (BDEW, 2015).The shares for the three neighboring states, Rhineland-Palatinate, Hesse, and Bavaria are 50 %, 40 %, and 29 %, respectively.

and security were the primary reasons for their introduction in Germany, but concerns about climate change have recently spurred further tightening of the regulations. In addition to energy efficiency requirements, Germany has a federal law mandating the use of renewable energy for heating in new homes. One federal state, namely Baden-Wuerttemberg, goes even further and mandates homeowners to use renewable heating technologies when replacing their heating system in the existing building stock. While still uncommon, it is likely that such renewable heating mandates will spread in the future, both across Germany and other countries. It is therefore important to understand how they affect the uptake of renewable heating systems.

This paper investigates the effect of the state-level renewable heating mandate for existing homes in Baden-Wuerttemberg. Based on data on granted government subsidies in the period from 2007 until 2014, we compare the uptake of renewable heating systems on either side of the state border before and after the state law became effective. We find no evidence of an economically or statistically significant effect after we control for distance to the border and match on population and building characteristics.

Economists often criticize the use of energy efficiency and renewable standards for not being cost-effective in saving energy and emissions. Our results here challenge the widespread view that a standard is nevertheless successful in achieving its policy goal. One purpose of the state law under study is to increase the adoption of renewable heating systems in the existing building stock. In this objective, the law seems to fail. It may have been expected that a mandate would induce households otherwise unlikely to invest in renewable heating technologies to do so - and such households would be expected to be interested in reducing their costs of doing so by taking advantage of available subsidy schemes. However, our findings suggest that - in this case - the stick does not affect the attractiveness of the carrot.

A limitation of our study is that we proxy the uptake of renewable heating systems by the uptake of related subsidies. The state law also allows alternative measures of compliance, such as to improve the home's energy performance or to use biogas to fuel a new conventional heating system. Since our data is silent about these alternative measures, we are not able to assess the law's impact in this respect and it may well be, that the law is effective in reducing emissions related to space heating. For the overall cost-effectiveness of emission reductions from heating, allowing the standard to be met in a flexible way is likely to be superior to a standard without compensatory measures as owners can choose the measure that suits them best to comply with the mandate. Nevertheless, for the state mandate's target to support the diffusion of renewable heating technologies our findings are disappointing.

Finally, in response to the law, homeowners may be tempted to postpone the replacement of their heating because of the higher retrofit costs. If this is true, then our study may underestimate the effect of the state mandate by analyzing only the first five years after its introduction. Future research should cover a greater time span and evaluate the long-term outcome.

8 Acknowledgements

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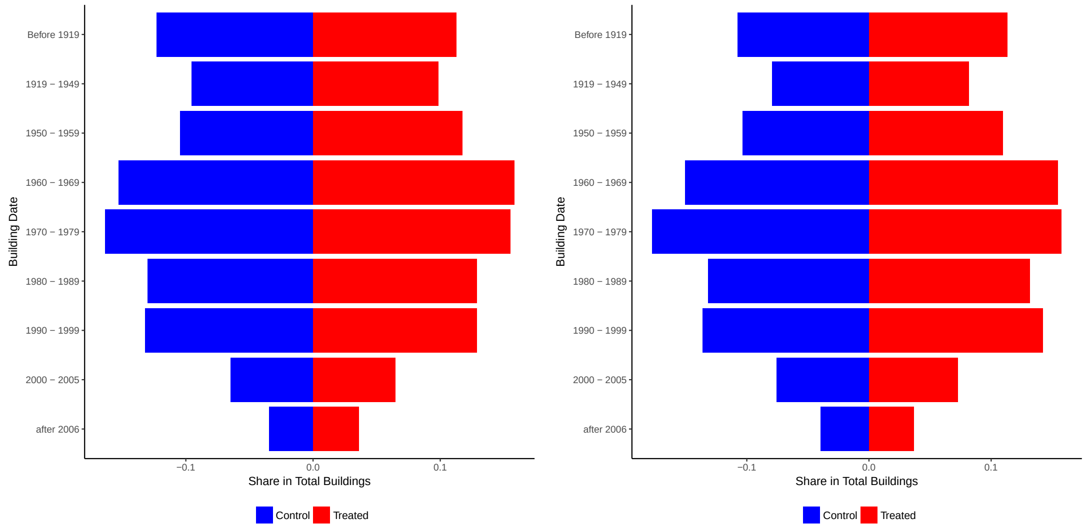
Appendix

Matching

Figure 9: Building vintages: Treatment and control municipalities within 25 km of the border



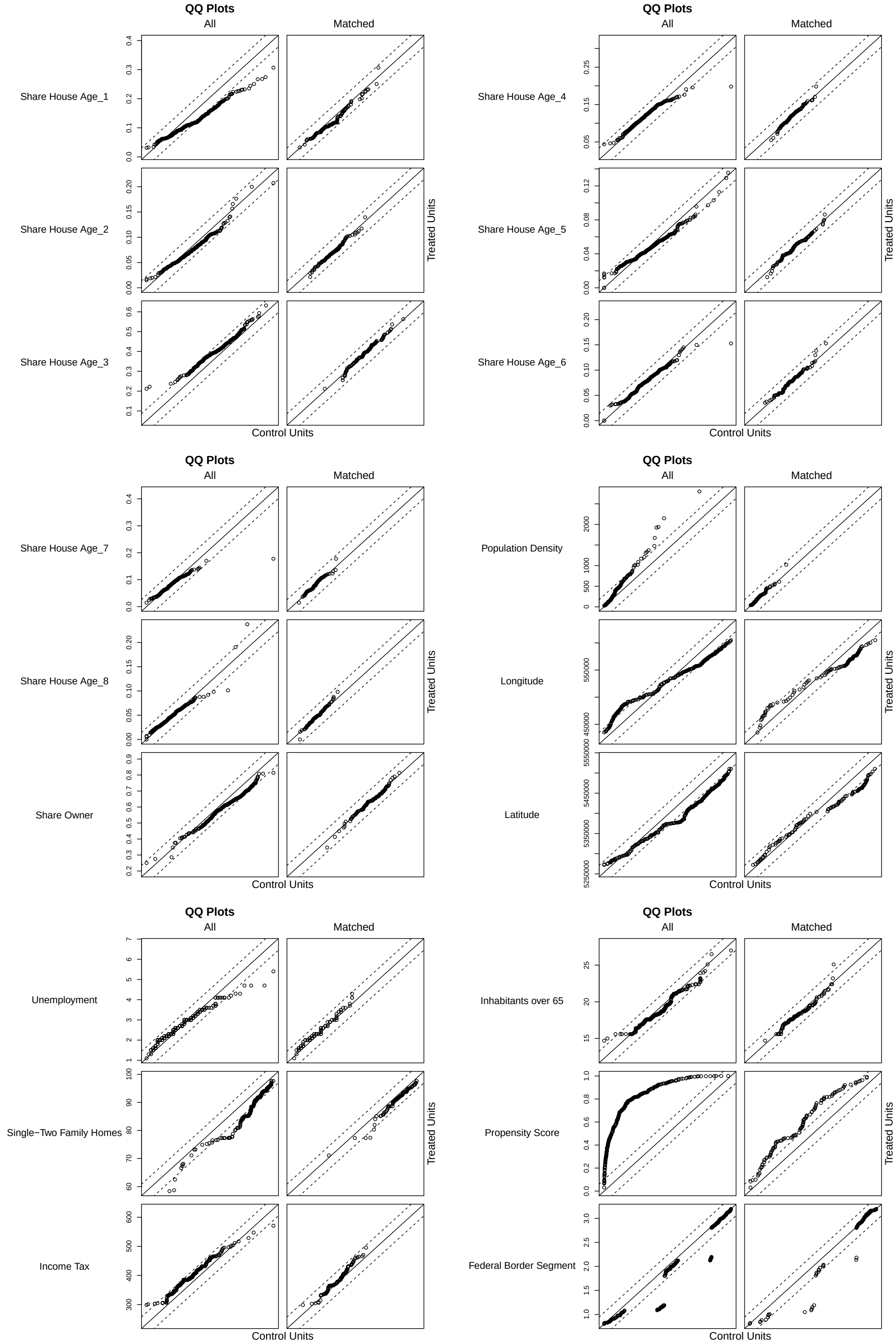
Notes: Based on own computations. The figure shows the building vintage in the treatment municipalities in Baden-Wuerttemberg (*red*) and the control municipalities in the other three states (*blue*) within 25 km of the border. On the left hand side, the distribution is shown for all municipalities within 25 km of the border. On the right hand side, distribution for the matched treatment and control municipalities are shown where the latter are weighted using the weights from the matching procedure.

Table 7: Distance between treated and matched control municipality

Design	p10	p25	p50	p75	p90
25 km	18.46	29.25	43.29	57.96	77.03
50 km	26.66	40.46	55.75	71.82	96.21
All four states	40.00	59.58	87.84	119.27	146.71

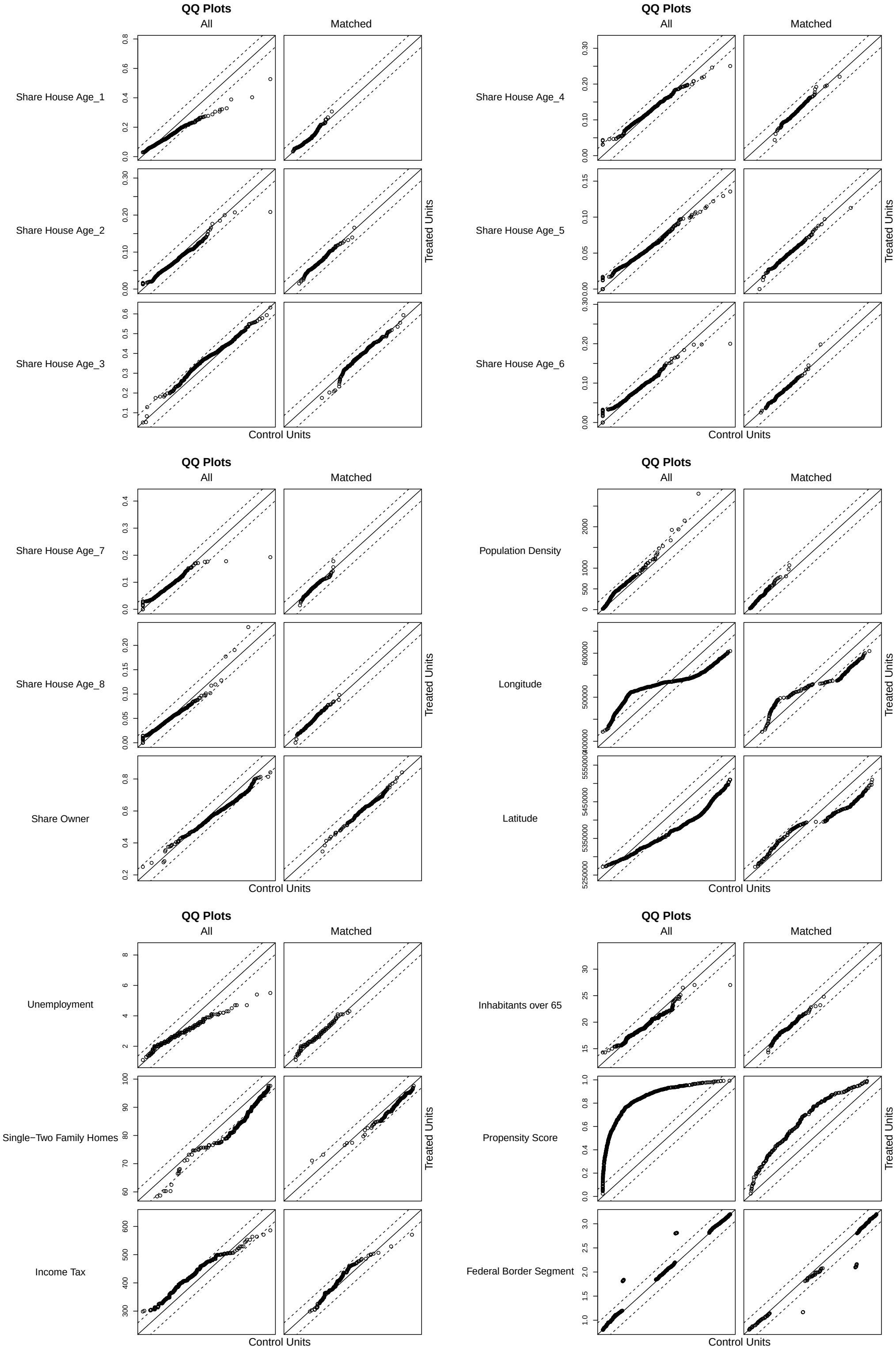
Notes: Based on own computations. The table shows the distribution of the distance to the matched control municipality for municipalities in the three border designs: 25 km from the border, 50 km from the border or all municipalities in the 4 states sharing the border.

Figure 10: QQ-Plots: Treatment and control municipalities within 25 km of the border



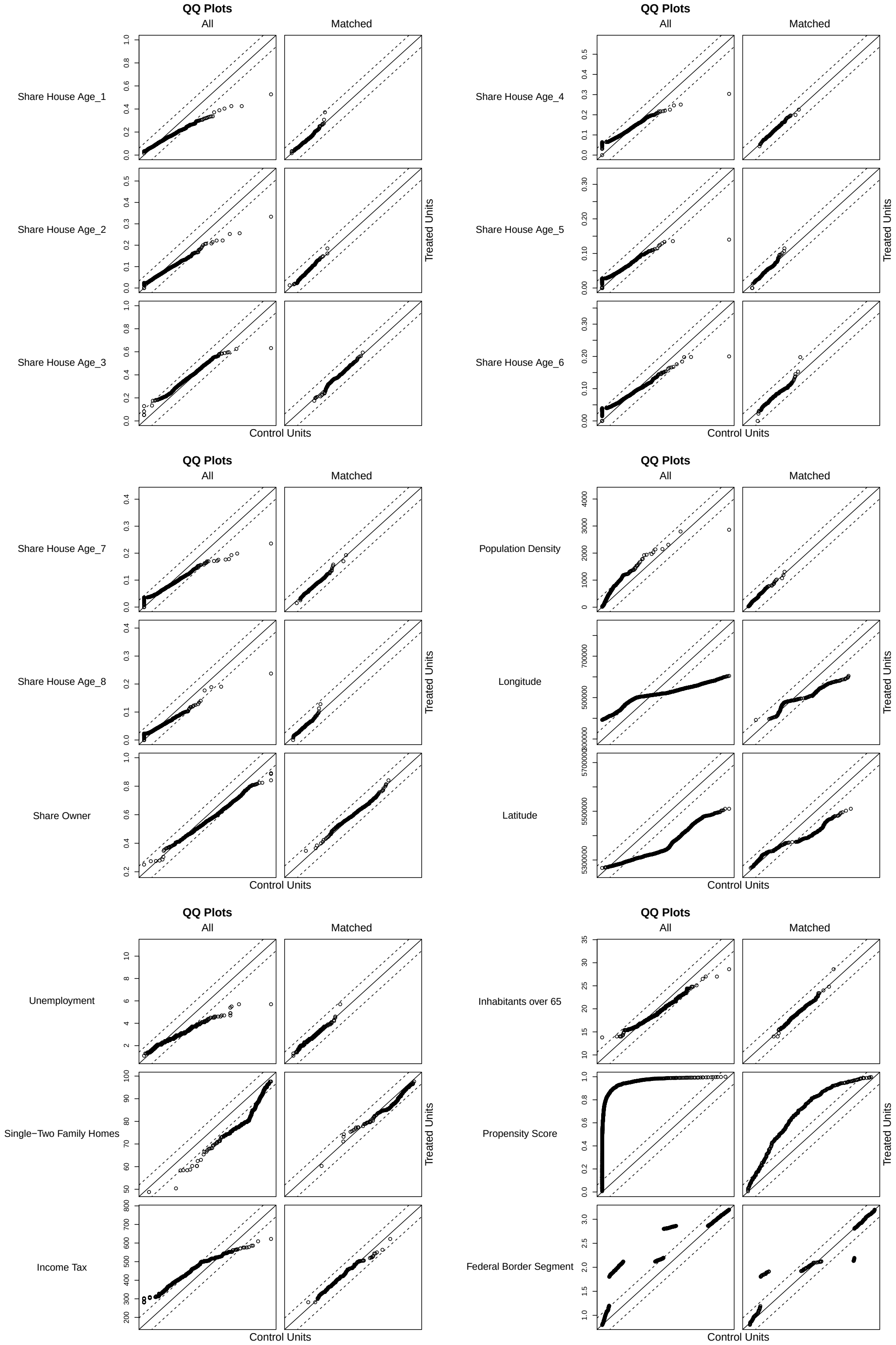
Notes: Based on own computations. The figure shows the quantile-quantile (QQ) plots for the different matching variables in the original and matched sample for municipalities within 25 km of the border. "Share House Age_1" up to "Share House Age_8" is the share of buildings within the respective vintage category based on the census' categories, "Share Owner" is the share of owner-occupied homes, "Population Density" is population density of the respective municipalitiy, "Longitude" and "latitude" are longitude and latitude of the municipality's centre, respectively. "Unemployment" is the unemployment levels, Single-Two Family Homes is the share of single and two family homes, "Income Tax" is income tax revenues, and "Inhabitants over 65" is the share of population aged 65 and older. "Propensity Score" is the estimated propensity score and "Federal Border Segment" is the assigned border segment.

Figure 11: QQ-Plots: Treatment and control municipalities within 50 km of the border



Notes: Based on own computations. The figure shows the quantile-quantile (QQ) plots for the different matching variables in the original and matched sample for municipalities within 50 km of the border. "Share House Age_1" up to "Share House Age_8" is the share of buildings within the respective vintage category based on the census' categories, "Share Owner" is the share of owner-occupied homes, "Population Density" is population density of the respective municipalitiy, "Longitude" and "latitude" are longitude and latitude of the municipality's centre, respectively. "Unemployment" is the unemployment levels, Single-Two Family Homes is the share of single and two family homes, "Income Tax" is income tax revenues, and "Inhabitants over 65" is the share of population aged 65 and older. "Propensity Score" is the estimated propensity score and "Federal Border Segment" is the assigned border segment.

Figure 12: QQ-Plots: Treatment and control municipalities in all four states



Notes: Based on own computations. The figure shows the quantile-quantile (QQ) plots for the different matching variables in the original and matched sample for municipalities in the four states (Baden-Wuerttemberg, Rhineland Palatinate, Hesse and Bavaria). "Share House Age_1" up to "Share House Age_8" is the share of buildings within the respective vintage category based on the census' categories, "Share Owner" is the share of owner-occupied homes, "Population Density" is population density of the respective municipalitiy, "Longitude" and "Latitude" are longitude and latitude of the municipality's centre, respectively. "Unemployment" is the unemployment levels, Single-Two Family Homes is the share of single and two family homes, "Income Tax" is income tax revenues, and "Inhabitants over 65" is the share of population aged 65 and older. "Propensity Score" is the estimated propensity score and "Federal Border Segment" is the assigned border segment.