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Does the stick make the carrot more attractive? State mandates and uptake of renewable heating technologies

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ABSTRACT

Command and control regulation is a popular tool for mitigating greenhouse gas emissions from the building stock. We exploit the introduction of a state-specific mandate in Germany on renewable heating when replacing the heating system in existing homes. We study the effect of the mandate on the uptake of subsidies for renewable heating technologies using unique data from a pre-existing federal government subsidy scheme. Using a geographic discontinuity design, we find that the mandate has positive effects on take-up of these subsidies, with 2 additional subsidized installations per 1000 eligible buildings in the existing building stock on average. Effects are larger in municipalities where adoption rates as measured by the subsidy scheme were below median prior to the introduction of the mandate. However, we also find suggestive evidence that retrofitting activities in the state declined in response to the introduction of the mandate.

1. Introduction

Climate change is considered a main challenge for policy makers in our time. Achieving the transformation to a low-carbon economy requires substantial abatement effort across all sectors. Innovation and technology diffusion play an important role in this transformation by reducing abatement costs. Often several overlapping tools are implemented to achieve emissions reductions and spur innovation and technology uptake. This is true for the building sector where command and control regulation is popular in most developed countries, and generally supplemented by tools such as energy labeling and subsidy programs (e.g., IEA, 2013). The plethora of tools used makes it difficult to evaluate the additionality in terms of efficacy and cost-effectiveness of any single instrument in the policy mix. Nevertheless, understanding the effects of individual policy measures is key to developing a cost-effective climate policy.

In this paper we exploit a quasi-experiment provided by the introduction of a state-level renewable energy heating mandate for the residential building stock. We study its effect on the number of granted applications for subsidies for renewable heating technologies in that state. A federal mandate requiring the use of renewable heating technologies in construction of new buildings was introduced for buildings with a planning permit dating from January 1st, 2009 across all of Germany. However, the federal state of Baden-Wuerttemberg, located in the southwest of Germany, introduced its own equivalent mandate 8 months earlier for new buildings, and - in contrast to the federal mandate - also introduced requirements for the existing building stock. Specifically, starting in 2010 the state mandate requires homeowners who replace their existing heating system to meet at least 10% of their heat demand with renewable energy. No other federal state has such a law for the existing building stock in place.

Our main objective is to assess the impact of Baden-Wuerttemberg's mandate on uptake of renewable heating systems. However, no micro data on technology uptake for heating systems is available. Instead, we use unique data on a pre-existing federal government subsidy scheme applicable to all German states and exploit geographic differences in

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regulations for buildings for identification. We compare the number of granted applications from the subsidy scheme in German municipalities on either side of the Baden-Wuerttemberg border before and after the introduction of the policy. The municipalities outside Baden-Wuerttemberg and close to the border 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 as well as salience about the subsidy scheme. To further reduce heterogeneity between treatment and control municipalities, we match on observable characteristics of the population and the building stock.

Technology adoption is commonly described as following an S-shaped curve referred to in the literature as the S-curve (Griliches, 1957). Initially, adoption is slow, but then increases rapidly before reaching a plateau and flattening out again as the market becomes satiated. In an analysis of technology adoption it is important to take these underlying dynamics into account as the impact of a policy may differ substantially depending on where on the S-curve a market is when the policy is introduced. We address this issue by controlling for cumulated renewable heating installations prior to the introduction of the mandate.

The data we use to proxy for uptake of renewable heating technologies derives from 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 MAP 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 (BMWi, 2015). Our data contain information on all granted subsidy applications in the period from 2007 until 2014.

The use of the subsidy scheme data has two main limitations, which we aim to minimize in the research design: 1) Our data may underestimate the actual uptake of renewable heating technologies if many of these are not subsidized through the MAP scheme. Comparisons of MAP grants and the number of renewable heating installations overall for 2007–2008 suggest that 75% of the installations received financial support through the MAP. It is generally possible to combine MAP subsidies with other grants so that a household does not have to choose between schemes. Moreover the application process is simple and generally supported by the skilled worker installing the heating system. If the renewable standard 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. 2) Our data may overestimate impacts on uptake if a main effect of the mandate is to increase the salience of the subsidy scheme as a source of funding to comply with the requirements. In that case the mandate leads to more applications for subsidies, but not necessarily to more installations of renewable heating technologies. Our research design in which we limit the sample to similar municipalities close to the border aims to minimize this concern as we argue that our preferred specification (within 25 km distance of the shared border) is likely to hold the stock of skilled workers (and thereby the main source of information on the subsidy scheme) constant, so we estimate effects net of salience of the subsidy scheme.

Our main results show evidence of a significant and positive effect of the introduction of the state mandate on applications for the MAP - both for existing buildings and the new building stock. After restricting distance to the border and using matching, we find an average effect of around 2 additional applications per 1000 eligible buildings in the existing building stock. This basic finding does not change after we test for spatially- and time-varying treatment effects in robustness checks. Given the dynamics of the S-curve of technology adoption, we also allow for heterogeneous effects depending on the cumulated level of granted subsidy applications prior to the mandate. In this specification we find evidence that the effect of the mandate for the existing building stock was larger in municipalities with below median adoption levels prior to the mandate. In addition, our results also indicate an effect of the mandate for new buildings with an average impact of at least 3.5 granted applications per 1000 eligible buildings. In sum, our empirical results suggest that the stick (renewable energy mandate) does indeed make the carrot (subsidy scheme) more attractive.

The mandate increases the cost of retrofitting and so we further examine whether the mandate had an undesirable effect in terms of delaying retrofitting decisions in the spirit of Rust(1987). To this purpose we carried out an additional analysis based on state level data on the age distribution of existing heating systems. Using the synthetic control method we find evidence to suggest that households postponed the decision to retrofit resulting in lower replacement rates of fossil fuel heating installations at the residential level in the state of Baden-Wuerttemberg than we would have expected. Consequently, our results are mixed with regard to the mandate's target to support the diffusion of renewable heating technologies in the existing building stock at least in the short term.

Our paper contributes to the literature on improving energy efficiency in the building stock and in particular the effectiveness of building regulations to make homes greener. The salience of energy costs for home buyers has been demonstrated in several different contexts (cf. Myers, 2019; Aydin et al., 2020). Moreover, Hilber et al. (2019) find that rising energy costs have led households to reduce energy consumption by investing in energy saving technology for their homes such as insulation or new heating systems. Several papers have examined the impact of building regulations on energy consumption (cf. Jacobsen and Kotchen, 2013; Kotchen, 2017; Levinson, 2016; Novan et al., 2017). To our knowledge, we are the first to provide empirical evidence on the impact of building codes mandating 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, except for a recent study by Bruegge et al. (2019) that was undertaken in parallel. They investigate the effects of building energy codes in California on energy consumption, house values, and house characteristics, using variation over time and across different climate zones that relate to the code's strictness. Their study focuses on buildings constructed under different energy codes whereas our study deals with a mandate affecting refurbishment of the existing building stock.

Our paper also contributes to the sparse empirical literature on the determinants of renewable heating adoption (cf. Mills and Schleich, 2009; Michelsen and Madlener, 2012).[1] A few studies 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 variation over time in the number of granted MAP subsidies to identify the effect of a state mandate on the adoption of renewable heating systems.

Finally, our paper contributes in terms of methodology to the literature using quasi-experimental methods to evaluate causal effects of policy on technolgy uptake. In contrast to the existing literature, cf. Houde and Aldy (2017) or Buettner and Madzharova (2019), we pay careful attention to the S-curve relationship underlying the technology adoption (e.g., Griliches, 1957; Geroski, 2000; Young, 2009). Even within a difference-in-differences framework, the position of a unit of observation on the S-curve is important both to the interpretation of results and the validity of potential control units. On the convex part of the S-curve a positive treatment effect is associated with an increase in adoption

[1] Our analysis is also relevant to the literature investigating the effects of different policy instruments on the diffusion of "green" technologies (see, for example, the review by Allan et al., 2014).

rates, whereas the opposite is true on the concave part of the S-curve. Moreover, on the S-curve, different units may have similar trends at a point in time but very different future trends depending on where on the S-curve they are located. We carefully compare pre-treatment levels in the treatment and control group to ensure that potential controls are on the same convex part of the S-curve as our treatment group. In applications where adoption of new technology is advanced or very heterogeneous among treated and potential control units, the implications of neglecting the S-curve relationship may be substantial.

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 and section 4 explains our empirical strategy. Section 5 presents the econometric models and results. Section 6 discusses our findings, and Section 7 concludes.

2. Background and conceptual framework

According to the United Nations Economic Commission for Europe, buildings are responsible for roughly a third of total energy consumption and 40% of carbon dioxide emissions from combustion in Europe (UNECE, 2018). Germany is an interesting case because it is one of the world's largest economies and has embarked on an ambitious energy transition, aiming to decarbonize the economy by 2045. In Germany, there are 18.5 million residential buildings, 83% of which 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 includes energy codes. Roughly two-thirds of Germany's residential buildings were built before 1979. Most of them did not meet the requirements of the first ordinance on thermal insulation introduced in 1977. 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%) (ARGE, 2016).

The energy transition has had a large impact on electricity generation,[2] but high electricity prices impede the adoption of electricity for heating and cooling of buildings. Space and water heating accounts for 84% of the energy consumed in German households, representing 22% of the country's total final energy consumption (BMWi, 2018b). Most of the domestic heating still comes from natural gas and oil, both associated with the release of carbon dioxide. However, the share of renewable heat is steadily growing. In 2017, solar thermal systems, heat pumps, and biomass-fired installations (e.g., pellet stoves) together supplied 16% of space heating and some 11% of hot water in residential buildings (AG Energiebilanzen e.V, 2018).

In the following we briefly describe the state mandate and the federal context into which it enters. We also provide a conceptual framework for the analysis.

2.1. 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 for new buildings and with effect from 1 January 2010 for the existing building stock. 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 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.[3] 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. From 1 January 2010 onwards existing 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 (i.e., houses constructed before 2009).

To comply with the law's requirements, homeowners may install e.g., solar thermal collectors, heat pumps, heat with biomass or biofuels. Alternatively, homeowners can comply with the law by substantially exceeding energy efficiency standards. Other options include the use of a local and district heating coming from cogeneration or renewables, or a photovoltaic system if this precludes the installation of solar thermal collectors for heating purposes. Listed buildings are exempt from the regulation if the installation of solar thermal collectors is not feasible due to this status. Homeowners can be fined up to 100,000 euro for failing to comply with the law. Homeowners must provide evidence of compliance to the local building authorities within 3 months of installing the new heating system. A table summarizing details of the state mandate can be found in appendix A.1.

On 1 January 2009, eight months after the Baden-Wuerttemberg mandate became effective for new buildings, a federal law on the use of renewable energy for heating (EEWaermeG) entered into force. The federal law aimed 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. But in contrast to the state law, the federal law only applies to new buildings (i.e., with planning application from 1 January 2009). In consequence, only the existing building stock in Baden-Wuerttemberg is subject to a renewable energy mandate when the heating system is replaced.

2.2. Conceptual framework

For homeowners or landlords building a new home after the mandate became effective, the mandate is likely to lead to the adoption of more renewable heating technologies. The shift in costs induced by the mandate is unlikely to be large enough to change the decision to build rather than buy an existing home, especially considering that the existing building stock would be subject to the same regulation shortly after. For a homeowner or landlord in the existing building stock the problem with regard to retrofitting the heating system is very similar to the optimal stopping problem faced by the immortal Harold Zurcher for the replacement of bus engines in the seminal paper by John Rust (1987). Here we do not estimate a structural model of dynamic optimization, but a brief discussion of the expected effects of the regulation on individual behavior is helpful to fix a conceptual framework.

The state mandate comes into effect when a heating system is replaced. This implies, that a homeowner with an old heating system faces a trade-off between repairing the existing system or installing a new system in compliance with the mandate, when the old installation breaks down or becomes uneconomical. Factors affecting the decision include expectations about the future operating cost of the existing installation (fuel costs, maintenance), costs of breakdown (e.g. freezing, tenant complaints in the case of landlords), and replacement cost.

[2] The share of electricity generated from renewable energy technologies increased from around 6% in 2000 to about one third in 2017 (BMWi, 2018a).

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

The higher the expected future operating cost of an existing installation and cost of potential breakdown, the higher the likelihood of replacement with a new installation. The higher the replacement cost on the other hand, the higher the likelihood that an existing heating system is allowed to run a little longer. In this setting, the mandate therefore has two effects: On the one hand, it is likely to increase the share of renewable heating over time in the regulated state as older installations are replaced with compliant new installations due to the mandate. On the other hand, the state mandate may be expected to increase the replacement cost as it requires the use of more expensive renewable energy sources or, e.g., increased insulation for compliance. Thus, another effect of the mandate may perversely be to slow down replacement of heating installations in the regulated state. Unfortunately, we do not have individual level data on existing heating installations, which would allow us to model each replacement decision. What we observe is the aggregate number of granted subsidies for renewable heating installations at the municipality level. These aggregate numbers will reflect both channels, i.e., simultaneously an increase in the share of renewable installations in terms of all heating system replacements, and a decline in overall replacement activity.

3. Data

The main data source is the data on subsidy applications for the Market Incentive Programme subsidy scheme. We combine this data with information from the German Building Census and sociodemographic characteristics of German municipalities. We further use data on the age distribution of fossil fuel heating systems at the state level.

3.1. Market Incentive Programme 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. The 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. It mainly promotes solar thermal collectors, biomass, and heat pumps. 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. All subsidies granted after 2010 therefore go to buildings in the existing building stock. The size of the subsidies varies by technology and scale of the installed capacity. The share of investment costs covered is generally rather modest (<20%). The subsidy does not suffice to make the renewable alternative cheaper than a conventional heating system. A comparison of the costs across three specific renewable alternatives (solar thermal collectors, biomass and a heat pump) and heating with gas can be found in appendix A.3 for a given type of dwelling together with details about the subsidy scheme in appendix A.2. The application procedure is fairly unbureacratic and consists of submitting a simple application form within 6 months of the initial operation of the heating system. The data that we use in the analysis derives from information contained in that application form anonymized at the postal code level.

The data was provided to us by the BAFA directly and contains information on the individual installation in terms of the type of technology, the size of the installation, and 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. 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. To control for installations prior to our study period we obtained access to data on granted MAP applications for biomass and solar thermal collectors from 2001 onwards from a private firm eclareon GmbH.[4]

The MAP data forms the basis of our analysis as no other micro data is available on heating installations for Germany. The extent to which MAP applications are representative of the overall investment activity in renewable heating technologies is therefore a key question. 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 20–25% 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 absolute 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 annual correspondences 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 9 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.[5]

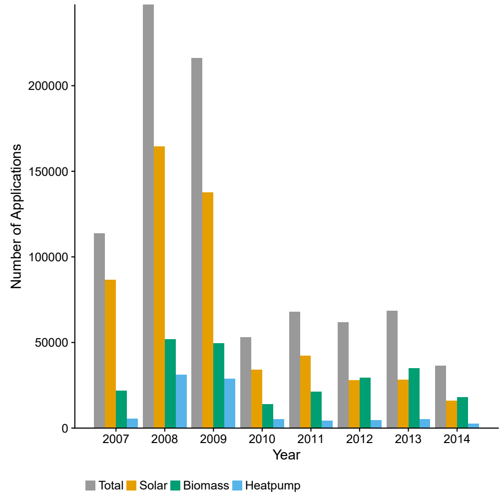
3.3. Municipality sociodemographic characteristics

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 set 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 4567 municipalities or municipal associations (*Gemeindeverbände*). We assigned the data to the municipal level based on an identifier assigning individual municipalities to municipal associations.

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

[4] We were able to compare the data from eclareon with the data provided from the BAFA and found no major inconsistencies. The BAFA data is used for the main analysis as it also includes heat pumps and is thus complete across technologies.

[5] 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.



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.

Fig. 1. Number of granted applications per year, 2007–2014.

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.

3.4. Chimney sweep data

In a supplementary analysis we assess whether the mandate may have had an effect on retrofitting activities as revealed by the changing age distribution of heating installations. No microdata exists on the age distribution of heating installations. However, at the state level the annual reports of the German Federal Association of Chimney Sweepers contain information on residential heating installations by fuel type, age, and size. All residential heating installations are regularly inspected by chimney sweeps to ensure safety and compliance with emissions regulation. These inspections provide the basis for the data. The annual reports for the years from 2010 to 2016 are available to us (ZIV, 2018).

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 for the existing building stock. Moreover, the state mandate for new buildings came into effect while new buildings were still eligible for subsidies. We therefore have to account for the change in the stock of eligible buildings and the introduction of mandates for different segments of the housing stock at different times. We address this issue by adjusting our outcome variable and controlling for the introduction of the mandate for new buildings. 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, as well as the extent to which the MAP subsidy scheme is known to homeowners. To minimize the likelihood that such factors drive our results, we use a combination of geographic differences in state regulation over time and matching techniques for identification. We discuss each of these challenges in more detail in the following.

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 technologies for this category of homes. As a result, uptake of the MAP dropped substantially between 2009 and 2010, as shown in Fig. 1.[6] Unfortunately, the data from the MAP applications do not include information on the age of the building in which an installation is made.[7] Nevertheless, the figure suggests that a substantial share of subsidies went to newly constructed homes prior to the change.

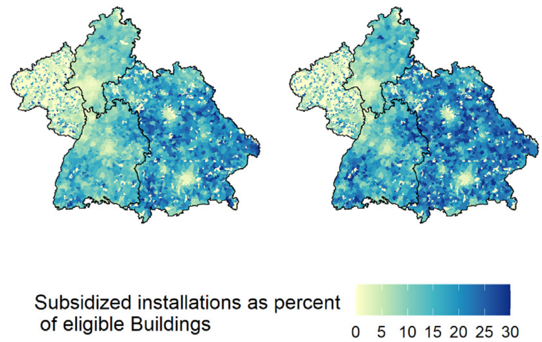
The change in eligibility was the same across all German states. The impact on uptake of the MAP, however, is likely to vary across states and municipalities due to differences in the housing structure and construction activities. To account for this, we construct our outcome variable as the number of 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”.[8] There is substantial variation across space in the uptake of the MAP as can be seen in Fig. 2. Furthermore, especially for the long border between Bavaria (on the right side) and Baden-Wuerttemberg (in the bottom left), it becomes apparent that there is a substantial uptake in border regions relative to the amount of eligible buildings.

It remains important to control for differences in building structure as the propensity to apply for a subsidy and the retrofitting rate are likely to differ across building vintages.

[6] 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.

[7] After 2010 the data contains information that the building was constructed prior to 2009 from the application form, but not in which year. Prior to 2010 no information about age is available at all.

[8] To obtain year specific numbers of new buildings, we assumed a uniform distribution of construction years within each time category that we have used, i.e., from 2005 to 2008 and from 2009 to 2011.



Notes: Based on own computations. The map on the left shows the share of cumulative occurrence of subsidized installations in eligible buildings at the municipality level in 2009. The black lines denote the state borders, with Rhineland-Palatinate in the top left position within this figure, Hesse at top center, Bavaria on the right and Baden-Wuerttemberg in the bottom left position. The map on the right shows the same information 6 years later in 2014. The darker areas are areas with larger shares of cumulative occurrences.

Fig. 2. Installations with MAP subsidies, 2009 (left) and 2014 (right).

4.2. State mandate for the new building stock

Given the introduction of a state mandate for renewable heating in new buildings in Baden-Wuerttemberg 8 months prior to the federal mandate, the regulation for new buildings varies across states in the second half of 2008. We expect the impact of this mandate to affect MAP applications in 2009 given the fact that the MAP application window of 6 months starts at the date of first operation of the heating system. There is likely to be a considerable time lag between being granted a planning permit on 1 April 2008 or later, and first operating the heating system. We control for the introduction of the mandate for new buildings in the econometric specification and discuss the issue further in the section on pre-trends below.

4.3. 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. These factors would also likely affect salience of the availability of subsidies for renewable heating systems through the MAP. At least three possible sources of correlation between investment in renewable technologies and environmentally ambitious building regulations come to mind.

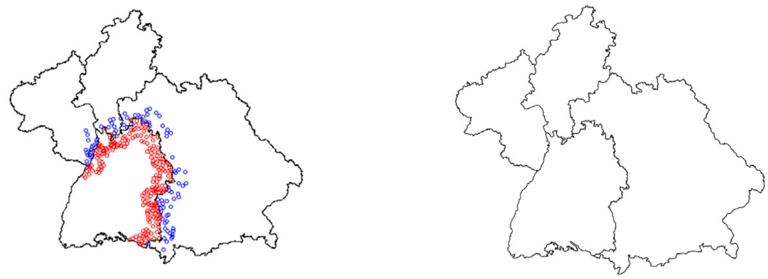
First, political beliefs may induce households to vote for an environmentally ambitious government and simultaneously drive private investments in renewable technology. This would lead to correlation in investments and regulation without the former being driven by the latter in a causal sense. A second 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 make it relatively cheap to use renewable energy, e.g., because of the high 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 if there is learning-by-doing 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 regulation 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 as well as within 50 km of the state border, as shown in Fig. 3. 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 discretely at the border. Neither are the natural resources or the sunshine hours.

The research design comes with a caveat: It is likely that the policy environment or the general sentiments in Baden-Wuerttemberg could 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 deliberately 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. If the only or major effect of the regulation is 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 analysis. In our case, we use subsidy data from the MAP to measure the effect of the mandate on uptake of technologies. Our border research design aims at keeping salience about the MAP constant among treated and control municipalities so that the data provides an equally good measure of uptake in both groups.

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



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.

Fig. 3. Treatment and control municipalities within 25 km of the border, full (left) and matched (right) sample. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Number of municipalities in the treatment and control group.

Design	25 km		50 km		All four states	
	Control	Treated	Control	Treated	Control	Treated
Full sample	644	311	1279	622	4974	1103
Matched	91	220	151	480	238	882
Unmatched	553	91	1128	142	4736	221

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. Additionally, we show the details of the sample using all municipalities in the 4 states sharing the border.

relies on the assumption of “Conditional Local Geographic Treatment Ignorability”, as specified by Keele and Titiunik (2016), which formally states that:

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

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 proximity of the border, with d_i being the (shortest) distance to the border and D a specified maximum distance to the border. We use a distance of 25 km to the state border as our reference, but present results based on 50 km distance and naive results including all municipalities in the four states as well.

4.4. Matching on observables

We use genetic matching as developed by Diamond and Sekhon (2013) to match our treatment and control municipalities.[9] We match on municipality characteristics in 2007, i.e., the year before the state mandate was enacted, 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 as well as the cumulative share of granted MAP applications until 2007 from eclareon. In addition, we also use information on the 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 fixed. Finally, we include information on population density at the municipal level. We do not match on natural gas prices but trends in the four states appear similar, in particular in municipalities in close proximity to the state borders as shown in Figure A.8 and A.9 in appendix A.4.

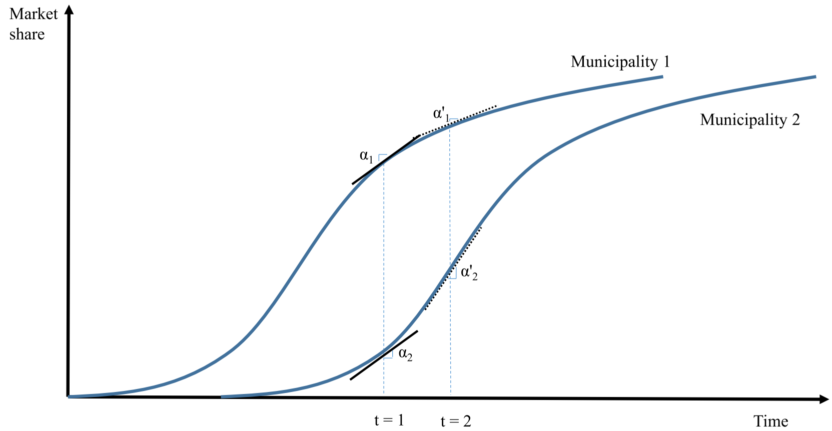
The genetic matching algorithm combines propensity score matching and Mahalanobis matching. We estimate a propensity score using a generalized additive model with a logistic distribution to allow sufficient flexibility in the functional form.[10] To strengthen our border research design, we match exactly 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. Summary statistics for the distance between matched treatment and control municipalities are given in Table A.5 in appendix A.4.

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 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 municipalities in each data set with and without matching.

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

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

[10] 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.



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: $\alpha_2' > \alpha_1'$.

Fig. 4. The S-curve and the common trends assumption.

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 Fig. 4. 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. In Fig. 4 the 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: $\alpha_2' > \alpha_1'$.The ideal comparison is therefore between a treatment and control unit which are at the same point on the S-curve prior to treatment. The assumption of parallel future trends in the absence of treatment is clearly not satisfied in other instances.

Our research design goes a long way towards reducing the heterogeneity in adoption levels in the data.[11] The cumulative distribution of the number of applications between 2001 and 2009, the average number of granted applications from 2007 to 2009, and the age distribution of the building stock in treated and control municipalities are found in appendix A.4 together with QQ-Plots showing balance on the categories used in matching.

4.5. Common trends

To examine the pre-trends we carried out a series of event study regressions in which an indicator for location in Baden-Wuerttemberg is interacted with a dummy variable for each year. We carry out this analysis for our estimation sample based on the period 2007–2014. Fig. 5 shows the plotted coefficient of the interaction terms for the matched sample within 25 km of the shared border in the shorter estimation sample. There is a significant coefficient in 2009. This measured positive impact in 2009 is consistent with the introduction of the state mandate for new buildings in Baden-Wuerttemberg in 2008. Given the time lag between applying for a planning permit, construction of a building, taking the heating system into operation, and subsequently applying for a subsidy, it is likely that the effects of the mandate would show up in 2009. Since heating installations in new construction were still eligible for subsidies in 2009, this seems a likely explanation for the estimated coefficient. The coefficient for 2008 is small and not statistically different from zero. We control for the mandate for new buildings in our econometric model by including a separate control variable for municipalities in Baden-Wuerttemberg in 2009, so that uptake in 2010–2014 is compared to the base period 2007–2008.

We analyze pre-trends in detail in appendix A.5 for all our different samples, including also additional data purchased from eclareon to allow us to examine the period from 2001 to 2014. We find further evidence of differential pre-trends in the full sample, which underscores the necessity of our matching approach to identify municipalities at similar points on similar S-curves.

5. Econometric model and results

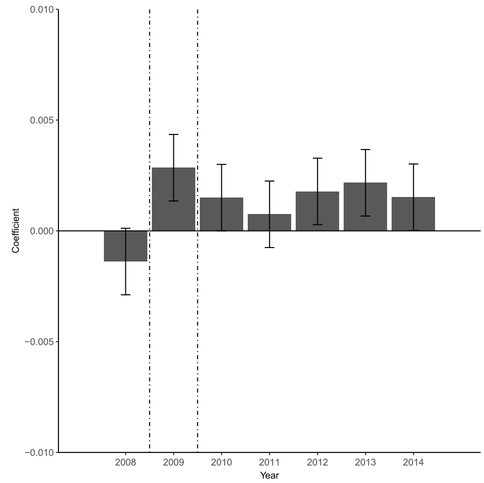
We estimate a difference-in-differences model. Our model relates the annual number of newly granted applications per eligible building, y_{ijt}, to the introduction of the state mandate for new buildings, $BW2009_{it}$, and the introduction for existing buildings, T_{it}. We further include municipality level fixed effects, μ_i, and time fixed effects, δ_t. The error term is clustered at the 25 km border segment (j), ϵ_{ijt}, to account for spatial and time correlation in the error term:

$$y_{ijt} = \alpha\, BW2009_{it} + \beta\, T_{it} + \mu_i + \delta_t + \epsilon_{ijt} \quad (1)$$

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 and our main focus. Under certain circumstances, the estimate of α captures the effect of the mandate on uptake of renewable heating

[11] Here we have focused on adoption levels because our sample period is relatively short and market penetration levels of renewable heating technologies are still rather low. In other applications, however, assessing second derivatives of the diffusion process may be important to ensure that treatment and control units are both on the same convex or concave part of the S-curve.



Notes: Based on own computations. The bars show the point estimates of the coefficients in a regression of annual new granted MAP subsidy applications on an indicator whether the municipality is located in Baden-Wuerttemberg interacted by year dummies for the matched sample of municipalities within 25 km of the state border. The error bars illustrate the 95 % confidence intervals.

Fig. 5. Trends of matched sample within 25 km of the border, 2008–2014.

technologies in the new building stock.[12] 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. 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.[13] Both the state mandate on renewable energy technology in heating and the federal subsidy scheme aim to increase penetration of renewable technologies. This is also reflected in the cumulated share of granted applications up to 2009 as shown in Table A3, which states that for over 90% of municipalities the share is below 20%. 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. Although the linear specification of the model might not be suitable to describe the evolution of an entire S-Curve, we assume that a linear model is still an appropriate approximation for the rather low diffusion levels observed in our data set. We assess heterogeneity in treatment effects by adoption levels in an additional specification below in Table 2.

Table 3 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. The point estimates are generally positive suggesting an effect of 2 additional applications per 1000 eligible buildings in the existing building stock. These findings are statistically significant at the 5% level and quantitatively similar in all three matched data sets. The effect of the state mandate for new buildings captured by the dummy $BW2009$ suggest an even larger impact of 3.5 additional applications per eligible building in our preferred specification. The point estimate is a little smaller in the other matched samples, but not statistically significantly different. In all three cases, the effect is significant at the 1% level. Our results thereby consistently show a positive and significant effect of the introduction of the state mandate on applications for the MAP *on average*. The adjusted R^2 is generally quite high, suggesting that the model does a fair job of explaining the variation in the data.

Given the potential for heterogeneous impacts along the S-curve, we investigate whether treatment effects differ with respect to the initial level of granted subsidy applications.[14] The slope of the S-curve (i.e., the first derivative of the S-curve) is bell-shaped, increasing towards the maximum at the point where the S-curve becomes concave, after which the slope declines towards zero. We therefore expect heterogeneous effects depending on where on the S-curve a municipality is located also in the size of the effect and not just the sign. To assess such heterogeneity, we interact the treatment indicator with binary indicator variables reflecting the different quantiles ($25 < p \leq 50$; $50 < p \leq 75$; $p > 75$) of the initial adoption levels (in 2007) in Table 2. The base category is the smallest quantile ($p < 25$). There is substantial heterogeneity in effects across initial adoption levels. In our preferred specification (Column 2), there is a statistically significant positive effect for the smallest quantile (base category) of about 6 additional applications per thousand eligible buildings. The interaction terms are all statistically significant and negative. Furthermore, point estimates of these coefficients increase in absolute terms, suggesting that the effect becomes smaller for larger initial adoption levels. However, the combination of the coefficients for the base category and the interactions are jointly statistically significant only up to the median of initial adoption levels (i.e., base and $\text{Adopt}_{(25<p \leq 50)}$). Thus, positive and statistically significant treatment effects appear only for lower initial adoption levels.

[12] Treatment status in the new building stock differs for just 8 months whereas β measures the average impact over several years. We have no detailed information on the timing of events in terms of getting a planning permit, building, and applying for the subsidy, so it is hard to say to what extent we capture the full effect of the mandate in the 2009 data in α. Moreover, the estimate of α may not be directly comparable to β because there is no incentive to delay installation of a heating system in the new building stock in contrast to the existing building stock. Depending on the extent of delays induced the estimate in β should be viewed as a short term effect on uptake in the existing building stock.

[13] We have calculated S-curves based on the MAP data for the matched sample within 25 km of the border in Baden-Wuerttemberg and each of its neighbors. These can be found in appendix A.5, Figure A.24. Except for the change in slope in 2010 after eligibility was restricted to the existing building stock, we find no evidence to suggest that the adoption process has entered the concave part of the S-curve.

[14] We thank an anonymous referee and the editor for this suggestion.

Table 2
Results, treatment effects on the treated by initial adoption levels.

Design Sample	25 km		50 km		All four states	
	Full (1)	Matched (2)	Full (3)	Matched (4)	Full (5)	Matched (6)
BW 2009	0.0031***	0.0035***	0.0033***	0.0028***	0.0036***	0.0022***
	(0.0004)	(0.0011)	(0.0003)	(0.0008)	(0.0002)	(0.0009)
Treatment	−0.0044***	0.0060***	−0.0016***	0.0058***	0.0012***	0.0066***
	(0.0006)	(0.0011)	(0.0004)	(0.0013)	(0.0001)	(0.0011)
Treat. x Adopt$_{(25<p \leq 50)}$	−0.0058***	−0.0031***	−0.0078***	−0.0030***	−0.0090***	−0.0036***
	(0.0007)	(0.0009)	(0.0005)	(0.0007)	(0.0002)	(0.0006)
Treat. x Adopt$_{(50<p \leq 75)}$	−0.0082***	−0.0047***	−0.0104***	−0.0051***	−0.0125***	−0.0052***
	(0.0007)	(0.0008)	(0.0005)	(0.0008)	(0.0002)	(0.0006)
Treat. x Adopt$_{(p > 75)}$	−0.0113***	−0.0073***	−0.0133***	−0.0065***	−0.0150***	−0.0071***
	(0.0011)	(0.0013)	(0.0008)	(0.0013)	(0.0005)	(0.0010)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7640	2488	15,208	5048	48,616	8960
Adj. R^2	0.039	0.791	0.031	0.781	−0.049	0.762

Notes: The table shows the results of the regression for two versions of the border design (25 km, 50 km) and all municipalities in the four states. The dependent variable is granted applications per eligible building. For each data set we carried out the analysis for the full and the matched samples. 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 with $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 3
Results, average treatment effects on the treated.

Design Sample	25 km		50 km		All four states	
	Full (1)	Matched (2)	Full (3)	Matched (4)	Full (5)	Matched (6)
BW 2009	0.0019***	0.0035***	0.0016***	0.0028***	0.0022***	0.0022***
	(0.0005)	(0.0011)	(0.0004)	(0.0008)	(0.0003)	(0.0009)
Treatment	0.0009	0.0022**	0.0004	0.0021**	−0.0013***	0.0025***
	(0.0006)	(0.0009)	(0.0004)	(0.0010)	(0.0003)	(0.0009)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7640	2488	15,208	5048	48,616	8960
Adj. R^2	0.478	0.777	0.433	0.767	0.296	0.747

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. The dependent variable is the number of newly granted subsidy applications per eligible building. For each data set we carried out the analysis for the full and the matched samples. 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 with $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

This result could indicate that municipalities with higher initial adoption levels have already reached the concave part of the S-Curve. However, inspecting S-curves calculated on the basis of the grant application data, we clearly see that these remain steeper in municipalities with higher cumulated levels of adoption (as can be seen in Figure A.24 in the appendix). That observation is consistent with these municipalities remaining far from their satiation point. In other words, it seems that the mandate has had an impact on adoption as measured by granted applications in municipalities where initial levels were low.[15]

5.1. Robustness checks

Our identification relies on the assumption that potential confounders vary continuously at the border over time. We therefore investigate whether other potential variables evolve differently across municipalities in Baden-Wuerttemberg and in the neighboring federal states after the state mandate entered into force for the existing building stock. These different “outcome” variables include all time varying variables used in the matching procedure. We run regressions similar to our main specification for the different samples and find several significant average “treatment” effects using the full data set (cf. appendix A.6). In the matched samples only population density and income tax revenues differ in a statistically significant way across the border. However, once the distance band around the border is restricted to 25 km none of the treatment coefficient estimates are statistically significant. This result strengthens the credibility of our preferred specification and identification strategy.[16]

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

[15] A caveat is that our measure of adoption through granted subsidy applications may be less appropriate in locations where few subsidies had been granted in the past. In this case it may be, that the mandate has led to increased salience of the subsidy scheme in these locations through the discussions surrounding the introduction of the mandate. We cannot disentangle effects on salience of the subsidy scheme from effects on actual adoption though we attempt to keep salience constant through the border research design.

[16] We estimated the model in the same specification as our main regression. The estimated coefficient on the dummy $BW2009$ is sometimes significant even in the strictest specification, suggesting that care is warranted in attributing the total estimated effect to the state mandate for newly constructed buildings.

2010. The results are found in appendix A.7 in Table A.7 and are consistent with the time averaged treatment effects. In our preferred specification there is no statistically significant evidence of time varying effects. The matched samples within 50 km of the border and across all four states suggest that the strongest impact of the mandate was in 2013 (approximately 3 granted applications per 1000 eligible buildings on average), with no statistically significant effect in the base period (2010).

Treatment identification based on geographic differences in regulation is potentially vulnerable to the existence of compound treatments when other factors vary discreetly at the border. This is especially a concern when the border is administrative as in our analysis. Given that we are able to eliminate time constant differences in our difference-in-differences model such factors would additionally need to vary over time to threaten identification in our setting. 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. We carry out the analysis using the unmatched data set within 50 km of the border to ensure sufficient observations for the kernel estimation. These results are therefore not comparable to our main results for the matched data sets. In the unmatched data within 50 km of the border we found no significant impact of the mandate. We nevertheless think this exercise is useful as a test of whether we observe patterns in the outcomes along the border that are suggestive of compound treatment effects. The results are shown in Table A.8 in appendix A.7. The robustness check does not differ from the main result for the comparable unmatched sample and provides no evidence of compound treatment effects along the border.

6. Discussion

Our results indicate that the introduction of the mandate on renewable heating technology affected technology adoption in municipalities as measured by the subsidy scheme. We estimate an increase in the number of granted applications of 2 per 1000 eligible buildings in the existing building stock on average. The effect is larger with up to 6 granted applications in municipalities where adoption levels prior to the mandate were below median. In this section we discuss the magnitude of this effect. We also assess whether the introduction of the mandate had an impact on replacement rates of existing fossil fuel heating systems.

While no actual data on retrofitting activities in Germany exist, standard estimates are that approximately 1% of existing buildings are retrofitted every year (Dena, 2019). Assuming that this value applies to Baden-Wuerttemberg, the mandate has led to an increase in the adoption of renewable heating technologies of about 20% compared to an expected 100% if all retrofitted homes used renewable technologies to comply with the mandate. This back of the envelope calculation leaves a wide gap to be covered by alternative compliance options or otherwise explained.

In principle, there could be at least four possible explanations, which we discuss in turn. 1) It could be that the state mandate is not perfectly enforced: The institutional framework within which the mandate operates makes this explanation unlikely. In Germany, chimney sweeps are responsible for reporting changes to heating systems as well as for regularly carrying out maintenance and supervision of existing installations. Moreover, the state mandate in its current form requires the responsible local authorities to report the compliance measure used in each case to the state statistical office. Unfortunately, there is no deadline for this reporting which means that a substantial backlog of cases are located at the municipal authorities but have yet to be included in the database according to the evaluation of the 2015 amendment of the state mandate (Pehnt et al., 2018).[17] In sum, it seems unlikely that the law is not enforced.

2) It could be that the state mandate is often not binding: This would imply that many households in Southern Germany switch to renewable heating technologies even in the absence of the mandate. Given the observed levels of adoption so far, and the relative price of renewable heating installations compared with the conventional gas alternative, this explanation seems unlikely to play an important role.

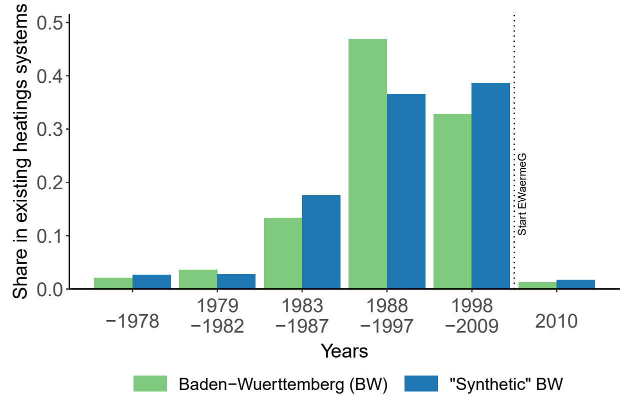
3) It is possible that households comply with the mandate using measures not observable in the data available: One explanation lies in the alternative measures allowing homeowners to comply with the regulation without installing renewable heating technologies (i.e., solar thermal, heatpumps or biomass installations, such as pellet stoves). One alternative measure to comply with the law is to replace the old conventional heating installation with a new conventional installation but using bio-fuels. For instance, it would be possible to use a mix of standard gas and biogas to heat in a conventional gas heating system.[18] The evaluation report indeed suggests that the share of cases in which renewable heating technologies covered by the MAP are used to comply with the mandate have declined over time. According to those cases for which compliance measures were reported to the statistical office, in 52% of the cases in 2010 either solar thermal collectors, biomass or heat pumps were used. In 23% of the cases bio-oil or biogas were used, whereas in 9% of the cases exemptions were granted (listed buildings). The remaining 16% used alternative compliance measures, e.g., insulation. In 2014, the share of MAP technologies had declined to 40% while the share of bio-oil and biogas had increased to 35%.[19] This shift is not necessarily in conflict with the mandate's objective of reducing emissions related to residential heating, although there have been questions raised about the additionality of biogas. Biogas in Germany is largely produced based on crops such as maize. As energy and fertilizer are needed for the production of biogas the resulting net GHG reductions are smaller than if biogas had been created based on waste (cf. Weiß, et al, 2013). The increased use of biogas and bio-oil is also at odds with the second declared objective of furthering technological developments in renewable space heating.

4) The increased cost of retrofitting due to mandated investments in more expensive technology may reduce the retrofitting rate in the short run as explained in the conceptual framework: An increase in the replacement cost of a heating system would likely lead to a later replacement, all else equal. Bushnell and Wolfram (2012) find such effects in their analysis of vintage based regulation for power plants where "major modifications" to existing plants implied the loss of their exemption status from installing expensive pollution control equipment. Unfortunately, there is no reliable data available on the retrofitting rate at the municipality level, so it is not possible to tell whether retrofitting activity has declined. However, circumstantial evidence based on the annual reports of the German chimney sweeps suggests that there may indeed be such an effect. The chimney sweeps collect data on fuel, size and vintage of residential heating systems. We use this data to examine how the age distribution of conventional heating systems has evolved over time in Baden-Wuerttemberg and other states. Based on data at the state level for the years 2010–2016, we construct a synthetic control

[17] The evaluation reports that the central database contained information about the measures used in about 30% of the cases for 2010 and 2011 by the end of 2017.

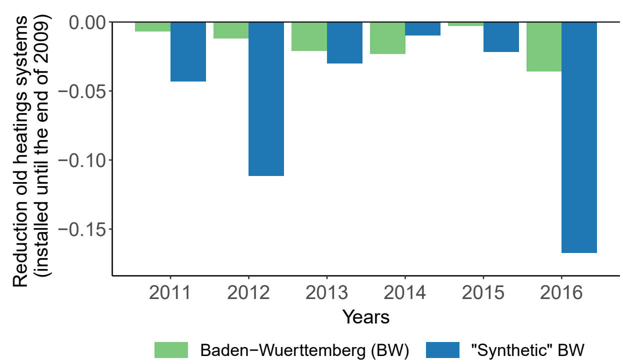
[18] Approximately 31% of the homes in Baden-Wuerttemberg are equipped with a gas (self-contained) central heating, compared to 47% across Germany (BDEW, 2015).The shares for the three neighboring states, Rhineland-Palatinate, Hesse, and Bavaria are 50%, 40%, and 29%, respectively.

[19] Bernauer and Reisch (2018) report that whereas 20% of gas suppliers across Germany offered a biogas tariff in 2017, 97% of the gas companies in Baden-Wuerttemberg offer a biogas product suggesting that the mandate may have affected supply of biogas. Biogas is generally available in the study period across all four states in our main estimations according to data from ene't GmbH.



Notes: Own computations based on data from ZIV (2018). The figure shows the share of vintage categories of gas heating systems in total gas heating systems installed at the end of 2009 on the left hand side. The green bars depict the observed values in Baden-Wuerttemberg, while the blue bars present the estimated values of the "synthetic" Baden-Wuerttemberg. The age distribution in the real and synthetic Baden-Wuerttemberg are fairly similar.

Fig. 6. Age distribution of existing gas heating systems.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Notes: Own computations based on data from ZIV (2018). The figure shows the reduction of gas heating normalized by the number of total gas heating systems installed until the end of 2009. For most years, the rate of reduction is much larger in synthetic Baden-Wuerttemberg than in the actual Baden-Wuerttemberg.

Fig. 7. Reduction in existing gas heating systems.

for the state of Baden-Wuerttemberg using information on the age distribution of installed heating systems for single- and two-family homes before 2010 in neighboring states.[20] We then compare reductions in old heating systems after 2010 in Baden-Wuerttemberg and our synthetic control.[21]

For gas heating systems, Fig. 6 illustrates the age distribution of Baden-Wuerttemberg and its calculated "synthetic" counterpart ("synthetic" BW) before the EWaermeG became effective for the existing building stock in 2010. Although there are differences across both age distributions, the majority of installed gas heating systems were installed after 1982 in both "states". In particular, the shares of heating systems installed from 1988 to 2009 (the last two categories before the start of the EWaermeG in the existing building stock) appear to be rather similar in Baden-Wuerttemberg and its synthetic version. In 2010, the shares of new gas heating systems seem to be of a similar magnitude, with a slightly larger share in the "synthetic" BW.

Fig. 7 shows that the estimated reductions in the synthetic version are larger than the ones observed for Baden-Wuerttemberg (except for 2014). This is consistent with a slower replacement of gas heating systems in Baden-Wuerttemberg compared to the synthetic control after the introduction of the policy. Findings are similar for oil heating systems. The chimney sweep data is not perfect, but we find the evidence it provides suggestive of a decline in retrofitting activities in Baden-Wuerttemberg in the years following the introduction of the mandate for the existing building stock. If the mandate reduces retrofitting activities in the short term, it may be that the time window we observe is too small to capture the total effect.

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 and security were the primary reasons for their first 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

[20] We also carried out the analysis based on all sixteen German states, but the results were unchanged.

[21] The synthetic control analysis is more carefully explained in appendix A.8.

replacing their heating system in the existing building stock. While still uncommon, it seems likely that such renewable heating mandates will spread in the future, both across Germany and other countries in order to achieve the target of net-zero CO2-emissions in the future. It is therefore important to understand how such mandates 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. One purpose of the state mandate is to increase the adoption of renewable heating systems in the existing building stock. A mandate should 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. 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 mandate became effective. We find evidence of a positive and statistically significant effect of 2 additional granted applications per 1000 eligible buildings *on average* after we control for distance to the border and match on population and building characteristics. The mandate induced more adoptions of renewable heating technologies (approximately 6 granted applications per 1000 eligible buildings) in municipalities where adoption was below median levels prior to the introduction of the grant. Our findings therefore suggest that the stick does indeed make the carrot more attractive. However, we also found suggestive evidence that the mandate may have led to a (temporary) decline in retrofitting activities consistent with what has been found in past research in other contexts.

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. For the overall cost-effectiveness of emission reductions from heating, allowing the standard to be met in a flexible way may be superior to a standard without compensatory measures, as owners can choose the measure that suits them best to comply with the mandate.

Finally, our study may underestimate the long run effect of the state mandate on the deployment of renewable heating systems by analyzing only the first five years after its introduction. Given our suggestive findings indicating that retrofitting activities may have declined following the introduction of the mandate, this seems likely. However, such reductions in retrofitting activities following the mandate would at least in the short term imply higher emissions associated with heating than would otherwise have been the case.

Author statement

Robert Germeshausen: Conzeptualization, Methodology, Formal Analysis, Data Curation, Writing – Original draft, Writing – Review and editing. Kathrine von Graevenitz: Conzeptualization, Methodology, Formal Analysis, Data Curation, Writing – Original draft, Writing – Review and editing. Martin Achtnicht: Conzeptualization, Methodology, Formal Analysis, Data Curation, Writing – Original draft, Writing – Review and editing.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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