State Mandates on Renewable Heating Technologies and the Housing Market

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ABSTRACT *We study the effect of a state-level mandate on renewable heating technologies on the housing market. The mandate requires a minimum share of 10% renewable energy sources when changing the heating system in the existing building stock. The mandate could lower the relative price of homes in the existing building stock. We implement a two-stage difference-in-differences nearest neighbor matching approach to identify the effect on prices taking advantage of differences in regulation by location and vintage of the building stock. We find no evidence of a negative effect of the mandate on housing prices.* (JEL Q42, Q48)

1. Introduction

Climate change is one of the biggest challenges currently facing the world's policy makers. It requires massive changes in how energy is generated and consumed across the board. Several countries have ambitious targets and policies in place to shape the transition toward a low-carbon society. The energy transition in Germany is a prime example with its demanding targets for German energy policy. One of the serious challenges concerns residential heating. In Germany, residential heating accounts for more than 20% of final energy consumption, and energy used for heating is only weakly linked with power generation (BMWK 2021). Because space heating still relies on decentralized fossil fuel installations, the need for a heating transition in addition to a power transition is apparent. Recent years have seen some progress being made, and the current share of renewable energy source in heating is approximately 15% at the federal level. Renewable energy sources are predominantly used in housing built after 2009 and much less so in the older housing stock, which makes up the majority of residential homes in Germany. In consequence, close to 70% of households heat with fossil fuels. A variety of policy measures at the state and federal levels incentivize the heating transition. Little is known about the effect these policies have on the housing market. This article studies the effects of a state mandate directed at increasing the share of renewable energy sources used in the older building stock on the housing market.

Federal regulation for heating in Germany comes mainly in the form of building codes that apply to new construction, including a federal mandate on renewable heating technologies. Making the existing building stock more energy efficient has become ever more pressing. As a result, a federal mandate on renewable heating in the existing building stock is planned to come into effect in 2024. This mandate is expected to require homeowners to cover 65% of energy use for heating with renewable sources when a heating system is replaced. Until now, the federal tools used in the existing building stock have been subsidy schemes, such as the Market Incentive Program (Marktanreizprogramm) for heating technologies based on renewable energy sources and the subsidized loans offered by the government-owned development bank KfW (Kreditanstalt für Wiederaufbau). This

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article takes advantage of the fact that the federal state of Baden-Wuerttemberg introduced a state law mandating the use of renewable energy sources in existing building stock when exchanging the heating system, effective 2010. We use the introduction of this state mandate to assess the effects such regulation has on the housing market. The Baden-Wuerttemberg state mandate on renewable heating technologies increases the costs of retrofitting existing homes by mandating use of renewable heating technologies or the implementation of other compliance options, such as superior insulation to reduce greenhouse gas emissions associated with the existing building stock.[1] At least two effects on the housing market are conceivable: (1) retrofitting activity could decline in response to an increase in costs as more homeowners decide to repair an existing heating system rather than replace it, and this could lead to a lower quality of the existing housing stock than would otherwise have been the case and consequently lower prices; and (2) the expected compliance cost could be capitalized into property prices, and such capitalization should reflect the perceived extra cost induced by the mandate and the (subjective) probability of a heating system failure making retrofitting necessary and provides an indication of the perceived financial burden associated with the mandate; this information is relevant to policy makers in assessing the distributional effects of climate policies in the building sector.

Unfortunately, there are no microdata available on retrofitting activity in Germany, and we cannot assess whether the mandate influenced retrofitting directly.[2] However, capitalizing retrofitting cost into housing prices for existing homes with preinstalled heating systems can be assessed using available housing market data on asking prices. We ask whether the state mandate had an effect on asking prices of affected homes. We construct a research design based on the spatial discontinuity at the state border and the variation in applicability of the mandate by building vintage. Specifically, we estimate a spatial difference-in-differences model comparing the prices of old and new houses for sale within and outside of Baden-Wuerttemberg. This design allows us to identify effects on the prices of houses for sale in the existing building stock in this state.

Our findings reveal no statistically significant evidence of capitalization in terms of rebates on houses built prior to 2009 in the housing market. The lowest cost compliance option (using conventional heating systems with biofuels) lies within our 95% confidence intervals in two out of three years. In contrast, the higher compliance cost associated with switching to a renewable heating technology lies outside the confidence intervals except in the last year. The availability of relatively low-cost measures to comply with the mandate may explain these findings. It may be that the cost of complying by using these measures is sufficiently low that they are dwarfed by other expenditures associated with retrofitting. Other possible explanations for this result include the salience of the regulation, which may be low among sellers (or they may perceive it as low among buyers), resulting in a failure to incorporate such capitalization in their asking prices.

2. Related Literature

This article contributes to the growing literature addressing rationality of homeowners and saliency of energy costs related to space heating. Past research has found that energy costs are salient to home buyers. For example, several studies show that homes with energy labels certifying them as relatively efficient sell at a price premium (Brounen and Kok 2011; Hyland, Lyons, and Lyons 2013; Bruegge, Carrion-Flores, and Pope 2016). Myers (2019) investigates the effect of fuel prices on the housing market and finds that effects on house (transaction) prices are consistent with

[1] Germeshausen, von Graevenitz, and Achtnicht (2022) study the effect of the same mandate on the uptake of renewable heating technologies and find evidence that homeowners have complied by installing more renewable heating technologies.

[2] Germeshausen, von Graevenitz, and Achtnicht (2022) find suggestive evidence that retrofitting activities declined after the introduction of the mandate, using information on the age distribution of fossil heating systems, but a general decline in the average quality of the existing building stock due to delayed retrofitting would take time to capitalize into prices.

full capitalization of future energy cost. Mandatory disclosure policies have been found to lead to higher capitalization rates of energy efficiency in Myers et al. (2022), although they also find evidence to suggest that sellers and buyers may be symmetrically uninformed about energy efficiency levels of homes.

For Germany, evidence has been found that mandatory disclosure of energy use information in the shape of energy performance certificates reduces asking prices of the relatively energy-inefficient houses. The study by Frondel, Gerster, and Vance (2020) focuses on 2013–2015 and examines the introduction of mandatory energy performance certificates in May 2014. They hypothesize that particularly sellers of less efficient houses would be reluctant to reveal accurate information on energy performance in the absence of mandatory disclosure. Their findings support this hypothesis. The introduction of mandatory energy performance disclosure causes asking prices to decline by up to 11% for those sellers who would not otherwise have disclosed this information. When distinguishing between building vintage, the effect is found to be insignificant for houses built in 2002 or later and increase with age for houses built before that (almost 4% for homes built between 1977 and 2002 and almost 10% for homes built prior to 1977).

Our study is also relevant to the emerging literature on the effect of building energy codes on energy consumption and home values. Bruegge, Deryugina, and Myers (2019) study the effectiveness and distributional effects of building energy standards in California. By exploiting spatial and temporal variation in the stringency of California's building energy standards, they identify the effectiveness of building energy codes in reducing energy use and the effects of varying levels of stringency on the prices and characteristics of homes. They find that stricter energy codes reduce by 4%–6% the size and number of bedrooms primarily in homes occupied by low-income households. They also find that building code stringency capitalizes into housing prices and increases dispersion across income quintiles. For low-income households, stricter energy building codes lower prices by some 8%–12%, whereas for higher-income households, prices increase by 2% on average. The authors conclude that these effects on prices are inadequately explained by the changes in observable housing characteristics, which suggests that unobservable characteristics also change in response to the stringency of the building energy codes. In contrast to existing studies, this article addresses the effect of a mandate on technology choice when retrofitting existing homes. Almost all building energy codes focus only on construction of new homes, neglecting the vast majority of houses in the existing housing stock. Our research design is similar to that of Bruegge, Deryugina, and Myers (2019), but in contrast to their study, the main characteristics of the houses subjected to the mandate on renewable heating are fixed and cannot be adjusted in response. Germeshausen, von Graevenitz, and Achtnicht (2022) study the effect of the same mandate on the uptake of renewable heating technologies. They find evidence that the mandate has induced additional uptake of renewable heating technologies, such as solar thermal collectors or biomass furnaces, which are more costly than conventional heating systems in the period under study. Moreover, alternative compliance measures involving insulation or the use of bio-oil or bio-gas come with additional costs in comparison to the status quo and may capitalize into housing prices.

3. Background

Building Energy Codes in Germany

Germany has had building energy codes regulating the thermal insulation of buildings since 1977 and energy efficiency requirements on newly installed and existing heating systems since 1978. Amendments have increased the stringency of these requirements at regular intervals. The Energy Savings Ordinance (Energieeinsparverordnung [EnEv]), introduced in 2002, regulates the annual primary energy requirement of newly constructed and renovated buildings. The energy performance standards in the EnEv have since become increasingly stringent in a series of amendments. Approximately two-thirds of the residential buildings in Germany were built before 1979 according to ARGE (2016). However, energy retrofitting has been carried out for a large majority of these homes. Popular energy efficiency measures include improved efficiency of heating systems, windows, and roof insulation.

Renewable Energy in Space Heating

The German Renewable Energies Heat Act (EEWaermeG) is a federal law mandating a minimum share of renewable energy sources for all new buildings with a building permit granted after January 1, 2009, when it entered into force. The federal law aimed to increase the share of renewable energy sources in heating to 14% by 2020. It mandates a minimum share of renewable energy use in space heating. The exact share depends on the technology employed (e.g., 15% for solar thermal collectors, 50% for biomass or a heat pump, and 30% for bio-gas). Alternative measures of compliance include exceeding the energy efficiency requirements in the EnEv to degrees specified in the law.

The federal law on renewable energy sources in space heating partly replaces a Baden-Wuerttemberg-specific law introduced in 2008. In contrast to the federal law, which applies only to new buildings, the state mandate addresses new and existing buildings. The Baden-Wuerttemberg state mandate (EWaermeG) requires a minimum share of renewable energy use in space heating of at least 10% when replacing the heating system in the existing building stock for residential use. It was introduced in 2008 with effect from 2010 for existing homes. Specifically, compliance requirements for the mandate for the existing building stock vary by technology, for example, for solar thermal collectors a homeowner would need to install 0.04 m^2 of living space to comply corresponding to a 6 m^2 installation for a house with 150 m^2 of living space. A homeowner switching to a wood pellet stove would over-comply as wood pellets are graded as renewable, whereas homeowners switching to a heat pump must choose one satisfying a minimum annual performance factor.

Alternatively, the homeowner can replace the existing fossil fuel heating system with a new one and use a bio-gas or bio-oil tariff certified to contain at least 10% biofuels. Compensating measures are similar to those allowed in the federal law for new buildings. The state mandate was amended in 2015 with stricter requirements (now 15%) but more lenient compliance measures (e.g., producing a refurbishment plan is equivalent to 5% renewables in energy use regardless of whether the identified measures in this plan are implemented). There is a fine for noncompliance of up to €100,000. The law is enforced by the local building authorities at the municipal level.[3]

Renewable heating technologies are generally more expensive than conventional heating with the cheapest conventional option on the market in the period being natural gas. The net present value (NPV) of the difference in costs amounts to between €9,000 and €11,000 when comparing natural gas and the cheapest renewable technology. This calculation assumes a lifetime of 18 years for an installation and a discount rate of 4.5%. Other compliance options, such as facade insulation, are much more expensive. The cheapest alternative is to use conventional fuels with a minimum share of bio-oil (NPV cost difference of €3,000–€13,000 over 18 years, depending on the condition of the building) or bio-gas (NPV cost difference of €2,000–€5,000 over 18 years, depending on the condition of the building), assuming the old heating system is replaced with a newer system with the same fuel type.[4] Although only about 31% of buildings used for housing in Baden-Wuerttemberg heat with gas according to BDEW (2015b), changing the heating system from oil to gas

[3] After replacing the heating system, the local district chimney sweep has to approve the new installation and informs the competent building authority. In addition, the house owner is required to submit a form about the applied compliance measure.

[4] These costs are estimated as in Germeshausen, von Graevenitz, and Achtnicht (2022) based on the heating energy demand for an example house described in the evaluations of the subsidy scheme for renewable heating technologies. A main factor is the condition of the house (renovated or unrenovated), as this has a substantial effect on the energy requirement. The procedure and results are described in more detail in Appendix A1. We use 2019 information on the price of bio-oil and bio-gas, both of which were approximately 10% more expensive than conventional oil and gas.

Table 1
Summary Statistics: Numeric Variables

Variable	Min.	Median	Mean	Max.	*N*
Price (€)	65,000	269,000	286,092	885,000	28,696
Space (m^2)	30	146	155	287	28,696
Year of construction	1901	1985	1983	2016	28,696
No. of rooms	1.00	5.00	5.65	10.00	28,696
Unemployment (%)	0.90	2.90	3.08	7.20	28,696
Income tax revenues (€ per capita)	243	441	440	636	28,696
Real estate tax factor (%)	150	350	352	800	28,696

Note: This shows the summary statistics for the numeric variables in our data set for 2012–2014. We excluded dwellings built before 1901, listed homes, homes with missing information on main characteristics, and homes posted online for more than 12 months. We also dropped houses with renewable heating systems built before 2009, those that are connected to district heating, outlier values on living space and number of rooms, and the lower and upper 0.5% of the price offers.

would involve additional one-time costs of €3,000–€8,000.

The 2018 evaluation of the state mandate commissioned by the Ministry of the Environment, Climate Protection and the Energy Sector, Baden-Wuerttemberg (Pehnt et al. 2018) considers the compliance methods chosen as reported by the local building authorities. In 2010, renewable energy technologies (solar thermal collectors, biomass, or heat pumps) were used in approximately 52% of cases, with solar thermal installations accounting for roughly 30% of the cases alone. Heating with bio-oil or bio-gas was used in 23% of cases, and alternative measures (e.g., insulation) were used in 16% of cases. However, the use of bio-oil and bio-gas has been increasing over time.[5] In 2015, prior to the amendment taking effect, compliance through bio-oil or bio-gas accounted for 46% of cases, and the share for renewable energy technologies dropped to 34%, with alternative measures at 12%. Over the whole period, the share of cases exempt from the mandate due to infeasibility remains stable at 8%–9%. In our empirical strategy, we let capitalization rates to vary over time to allow for changing compliance cost. The state mandate has also been accused of causing a decline in the state's rate of refurbishment. Although microdata to study this potential effect are not available (Ministry of the Environment, Climate Protection and the Energy Sector of Baden-Wuerttemberg 2011), Germeshausen, von Graevenitz, and Achtnicht (2022) investigate aggregate data and find suggestive evidence that the replacement rate of heating systems in Baden-Wuerttemberg was lower than expected after the introduction of the mandate.

Because the state mandate comes into effect when a heating system is replaced, an impact on housing prices would depend on the (discounted) extra cost of complying with the mandate and the perceived likelihood of having to replace the heating system within the ownership period. Depending on the technology, compliance costs would make up between 0.7% and 3.8% of the mean house price in our sample (Table 1; NPV of €2,000–€11,000 compared with a mean house price of €286,092). Furthermore, there are subsidy schemes at the federal level for investments in residential space heating. The investment cost subsidies for renewable heating technologies (solar thermal, wood pellets, or heat pumps) from the Market Incentive Program vary by technology and mostly lie in the region of 9%–11% of investment cost. The effect of the Baden-Wuerttemberg state mandate the KfW on uptake of this subsidy scheme is studied in Germeshausen, von Graevenitz, and Achtnicht (2002). The KfW also provides investment cost subsidies and subsidized loans for retrofitting existing homes (e.g., Energieeffizient Sanieren products 151 and 430). These cover 10%–30% of the investment cost with a maximum €30,000 per unit of housing but come with strict minimum requirements on the level of energy efficiency attained and

[5] As mentioned later in the discussion, suggestive evidence shows that there was a supply response making such biofuels more easily available in Baden-Wuerttemberg compared with neighboring states (Bernauer and Reisch 2018).

Table 2
Summary Statistics: Categorical Variables

Variable	Mean	N	Variable	Mean	N
Semidetached house	0.179	5,141	Building projected (no)	0.829	23,781
One-family house	0.512	14,697	Building projected (yes)	0.171	4,915
Unspecified 1- or 2-family house	0.059	1,679	Border Hesse	0.175	5,023
Row house	0.128	3,670	Border Rhineland-Palatinate	0.32	9,189
Two-family house	0.122	3,509	Border Bavaria	0.505	14,484
Garden (no)	0.366	10,496	Outside Baden-Wuerttemberg	0.442	12,697
Garden (yes)	0.634	18,200	Baden-Wuerttemberg	0.558	15,999
Good equipment	0.409	11,743	Built after 2008	0.25	7,161
High-quality equipment	0.289	8,283	Built before 2009	0.75	21,535
Normal equipment	0.302	8,670	No refurbishment after 2008	0.93	26,688
Good building condition	0.492	14,127	Refurbishment after 2008	0.07	2,008
Normal building condition	0.508	14,569			

Note: This shows the summary statistics for the numeric variables in our data set for 2012–2014. We excluded dwellings built prior to 1901, listed homes, homes with missing information on main characteristics, and homes posted online for more than 12 months. We also dropped houses with renewable heating systems built before 2009, those that are connected to district heating, outlier values on living space and number of rooms, and the lower and upper 0.5% of the price offers.

would typically require further investments than simply replacing the heating system.

4. Data

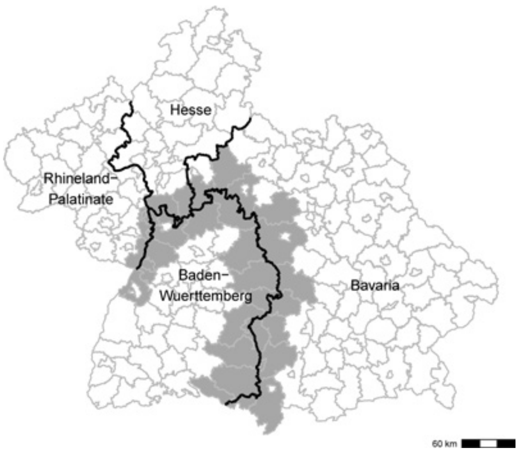
The state-specific regulation and the regional nature of housing markets make an empirical strategy based on comparing housing prices along the state border a natural choice. We make use of several data sets for the analysis. The primary data set is the data on housing prices provided by Empirica GmbH. These data consist of characteristics and asking prices for individual homes offered for sale through real estate websites. We merge the housing market data with data on regional socioeconomic indicators from the INKAR data set and data on the real estate tax factor determining the municipal property tax supplied by the German Federal Statistical Office (Destatis). The summary statistics of the full data set are shown in Tables 1 and 2.

Housing Market Data

Microdata on actual transactions in the housing market is considered the gold standard for hedonic research (Bishop et al. 2020). However, such information is not available at a large scale for Germany. Instead, we use data on asking prices scraped from online real estate portals and provided to us by Empirica GmbH. These data are available beginning in 2012 and cover all of Germany. The state mandate for existing buildings was introduced in 2010, so this implies that our sample does not cover the period before and after it became effective. Instead of comparing sales prices across time, we develop an identification strategy based on location inside or outside the regulated state of Baden-Wuerttemberg and building vintage as described further below. Our strategy has the advantage that it does not require the housing market or in particular the hedonic function to be stable over time. In contrast to many other developed economies, Germany has experienced a real estate boom starting in 2009, which makes the assumption of a stable hedonic function over this period less likely to hold.

We have obtained data for the state of Baden-Wuerttemberg and the neighboring states Hesse, Rhineland-Palatinate, and Bavaria. Our sample covers houses in counties on both sides of the Baden-Wuerttemberg state border, as shown in Figure 1. For 2012–2014, we have a total of 56,678 houses offered for sale. We reduce the data set by removing observations with missing information on important characteristics and houses built before 1901, listed properties, houses in a bad condition (as indicated in the data provided by Empirica GmbH), or houses without central heating. In addition, we exclude homes posted online for more than a year,

Figure 1
Counties on Both Sides of the Baden-Wuerttemberg Border



Note: Counties (in gray) are shown on both sides of the Baden-Wuerttemberg border and the neighboring counties of Rhineland-Palatinate, Hesse, and Bavaria for which housing offers were collected.

houses with renewable heating systems that were built before 2009—since these presumably already comply with the mandate—and houses that are connected to district heating.[6] Furthermore, we remove observations with outlier values (defined as observations that lie outside of the upper quartile by more than 1.5 times the interquartile range) on living space and number of rooms, as well as the lower and upper 0.5% of the price offers.

After data cleaning, we are left with 28,696 unique houses in the data set. The data include a wide variety of characteristics, such as size, number of rooms, year of construction, main source of heating, quality of the house as graded by Empirica GmbH, and availability of a garden. There is also information on whether the house was refurbished after 2008 when the mandate was passed. However, we have no information about what the refurbishment consisted of and whether the heating system was exchanged. We include the variable to control for the fact that a change of heating system may have taken place for these houses and treat them as a separate category. We thus have three classes of buildings: old (constructed before 2009), new (built 2009 and later), and those refurbished after 2008. While the data set does contain information on the location of the house, this information is generally limited to the centroid of the municipality or postal code area in question.

INKAR and Destatis

The INKAR data are provided by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development and are 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). We use the most disaggregated level of information available, which is at the level of the 4,567 municipalities or municipal associations (*Gemeindeverbände*). The real estate tax factor (*Hebesatz*) is set at the municipal level and determines the level of property tax paid by the owner along with the assessed value of the plot (*Einheitswert*) and the type and value of construction (*Grundsteuermesszahl*). The tax factor varies substantially across municipalities, as can be seen in Table 1. Income tax revenues relate to the share of income taxes appropriated to the municipality, which is currently 12% on capital income and 15% for other forms of income.

5. Empirical Strategy: Difference-in-Differences Nearest Neighbor Matching

We use differences in the coverage of the state mandate to identify the potential effect on housing prices adapting an approach

[6] We observe the type of heating for about two-thirds of the sample (distributed equally across new and existing buildings). For those existing homes with information on the heating system, 95% heat with fossil fuels. The remaining 5% heat with renewable energies and are already compliant with the mandate. For new buildings with information available, renewable technologies are installed in about 60%. The share of renewables in this building segment is high due to the federal building codes on renewable heating in new homes mandated by the EEWaermeG. We keep new homes with renewable heating in place in the sample. We also keep houses where the type of heating system is unobserved in the sample.

developed in Haninger, Ma, and Timmins (2017) in the context of brownfield remediation. In particular, homes constructed after January 1, 2009, in all German states were subject to the federal Renewable Energies Heat Act, requiring a minimum use of renewable heating technologies. In contrast, homes built before that date are only subject to a state mandate on renewable heating in existing buildings in the state of Baden-Wuerttemberg. We identify an effect on housing prices by analyzing differences in housing prices across the state border between new and existing buildings.

We write the hedonic price function to explain prices P_{itk} as a function of the home's covariates X_{itk}, where indexes refer to i (house), t (year), and k (border segment defined by neighboring state). Some of the homes are built before 2009 ($OLD_{ik}=1$) and some are built after ($OLD_{ik}=0$). Furthermore, we have a third category: homes built before 2009 that underwent a refurbishment after 2008 ($Refurbishment(>2008)_{ik}=1$). Similarly, some homes are located in the state of Baden-Wuerttemberg ($BW_{ik}=1$) and some are located outside ($BW_{ik}=0$). We model the house characteristics, including refurbishment status, using a flexible function $f(X_{itk};\theta_t)$. For those homes built before 2009 and located in Baden-Wuerttemberg, we expect to find an average treatment effect on the treated, π_t, of the state mandate if one exists:

$$P_{itk} = \beta_{0t} + \beta_{1t}OLD_{ik} + \beta_{2t}BW_{ik} + \pi_t OLD_{ik} \times BW_{ik} + f(X_{itk};\theta_t) + u_{itk}. \quad [1]$$

A goal of this estimation procedure is to cancel out the effect of the flexible function of a home's characteristics so that this function does not have to be estimated. The procedure is based on (bias-corrected) matching and requires two steps.

In the first step, consider all homes built before 2009 ($OLD_{ik}=1$), which include homes that were refurbished after 2008:

$$P_{itk} = (\beta_{0t} + \beta_{1t}) + (\beta_{2t} + \pi_t)BW_{ik} + f(X_{itk};\theta_t) + u_{itk}. \quad [2]$$

Each home in Baden-Wuerttemberg ($BW_{ik}=1$) is matched to a set of J control homes in the neighboring state using genetic matching (see Diamond and Sekhon 2013). For each treatment home, a counterfactual is constructed based on the matched controls (i.e., a weighted average of the price of each of the J control homes, $P_j^{(itk)}$). Based on the counterfactual, an individual treatment effect for each treatment home can be calculated and stored in the vector P_t^{OLD} of length N_t corresponding to the number of old homes in Baden-Wuerttemberg in year t. The average treatment effect for all old homes is given by

$$(\beta_{2t} + \pi_t) = \frac{1}{N_t}\sum_{i=1}^{N_t}\left(P_{itk} - \frac{1}{J}\sum_{j=1}^{J}P_j^{(itk)}\right). \quad [3]$$

Now consider all homes built after 2009 ($OLD_{ik}=0$):

$$P_{itk} = \beta_{0t} + \beta_{2t}BW_{ik} + f(X_{itk};\theta_t) + u_{itk}. \quad [4]$$

Following the same procedure with matching each home in Baden-Wuerttemberg to a new home outside delivers a set of individual treatment effects stored in the vector P_t^{NEW} and of length $\tilde{N}_t$ and an average treatment effect:

$$\beta_{2t} = \frac{1}{\tilde{N}_t}\sum_{i=1}^{\tilde{N}_t}\left(\tilde{P}_{itk} - \frac{1}{J}\sum_{j=1}^{J}\tilde{P}_j^{(itk)}\right).$$

We need to further correct for potential bias in the first-stage estimates. This is particularly important given that our treated and control homes are always located in different municipalities (i.e., we need to correct for characteristics of these municipalities that differ, such as the real estate tax factor). As in Haninger, Ma, and Timmins (2017), we apply the bias-corrected matching estimator from Abadie and Imbens (2011). The details on the implementation of this approach are found in Appendix A1.

In the second step the average treatment effect on the treated for each year is recovered by simply differencing the average treatments from the first step:

$$\pi_t = \frac{1}{N_t}\sum_{i=1}^{N_t}\left(P_{itk} - \frac{1}{J}\sum_{j=1}^{J}P_j^{(itk)}\right) - \frac{1}{\tilde{N}_t}\sum_{i=1}^{\tilde{N}_t}\left(\tilde{P}_{itk} - \frac{1}{J}\sum_{j=1}^{J}\tilde{P}_j^{(itk)}\right), \quad [5]$$

where the first and the second term correspond to the average treatment effect for old homes,

$P_{it}^{OLD,\,bcm}$, and for new homes, $P_{it}^{NEW,\,bcm}$, respectively. In other words, it is a bias-corrected difference-in-differences estimator using variation across the state borders and home vintages. The difference between the prices of new homes in Baden-Wuerttemberg and neighboring states should capture state-specific factors, such as the property transfer tax, which differ between states and are likely to capitalize into prices. The difference between the prices of old homes in Baden-Wuerttemberg and the neighboring states should capture such factors in addition to the effect of the state mandate on renewable heating.[7] Therefore, differencing the two differences isolates the effect of the renewable heating mandate.

The bias-corrected difference-in-differences estimator does not directly account for differences in the individual house vintages. In particular, it does not easily allow us to control for refurbishment status after the state mandate was introduced. To this purpose we estimate a simple linear model where we regress the bias-corrected estimates P_t^{bcm} on an indicator for construction prior to 2009, matching covariates including refurbishment status and control for municipality fixed effects (ν_r):

$$P_t^{bcm} = \pi_t OLD_i + X_{itk}\delta_t + \nu_r + \epsilon_{itk}. \qquad [6]$$

As a final robustness check, we estimate a standard cross-sectional hedonic regression with spatial fixed effects in which we specifically model $f(X_{itk};\theta_t)$ from equation [1].

Our research design is potentially vulnerable to spillover effects. As demand for older homes affected by the mandate declines along the border with Baden-Wuerttemberg, demand for substitutes in the neighboring states could increase. This would lead us to overstate the average effect on prices in comparison to capitalization for homes further from the border where substitutes are not available. Our estimates may therefore be seen as an upper bound on the capitalization of the private cost of the mandate.

6. Results

Matching

To control for differences in observable characteristics, we use the method of genetic matching as developed by Diamond and Sekhon (2013) and match on several housing characteristics: garden availability, quality indicators (condition, furnishing class), number of rooms, living space, and year of construction. We also match exactly with regard to homes undergoing refurbishment after 2008 and, for new buildings, whether they are projected. At the municipal level, we include information on unemployment, income tax revenues, and the real estate tax factor. We match exactly on housing type (e.g., detached house, row house) as well as the federal border segment to ensure spatial proximity of treatment and control houses. Finally, the propensity score estimated based on the same variables is included in the algorithm. The genetic matching algorithm comprises Mahalanobis matching and propensity score matching, and the weights determine the extent to which each approach influences the outcome. We match houses within and outside of Baden-Wuerttemberg for each calendar year separately. We match with replacement each treated house with two control houses ($J = 2$).[8]

We calculated several descriptive statistics showing the outcome of our matching procedure. The QQ-plots and tables showing standardized mean differences in the matched and full sample of the covariates used for matching can be found in the Appendix. They show that matching improves the balance in covariates significantly across the board, particularly with regard to income tax revenues, which proxy for the income level of the municipality,

[7] Although differences in price levels between existing and new homes induced by different property tax rates could provide a potential threat to identify the effect of the mandate, in our sample the difference in price levels in Baden-Wuerttemberg compared with the other states are similar for existing and new homes (about €24,000 vs. approximately €22,000, respectively). The average price of existing homes is €292,017 in Baden-Wuerttemberg and €268,304 in the other states; for new homes, the averages are €318,183 (Baden-Wuerttemberg) and €296,380 (outside Baden-Wuerttemberg).

[8] We found that covariate balance after 1:2 matching improves compared with 1:1 matching.

Table 3
Genetic Matching: Overview by Year of Sale in Baden-Wuerttemberg

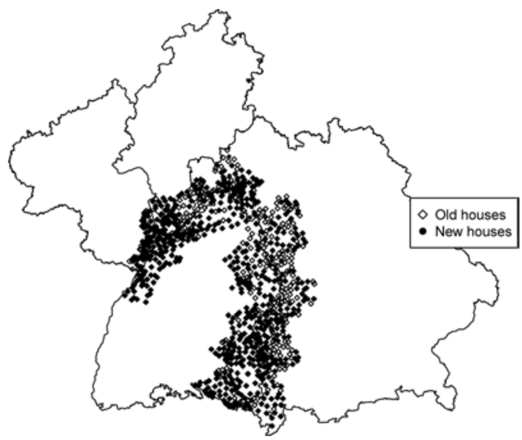
	Old BW	New BW	Total BW	Old Non-BW	New Non-BW
2012					
All	4,076	1,392	5,468	3,404	1,130
Matched	4,064	1,386	5,450	2,241	704
Unmatched	12	6	18	1,163	426
2013					
All	3,914	1,286	5,200	2,977	1,008
Matched	3,910	1,277	5,187	1,899	658
Unmatched	4	9	13	1,078	350
2014					
All	3,971	1,360	5,331	3,193	985
Matched	3,962	1,347	5,309	2,248	615
Unmatched	9	13	22	945	370

Note: This shows the number of observations by category (new/old) and location within or outside Baden-Wuerttemberg in the full and matched samples as well as the number of observations not matched.

and size of the house (the living area, number of rooms). A few significant differences do remain, such as in the real estate tax factor, but these differences are similar across building vintages, suggesting that the triple difference may correct for this bias.

The number of observations in the full and matched samples is shown in Table 3 and the spatial distribution is shown in Figure 2. Old houses (including refurbished ones) are dots, whereas new homes are diamonds. The matched sample is distributed along both sides of the state border without any obvious gaps or clustering.

Figure 2
Matched Sample: Old and New Houses on Both Sides of the Baden-Wuerttemberg Border



Note: The locations of old and new houses correspond to the centroid of the municipality in which the house is located.

Capitalizing the State Mandate into Prices

The main findings from the estimations of equations [5] and [6] are shown in Table 4, panels A and B, respectively. We expect a negative and significant effect of the mandate consistent with cost capitalization. Recall that our NPV calculations in Section 3 suggest that compliance costs lie somewhere between 0.7% and 3.8% of the mean house price. Table 4, panel A, shows the differences in means between the price differences of old and new buildings inside and outside of Baden-Wuerttemberg (equation [5]). Although these differences are negative (–0.8% to –1.2% of the house price) for two out of three years, they are not statistically significant. As noted, this estimator does not allow us to control for refurbished houses or municipality fixed effects. In Table 4, panel B, we regress the price differences that we obtained in the first step on an indicator for old homes, the matching covariates, and include municipality fixed effects (equation [6]). This allows us to control for potential confounding due to retrofitted older buildings and remaining differences in covariates after matching. Our preferred estimates are therefore those given in panel B.

Our results indicate no statistically significant effect of the mandate in the regression corrected results. In contrast to panel A, the point estimates are positive for two out of three years (from –0.4% to 4.5% of the house

Table 4
Results: Difference-in-Differences Nearest Neighbor Matching

	2012	2013	2014
Panel A: Mean Difference	−0.0084	−0.0127	0.0261
t-Statistic	−0.4783	−0.6838	1.4050
95% confidence interval	[−0.043; 0.026]	[−0.049; 0.024]	[−0.010; 0.062]
Panel B Variables			
Old	0.0118	0.0446*	−0.0043
	(0.0205)	(0.0230)	(0.0251)
	[−0.028; 0.052]	[−0.001; 0.090]	[−0.054; 0.045]
Refurbishment (>2008)	0.0012	0.0108	0.0285
	(0.0246)	(0.0276)	(0.0269)
	[−0.047; 0.049]	[−0.043; 0.065]	[−0.024; 0.081]
Observations	5,419	5,151	5,280
Adjusted *R*-squared	0.22	0.25	0.22

Note: Panel A reports the difference in means across bias-corrected estimates from the first stage and the corresponding *t*-statistic and 95% confidence intervals for the three different years. Panel B shows the results for the dummy variables "Old" and "Refurbishment (>2008)" while controlling for a set of individual housing characteristics and municipality fixed effects for 2012–2014. Each year is estimated in a separate regression. The standard errors are in parentheses and clustered on municipality level, and the 95% confidence intervals are in square brackets.
* $p < 0.10$.

price), though they remain mostly insignificant at conventional levels. The exception is a positive effect, significant at the 10% level for old buildings sold in 2013. In general, we fail to reject the hypothesis that the coefficients for old buildings are equal to the ones for buildings that underwent refurbishment after 2008.

Taken together, our findings suggest that the mandate had no substantial negative effect on asking prices for affected homes on average. The 95% confidence intervals include negative effects up to 5% of the house price.[9] In two out of three years, however, our estimated NPV for the cheapest renewable technology (€9,000–€11,000, corresponding to 3.1%–3.8% of the mean house price) does lie outside of the 95% confidence interval in panel B. In consequence, we can reject that capitalization of a magnitude similar to our calculated NPV for the cheapest renewable technology occurred in those years, although our lowest estimate of the compliance costs for households opting to use bio-gas or bio-oil are consistently in the confidence interval. The results from the standard hedonic regression are described in Appendix A7. These findings are consistent with our main results in that we find no significant and negative effect on housing prices for older buildings in Baden-Wuerttemberg. In general, our findings are in line with the results in Germeshausen, von Graevenitz, and Achtnicht (2022): although the mandate did have a positive and significant impact on take-up of renewable heating technologies, the size of that effect (20% increase in adoption, assuming a retrofitting rate of 1% per year) leaves a considerable gap to be explained by alternative compliance options also discussed in that study.

7. Discussion

There are several aspects of the analysis and the empirical setting that may contribute to explaining our findings. We discuss these in turn. Our analysis is based on matching of treated and control houses along the state border. While we match on a wide variety of housing attributes, some information is simply not available to us (e.g., exact location of the house in a municipality). Consequently, we cannot perfectly control for local amenities. In other words, treatment and control

[9] We also pooled the data across years and ran the regression in panel B. The point estimate of the treatment effect is positive but insignificant. Results are available from the authors on request.

houses may still differ in important ways. Our analysis is based on the assumption that there are no systematic differences in, for example, amenity levels across the state border correlated with the availability of new or old houses.

Another concern is the fact that we base our analysis on asking prices rather than transaction prices. This may raise the question of whether sellers are responsive to concerns regarding energy costs. Given the scarcity of transactions data for Germany, Frondel, Gerster, and Vance (2020) also use asking prices for their study of the impact of mandatory disclosure of energy performance for housing. For a subsample of observations in Berlin, they are able to obtain transaction prices and compare list and transaction prices. They find a small but relatively constant difference between the two over time. The introduction of mandatory energy performance certificates does not seem to affect this gap. Although this result may be specific to the Berlin subsample, it provides us with some confidence that our findings are relevant to the realized prices in the housing market. Moreover, the fact that Frondel, Gerster, and Vance (2018) find effects on the asking prices suggests that sellers are aware of the saliency of a house's energy performance for buyers. Their study focuses on 2013–2015, which overlaps with our time frame.

Assuming that sellers are indeed responsive to energy costs, why do we find little evidence of capitalization? One explanation may be that the state mandate—or the related compliance cost—is not well known among sellers. Whereas buyers have a strong incentive to investigate potential retrofitting costs, the same may not hold for sellers. They may be less aware of current legal requirements as a result. Myers et al. (2022) find evidence consistent with U.S. sellers not being well informed about a local mandate on energy audits prior to sales. We have no direct information on the awareness of the mandate. Instead, we use a variety of proxies that capture different factors, which may influence general awareness of the mandate:

- The experience of the population is included, since less experienced buyers may not be aware of costs of retrofitting and the rules that apply.
- The level of housing market activity may play a role for the spread of information and for capitalization. The German housing market has been on a positive trend since 2009 with substantial price increases in some regions. Local demand for housing is likely to be correlated with construction activities. In a seller's market, capitalization would be unlikely even if people were well informed.
- Owner-occupancy rates in Germany are relatively low at approximately 50%. Households in municipalities with more owner-occupiers are likely to be better informed about the rules for retrofitting.
- There may be differences between rural and urban municipalities (more urban municipalities are likely to have a larger share of highly educated inhabitants, who may be better informed).

We carry out an explorative analysis of whether effects of the mandate are heterogeneous in different municipalities depending on these four characteristics: experience of the population as captured by the age distribution, level of housing market activity as measured by the share of new flats constructed, owner-occupancy rates, and finally, urban versus rural housing markets. For this purpose, we use data on municipality characteristics from INKAR and Corine landcover databases.[10]

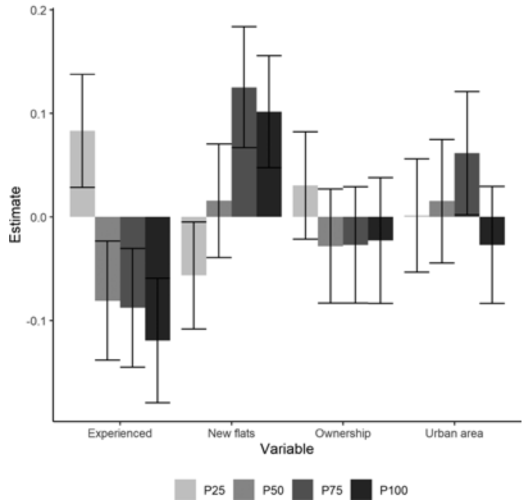
We divide municipalities into four bins based on the quartiles of the respective characteristic. In separate regressions for each characteristic, these bins are interacted with the *OLD* variable in equation [6]. We stress that this analysis should not be interpreted as a causal analysis but is purely descriptive in nature. With regard to experience, we find statistically significant negative capitalization rates for the higher quartiles (i.e., the more experienced population, in line with our hypothesis). Second, the level of market

[10]The Corine landcover database, provided by the European Environmental Agency, is an inventory of land cover and land use in all EU member states (https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-corine).

activity has a mixed impact on the effect of the mandate. We find negative capitalization rates for houses in municipalities in the first quartile of new flats per capita (i.e., in areas with less dynamic markets but positive effects for more active markets). This is consistent with a lack of capitalization in a "seller's market."[11] Third, owner-occupancy rates have no statistically significant effect on capitalization rates, although point estimates for the upper three quartiles are negative. Finally, we check whether there are differences between more and less rural regions. To this purpose, we use the share of urban area in a municipality based on the Corine landcover data. Though the distinction between urban and rural housing markets could explain some differences in capitalization and may be associated with the three former characteristics, we find that capitalization rates do not differ much among the first three quartiles of urbanity of a municipality.[12] Our results suggest that there may be some heterogeneity in capitalization of the mandate (Figure 3). In particular, municipalities with the highest shares of urban area seem to be different.[13] Overall, our heterogeneity analysis provides some suggestive evidence that both the general dynamics of the housing market and the level of salience of the mandate as captured by our proxies may play a role in explaining our findings.[14]

A further explanation may lie in the pending revision of the 2008 state mandate, which led to uncertainty about the stringency of the mandate in the future. The final revision increases the share of renewable energy from 10% to 15%, and it introduces several more compliance measures, some of which have very low cost. An official paper revealed

Figure 3
Capitalization by Municipality Characteristics, 2012



Note: This shows the point estimates and the 95% confidence interval of an augmented version of equation [6] for 2012; the term "Old" is interacted with quartiles of the municipality characteristic described on the *x*-axis.

several elements of the revision in 2013 with resulting critical newspaper coverage, including headlines such as "The intention alone counts" (*Die Absicht alleine zählt*) (Zeitung für den Energiemarkt 2013).

The expectation that the revised mandate may be more lenient could have reduced pressure on sellers to lower their asking price. The rising share of the use of bio-gas and bio-oil for compliance with the mandate is likely to explain our findings at least in part since these compliance options are relatively cheap. One of the effects of the state mandate has likely been to increase the supply of bio-gas on offer from gas providers in Baden-Wuerttemberg: Bernauer and Reisch (2018) study the structure of tariffs offered for gas across Germany in 2017 and find that at a national level 20% of gas suppliers offer a bio-gas tariff, whereas almost half of these suppliers were located in Baden-Wuerttemberg, with the remaining companies spread equally among the other 15 German states. In fact, they found that 97% of the gas companies in Baden-Wuerttemberg offered a bio-gas product. Although they have no historical data, it seems likely that this supply effect may be associated with the state mandate. Unfortunately, limited availability

[11] We have also investigated heterogeneous effect with respect to offer prices but did not find a consistent pattern. Results are available from the authors on request.

[12] In our sample, urbanity is not strongly correlated with the share of population above age 50 and new flats per capita, as shown in the Appendix. The correlation between urban area and ownership rates is –0.5.

[13] The heterogeneity analyses are purely descriptive, and the significance levels are likely inflated because we do not correct for multiple hypothesis testing.

[14] All results for 2013 and 2014 are qualitatively similar and are shown in the Appendix, along with the full-result tables and summary statistics for the municipality characteristics.

of housing market data before 2012 prohibits us from examining the impact of the mandate directly on its introduction before a biofuel supply response is likely to have occurred.

Finally, our analysis only recovers the immediate effect on asking prices. If the mandate indeed causes a reduction in retrofitting activities in the state of Baden-Wuerttemberg, it could be that over time the quality of the housing stock declines, which in itself could cause lower prices. Such an effect would likely take several years to manifest itself, however, and we would not identify it within the period covered by the present analysis.

8. Conclusion

In this article, we study the effect of a state mandate on renewable energy for heating on the housing market. We construct a research design based on the spatial discontinuity at the state border, taking advantage of the variation in applicability of the mandate by building vintage. Specifically, we estimate a spatial difference-in-differences model comparing the prices of old and new houses for sale in and outside of Baden-Wuerttemberg. This design allows us to identify effects on the asking prices of houses for sale in the existing building stock.

We find no statistically significant evidence of capitalization of the mandate into asking prices in the housing market. The confidence intervals are wide enough to include effects in the range of our lowest calculated NPV of compliance cost (i.e., for households opting to replace their fossil fuel heating system with a newer version of the same but use biogas or bio-oil). However, we can reject that the higher compliance cost associated with a switch to renewable heating technologies such as pellet stoves, solar thermal collectors, or heat pumps capitalizes into the house price, on average, in two out of three years. We discuss a variety of explanations for our findings including (1) low salience of the mandate among sellers and potentially related to market power of sellers in an expanding housing market; (2) the expected revision of the state law, which happened in 2015 and introduced more flexibility and additional compliance measures of lower costs; and (3) the increased availability of low-cost compliance measures in the form of bio-gas and bio-oil. If the last explanation is true, our findings suggest that the financial burden associated with the mandate is small. On the other hand, if retrofitting activity in Baden-Wuerttemberg has declined in consequence of the state mandate, a cost in terms of declining quality of the housing stock may emerge over time.

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