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Regulation, Innovation and Technology Diffusion - Evidence from Building Energy Efficiency Standards in Germany

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Abstract

The impact of environmental regulation on technology diffusion and innovations is studied using a unique data set of German residential buildings. We analyze how energy efficiency regulations, in terms of minimum standards, affects energy-use in newly constructed buildings and how it induces innovation in the residential-building industry. The data used consists of a large sample of German apartment houses built between 1950 and 2005. Based on this information, we determine their real energy requirements from energy performance certificates and energy billing information. We develop a new measure for regulation intensity and apply a panel-error-correction regression model to energy requirements of low and high quality housing. Our findings suggest that regulation significantly impacts technology adoption in low quality housing. This, in turn, induces improvements in the high quality segment where innovators respond to market signals.

JEL Codes: D2, Q4, R5

Keywords: environmental regulation, innovation, technology diffusion, residential real estate, energy efficiency

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1 Introduction

Since the March 2011 Fukushima Daiichi nuclear disaster, politicians are paying increased attention to sustainability, resource and energy efficiency issues. Many countries are seeking to restructure their energy supply systems and stimulate energy efficiency investments. In this context, residential housing plays an important role, since, according to OECD-data, it accounts for up to 40% of final energy needs in developed countries. The lion's share of residential energy demand stems from heating and cooling. In the US this constitutes for about half of all residential energy demand. In Europe even two-thirds of residential energy demand is for heating and cooling (OECD 2003). Politicians in the European Union (EU) are especially focused on the potential savings in the real estate sector and are seeking to implement the "Nearly Zero-Energy Buildings" (NZEB) standard by the end of 2020. Numerous policy measures and initiatives are being introduced in order to achieve this goal. Building energy codes are probably the oldest and most frequently used instrument designed to increase the energy efficiency of real estate (Jacobsen & Kotchen 2013, Annunziata et al. 2013, Iwaro & Mwasha 2010). In this context, politicians often emphasize the twofold importance of such regulations: First, to reduce actual energy requirements and to encourage investors to adopt existing energy efficiency technologies and, second, to create incentives to develop new innovative technologies for future modifications of energy efficiency standards (see Saheb et al. 2013, European Commission & European Parliament 2012).

While building energy codes are generally assumed to be effective in reducing energy requirements, empirical knowledge on their actual impact is relatively scarce. As pointed out by Jacobsen & Kotchen (2013), empirical assessment is important for several reasons. First, the effectiveness of regulation crucially depends on the real level of energy requirements. If regulation is not tight enough, construction industry's good building practice will remain unaffected. Second, actual energy savings often lag far behind engineers' promises (Metcalf & Hassett 1999, Michelsen & Müller-Michelsen 2010, Schröder et al. 2009, Brounen et al. 2012) due to either technical flaws or end-user behavior that partly offsets the increased technical energy efficiency of housing (Sunikka-Blank & Galvin 2012). Thus, engineers' calculations do not necessarily reflect real energy (cost) savings, which are the actual measures of interest for investors and policy-makers. Indeed, the few empirical studies available indicate that a energy efficiency regulation is an effective instrument to increase the real energy performance of newly constructed buildings.

In the early 1990s, the idea to stimulate innovation by environmental regulation entered the political arena. This approach goes back to the well received articles by Porter (1991) and Porter & Van der Linde (1995). In a nutshell, the so called "*Porter Hypothesis*" states that environmental regulation can result in Pareto-optimal outcomes. While effectively protecting the environment, regulation creates incentives to innovate and thereby increase the competitiveness of firms and the economy (Ambec et al. 2013). In this context, the various empirical studies do not provide clear cut evidence. It remains unclear whether regulation positively impacts economic performance and innovative capacities of firms, industries or regions. In particular, almost no empirically insights exist on the potential incentives of building energy codes to design new, innovative and less heating energy demanding buildings. The specific studies available

are small in number and all use qualitative methodologies (see Beerepoot & Beerepoot 2007, Gann et al. 1998, Vermeulen & Hovens 2006).

In the present study, we address this gap in the empirical literature and explicitly assess whether environmental regulation drives innovation in the residential building sector. Specifically, the analysis adds to the existing findings around building energy codes by taking a differentiated, longitudinal perspective on the diffusion/ adoption of *existing* technologies and the market uptake of *new innovations*. Thereby, we are the first to include a measure for real regulatory intensity. Our inquiry also contributes to the more general and still controversial discussion around the “*Porter Hypothesis*”, particularly by providing longitudinal evidence, which is frequently missing from the debate (Ambec et al. 2013).

Moreover, the construction and residential real estate sector can be seen as an interesting test case for the impact of regulation in general. The sector is large (e.g. the German construction sector accounts for about 11% of total GDP) and covers a wide range of services, crafts and branches in industrial manufacturing. In particular, the construction industry is not concentrated and is highly competitive (Buzzelli & Harris 2003) - this makes us believe that the pressure and incentives to innovate are spread out along the supply chain.

In our analysis, we assess the energy consumption of a large number of German apartment houses, built since 1950 under a variety of regulatory regimes. Incorporating the time dimension allows us to model the effects of regulatory intensity, measured as the share of houses affected by the regulation in the last year prior to its introduction, on the energy performance of buildings. Moreover, the longitudinal perspective allows us to disentangle the effects of regulatory interventions on technology diffusion (the adoption of existing energy saving technologies) and innovation in the house building industry. To do so, we analyze the effects of regulation on different quality segments in a panel framework, borrowing from quantile regression method.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on the effectiveness of energy efficiency standards in residential real estate and introduces the basic ideas behind the “*Porter Hypothesis*”. Section 3 introduces our data and presents some stylized facts on energy efficiency in German residential housing. The model is outlined in Section 4 and the results are discussed in Section 5. Section 6 concludes.

2 Related literature

2.1 Empirical evidence on the effectiveness of building energy codes

As pointed out by Jacobsen & Kotchen (2013), there are few empirical studies on the real energy saving effects of building codes in the real estate sector. For a long time, it was generally claimed that adequate data, especially to analyze the supply side of housing, was not available (Olsen 1987, Dipasquale 1999, Gyourko 2009, Eichholtz et al. 2011). This has changed with the availability of new micro-data sources, e.g. data on environmental certification like Energy Star[®]. The first studies on building energy codes, based on detailed micro-data gathered from consumption bills, were published starting in 2012.

The first paper to use energy billing information is Jacobsen & Kotchen (2013). The sample consists of 2,239 homes in Gainesville, Florida, in the US. Based on this data, the authors evaluate the effects of the 2002 modified state wide energy building code. Monthly electricity and gas bills for the period of 1999-2005 serve as basis for a twofold empirical strategy, consisting of (i) a set of linear regressions to test whether level effects can be identified on average and in a seasonal perspective; and (ii) a difference-in-difference approach to analyze the performance of regulated vs. unregulated dwellings. While controlling for observable housing characteristics and heating degree days, the authors conclude that building energy codes are an effective instrument for reducing energy consumption in residential real estate. Moreover, they find that, in the case of the Florida state regulation, engineer’s calculations and empirical observations are almost identical.

Another micro-data based study, Koirala et al. (2013), analyzes the effects of adopting the “International Energy Conservation Code” (IECC) in the US. The study combines an impressive amount of housing records (containing energy performance measures, housing attributes and individual information on residents) collected from the American Community Survey (the sample consists of 1% of US residences) with aggregate data on regulation, heating degree days and energy prices on the state level. They find that the application of IECC allows households to save about 1.8 % on electricity, 1.3 % on natural gas, and 2.8 % on heating oil compared to dwellings in states without this regulation.

Evidence from outside the US is presented by Michelsen & Rosenschon (2012). They analyze the effects of German regulation from a long term perspective, 1967 to 2006, using energy billing information for a sample of 41,496 apartment houses. Standardized energy consumption of explicitly non-refurbished homes is modeled as a function of building characteristics, spatial controls and, most importantly, housings’ age interacted with dummies for the regulation regime at the time of construction. They find evidence for two effects of tighter building codes: first and in line with the findings of Jacobsen & Kotchen (2013), the authors present level effects in energy consumption induced by changes in the legal setting. Secondly, they find regulation regime specific differences in energy consumption over time, which they interpret as differing trends in technological progress.

Other studies use aggregate information from US states to assess the impact of regulation. Aroonruengsawat et al. (2012) find significant effects of energy efficiency standards in US states based on panel data analysis. They conclude that regulation decreased electricity consumption by up to 5 % in states with high construction activity. Deason & Hobbs (2011) demonstrate, based on a set of panel regressions, that building codes decreased residential primary energy consumption by 1.3 % compared to states without regulation. In the first and frequently cited study on the impact of regulation, Jaffe & Stavins (1995) conclude that building codes did not affect observed building practice. Moreover, the adoption of energy efficiency measures is not affected by regulation.

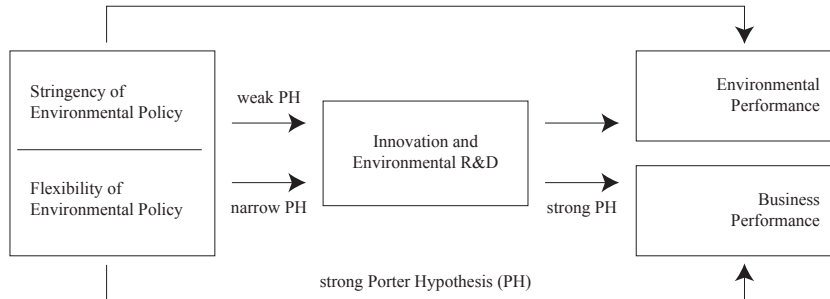
Table 1: Empirical studies on the effects of building energy codes

Study	Region	Period	Data	Methods	Key findings
Jacobsen & Kotchen (2013)	USA	1999-2005	micro; gas and electricity billing data; N=2,239	linear OLS; Dif-dif.	Regulation is effective; 4-6% decreases in energy consumption can be observed which corresponds to building codes requirements.
Koirala et al. (2013)	USA	2007	micro & aggregate data; American Community Survey 2007; N=1,137,886	IV; Hierarchical regression	The application of building codes can save up to 1.8 % of electricity, 1.3% natural gas and 2.8% oil.
Aroonruengsawat et al. (2012)	USA	1970-2006	aggregate data	panel regression	Introduction of building codes reduced electricity consumption in regions with dynamic construction activity.
Michelsen & Rosenschon (2012)	Germany	1967-2006	micro; heating energy bills of German apartment housing; N=41,496	linear OLS	Introduction and amendment of energy building codes comprise two effects: reduced level of energy consumption and decreasing energy requirements over time.
Deason & Hobbs (2011)	USA	1986-2008	aggregate data	panel regression	Primary energy consumption is by 1.3% lower in states that implemented building codes.
Beerepoot & Beerepoot (2007)	Netherlands	1996-2003	micro-data; energy performance calculations; N=352	Logistic regression	Building codes did not affect innovation at large but lead to incremental innovation in energy saving techniques.
Jaffe & Stavins (1995)	USA	1979-1988	aggregate; based on national association of home builders annual survey	OLS	Building codes did not affect observed building practice; adoption of energy efficiency measures is not affected by direct regulation.

2.2 Evidence for the “Porter Hypothesis” in the house-building sector

The “*Porter Hypothesis*” claims that, if adequately designed, regulation signals “*resource inefficiencies and potential technological improvements,*” increases “*corporate awareness,*” reduces “*the uncertainty that investments to address the environment will be valuable,*” creates “*pressure that motivates innovation and progress,*” and levels “*the transitional playing field. During the transition period to innovation-based solutions, regulation ensures that one company cannot opportunistically gain position by avoiding environmental investments*” (Porter & Van der Linde 1995, p. 100). All these factors can favor innovation activities and, ideally, result in better economic performances of firms as well as increased competitiveness of the economy as a whole. In the literature three forms of the Porter Hypothesis are discussed (see figure 1): the “weak” form links regulation to innovation activities. On the firm as well as the aggregate level, R&D expenditures or patenting activities are often used to proxy innovation effort (e.g. Jaffe & Palmer 1997). The “strong” version assumes that regulation increases firms’ competitiveness. Most studies in this context analyze productivity data of industries and branches (for a review of the literature see Jaffe & Stavins 1995, Alpay et al. 2002). The “narrow” definitions states that flexible regulatory policies give firms greater incentives to innovate. However, empirical tests for this type of relationship are difficult (Lanoie et al. 2011).

Figure 1: The causality chain of the porter hypothesis



Source: adopted from Lanoie et al. (2011)

For the construction sector, few studies deal with the question of whether environmental regulation, i.e. building energy codes, affect innovation activity. Beerepoot & Beerepoot (2007) analyze the impact of building codes on new technology development. They analyze this question against the background of the Dutch residential building industry’s innovation system. They assess a small sample of Dutch housing records and conclude that regulation does not provide sufficient incentives to create really new innovations. However, the authors argue that standards at least induce some incremental energy efficiency improvements in the Netherlands.

Based on 35 Dutch commercial office building projects Vermeulen & Hovens (2006) analyze the diffusion of ‘mature’ and the uptake of ‘young’ innovations.

They find that ‘young’ innovations, in addition to other factors, are adopted because they were needed in order for the projects to comply with the Dutch Energy Performance Standards (EPS). Based on the additional finding that EPS did not increase the adoption rates of ‘mature’ innovations, the authors conclude that, “*the instrument of Energy Performance Standards will, at best, be effective if it is regularly made more stringent and if it addresses more recently emerging appliances*” (Vermeulen & Hovens 2006, p. 2735).

Gann et al. (1998) analyzed the British “Building Regulation Part L, Conservation of Fuel and Power.” Based on 21 expert interviews, the authors discuss various channels how regulation enters the innovations process in the house-building sector. Overall, Gann et al. (1998) find evidence that the shift from a “prescriptive” regulatory regime (in terms of allowed construction materials and techniques) to a “performance-based” approach increased innovation activities, which provides indirect support for the strong “*Porter Hypothesis*.”

In summary, knowledge on the effectiveness of building energy codes and the incentives that such regulation creates to innovate can be characterized as being far from comprehensive. The consensus appears to be that, in general, building codes, by accelerating the adoption of energy efficiency measures, decrease energy consumption in the housing sector. But in absence of longitudinal studies almost nothing can be said about regulatory intensity. Existing literature focuses largely on the mere introduction, not the amendment of energy efficiency regulation over time. This is an important limitation of studies centered on addressing the question of whether environmental regulation stimulates innovation, i.e. the uptake of heating energy saving materials and building designs. We address these issues in a novel approach by explicitly considering regulatory intensity of building energy codes as explanatory variable of energy requirements of newly constructed buildings. Moreover, we disentangle potential effects for the groups of “technology adopters” in the low quality housing market segment and “innovators” at the high end of housing quality. This allows us to draw findings on the effectiveness of building energy codes for the diffusion of existing technologies, the uptake of new innovations (the “weak” form of the Porter Hypothesis) and, moreover, on the interaction of both aspects.

3 Empirical strategy, data and stylized facts

In line with the available studies on the energy performance of real estate, our analysis is based on the assessment of micro-data on real energy consumption gathered from energy performance certificates and energy billing information. We use similar data as Michelsen & Rosenschon (2012), but follow a different empirical approach. In contrast to Michelsen & Rosenschon (2012), who use the full set of German apartment houses to model the average energy requirement per year of construction under different regulatory regimes, our approach is to focus on the tails of the distribution, the 10th and 90th percentiles of the energy coefficients. We use this information to proxy the energy performance in the low quality market segment (90th percentile - where energy efficiency is low) and the 10th percentile, the high quality segment. Investors in the low quality segment are forced to *adopt* more efficient technologies when regulation is effectively tightened. Thus, regulation might promote the market diffusion of energy efficiency technologies. In the high quality segment, however, regulation

does not necessarily affect investor plans. Changes in the energy performance over time can be interpreted as a result of *innovation*, which might be an indirect result of regulation, as suggested by the “*Porter Hypothesis*.”

3.1 Housing data

micro-data At first glance the empirical data suggests that the energy performance of apartment buildings in Germany has increased substantially since the middle of the 20th century. The distribution of energy coefficients in our sample is illustrated in Figure 2. We observe a general decline in both the upper and lower percentiles of energy coefficients over time, indicating both technological progress in terms of energy efficiency and adoption/ market diffusion of the existing technologies. The median house build in 2007 has an energy performance roughly identical to the most energy efficient houses built 40 years earlier. That is, when it comes to fostering energy efficiency, creating incentives to adopt seems to matter more than creating incentives improve potential energy efficiency through innovation.

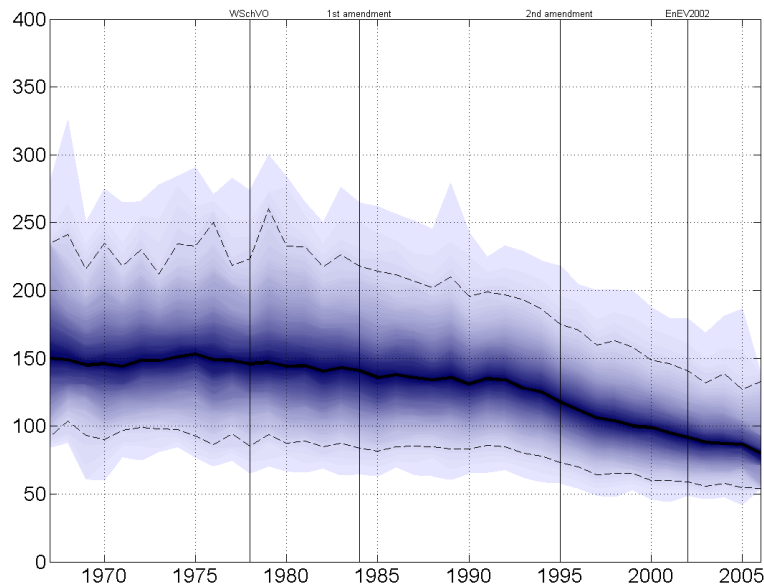


Figure 2: Distribution of energy coefficients by year of construction

The energy coefficients, as used in our sample, are computed based on a three year average of real energy consumption per square meter living space. To ensure comparability across observations, energy consumption is adjusted by climatic parameters that reflect differences in local as well as inter-temporal climatic and weather conditions.¹ Since energy requirements (in the type of

¹Data is provided by one of the leading energy billing service providers, *ista Germany GmbH*. Our sample contains approximately 300,000 apartment houses in Germany, which covers about 15% of the total apartment housing market. The procedure for climatic adjustment

houses analyzed in our sample) have a natural lower bound, the distribution has a positive skew for any construction year. Also, while energy efficiency improves, the gap between the most efficient and the most inefficient houses narrows over time.

The aim of this study is to identify the development of building standards under different regulatory regimes. Since we rely on real energy consumption today rather than engineers' assessment to evaluate the energy performance of buildings, *ex post* changes in housing quality, i.e. refurbishment of the facilities must be ruled out.² To ensure this, we use information on the refurbishment status for the five most important construction parts of a house (from the energy efficiency perspective): roof, facade, windows, basement ceiling and heating system. The energy certificates in our sample contain information whether these building parts have been refurbished or replaced within the past 15 years, more than 15 years ago, if they are non-refurbished or if the status is unknown. Observations are only included in the analysis if it was reported as being "non-refurbished" in all five construction parts. In total, our sample comprises of approximately 40,000 observations. Further, the energy certificates contain information on the year of construction, the location of the building (ZIP-code district), the fuel type, the size of the apartment house measured in square meter of living space and the number of apartments.

3.2 Regulation regimes and regulation intensity

Housing regulation in Germany In Germany building codes have a relatively long tradition of being used as a policy instrument to affect energy efficiency standards (Geller et al. 2006). The first, the "Heat Insulation Ordinance" (WSchV), came into force in November 1977. In the light of the first oil crisis in the early 1970s, politicians decided to define minimum standards for the energy efficiency for both residential and commercial buildings. Based on so called U-values, measures for the thermal conductivity of construction parts, the regulation defined an aggregate maximum level of annual (a) energy requirement of 250 kilowatt-hours (kWh) per square meter living space (m^2) for newly constructed homes. This regulation was amended twice, in 1984 and 1995. In 2002 WSchV was replaced with the "Energy Saving Ordinance" (EnEV), which is still in force.

The basis for regulation, however, changed over time. While WSchV was introduced against the background of strategic trade policy (i.e. to reduce the dependency on fossil fuel imports), EnEV was developed in response to sustainability issues and concerns about global warming (Geller et al. 2006, p. 567f). Since 2002, the EnEV has been amended twice: 2009 and 2013. The recent change in regulation is also associated with a switch in the guidance

follows the official guidelines for calculating energy performance certificates, as implemented in Germany's "energy saving ordinance" of 2009 (EnEV 2009). This procedure standardizes energy requirements to the German city of "Würzburg" in the year 2000. Thus, there is no need to control for heating degree days, as applied in many other studies. Further, the three year average of energy consumption ensures to some extent that individuals' behavior does not significantly bias the energy performance measure.

²Although some studies control for refurbishment and find substantial effects (e.g. Brounen et al. (2012) or Leth-Petersen & Togeby (2001)), other studies do not consider refurbishment in their analysis of vintage class specific energy performance of real estate (e.g. Costa & Kahn (2011) or Chong (2012)).

Table 2: Regulatory steps of energy building codes in Germany: 1978–2021

year	regulation	max. kwh/m^2a
until 1978	no regulation	∞ kWh
1978	Heat Insulation Ordinance (WSchV)	250 kWh
1984	amendment of WSchV	230 kWh
1995	amendment of WSchV	150 kWh
2002	Energy Saving Ordinance (EnEV)	100 kWh
2009	amendment of EnEV	60 kWh
2016	amendment of EnEV	45 kWh
2021	amendment of EnEV	0 kWh

regime: while previous building codes were issued without stating exact validity periods and without information on further regulatory steps, EnEV 2013 is the first that outlines a stepwise tightening of construction law to a carbon neutral standard by 2021.

Table 3: Panel structure

Regions (N)	Time Span (T)
Lower Saxony	1950–2005
North Rhine–Westphalia	1950–2005
Baden–Wuerttemberg	1950–2005
Bavaria	1950–2005
Berlin	1990–2005
North	1950–2005
Rhine–Hesse	1950–2005
East	1990–2005
N=8	
T=56	
Obs.=368	

Panel data The sample analyzed in this paper covers apartment houses constructed between 1950 and 2005. With this sample, we are able to observe energy coefficients of buildings constructed under five different regulatory regimes - ranging from unregulated buildings until the end of 1977 to EnEV 2002 standards. As Germany was divided until 1990, we drop all apartment houses constructed under GDR housing market regulation (built before 1990 and located in Saxony, Thuringia, Saxony-Anhalt, Brandenburg, Berlin and Mecklenburg-West Pomerania) to ensure identical institutional settings. To the extent possible, our regions coincide with the German federal states (Länder). However, to generate sufficiently large entities where the percentiles of the empirical distributions in our sample are meaningful approximations of the entire population, smaller Länder are combined to larger units. Hamburg, Bremen and Schleswig-Holstein form the “North” region, the Saarland, Rhineland-Palatinate and Hesse form

Rhine-Hesse, and the former GDR Länder of Brandenburg, Mecklenburg-West Pomerania, Saxony, Saxony-Anhalt, and Thuringia form the “East” group (see Figure 3).



Figure 3: Regions

We generate separate innovation and adaptation time series for each region, defined as the 10th and the 90th percentile of energy coefficients for houses of a specific year of construction in the respective region. Variables controlling for the attributes of the housing stock are computed as region/year mean values of the corresponding building features.

Measuring regulation intensity Instead of capturing regulation through a set of shift and slope dummies, as in most of the previous literature, we aim to actually measure regulation intensity in the present study. However, using the level of regulation itself (in terms of maximum allowed energy requirements) is difficult for a number of reasons. First, because energy building codes are amended over time, regulation is instationary by construction. Since economic reasoning suggests a relation between the level of regulation and the level of energy efficiency, this could not be solved by simply taking first differences, but requires some error correction type of indicator. Concerning energy regulation this, however, creates a new set of problems. Regulation is supposed to affect the behavior of economic agents, if it is binding to at least some agents, but

is not supposed to be neutral when irrelevant for every agent. In econometric terms this type of phenomenon is commonly treated using regime switching models. Both commonly used versions are problematic in our case. When using the difference between the maximum of the empirical distribution and the regulation level as indicator, we can use the sign of this error correction term as a plausible regime indicator in a model with deterministic regime switching. This indicator turns negative whenever a regulation does not affect any agent. However, this induces further noise into the model since this indicator is strongly affected by outliers. Using a more stable indicator, such as the difference between the median of the empirical distribution and regulation, requires an endogenous identification of regimes as done in threshold or Markov switching models. However, these models also come at the cost of substantial uncertainty, since regimes are often only weakly identified. To overcome these issues we borrow from quantile regression and propose to use a regulation index r at time t that is defined as the share F of houses built in $t - 1$ that would have been affected by the regulation R relevant at time t :

$$r_t = F_{H(t-1)}(R_t), \quad (1)$$

where $H(t)$ is the set of houses build at time t . R is scaled in $kWh/(m^2a)$. r_t indicates immediately when any agent is affected by regulation, while not being prone to outliers.

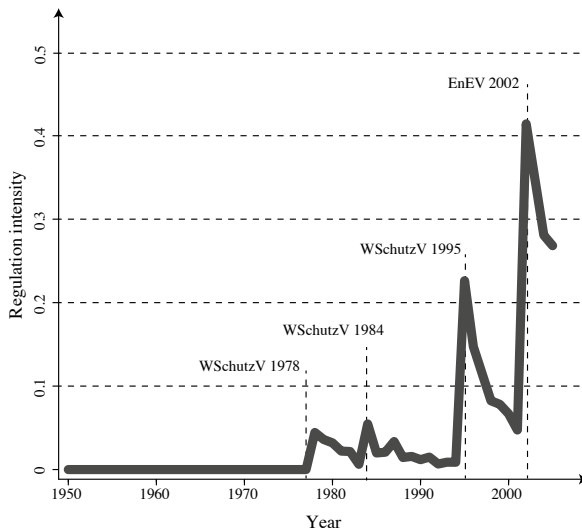


Figure 4: Regulation intensity

3.3 Macroeconomic, attitudinal and other control variables

Energy prices Energy prices are proven to be important predictors for the energy performance of buildings. As Costa & Kahn (2011) demonstrate for residential housing in the USA, electricity prices at the time of construction

determine to a large extent current heating energy needs. For the German case, the most important heating fuels are oil and natural gas. As implemented in long-term cross-border delivery contracts, the price of gas is to some extent tied to oil. Therefore, we include the oil price as a proxy for heating energy costs. One might argue that forward looking agents consider price expectations rather than the past energy price development when deciding on long term investments (such as real estate) (Quigley 1984, Nesbakken 2001), however, most institutional oil price forecasts are essentially flat (in real terms), taking past movements of the oil price as granted. Therefore, we account for lagged changes in the logged oil price measured as the US Dollar price of Brent crude oil (free on board).

Green attitude There are several studies on green technology diffusion addressing the roles of behavior and “green” attitudes, e.g. in the decision to adopt an innovative energy efficient heating system. It is frequently found that people who perceive environmental issues to be important are more likely to adopt environmentally friendly technologies and, moreover, have a greater willingness to pay for such technologies (Michelsen & Madlener 2012, Claudy et al. 2011). To differentiate whether it is truly the regulation that matters, or a generally more supportive attitude towards “green” ideas in society that might also be highly correlated to ecologically motivated regulation, we control for green support in the population using opinion polls. In the context of “green” buildings, this measure is also used by Brounen & Kok (2011). Our attitude control is based on a monthly, representative political survey conducted by “*Forschungsgruppe Wahlen*” to forecast German parliamentary elections. We include the first difference of vote shares for the green party differentiated by year and region to our estimations. As the Green party was founded in January 1980, information on green support is only available from the survey since 1979. We assume a vote share of 0 for the respective earlier years.

Spatial controls Studies address the role of local market conditions on real estate investor’s decisions to adopt energy efficient technologies. Kok et al. (2012, p.562), for example, find that, for the case of green office space, “*the diffusion has been more rapid in metropolitan areas with higher incomes, and in those with sound property market fundamentals.....*” In general, compared to rural areas, economic conditions tend to be better in urbanized agglomerations. To capture this effect, we control for urbanized housing markets including the share of apartments in our sample that is located in or the direct surrounding of a town with at least 50,000 inhabitants. Additionally, we include time fixed effects for each region as described in section 3.1.

Table 4: Descriptive Statistics

Variable	Definition	obs	mean	std.	min	max
Year	Year of construction	368	1979.2	16.5	1950	2005
q^{90}	90 th percentile of energy performance measures (adoption series)	368	190.3	41.3	102.0	305.1
q^{10}	10 th percentile of the energy performance measures (innovation series)	368	97.2	20.1	50.9	169.2
Regulation (r)	Share of buildings that would have been affected by the regulation in $t - 1$	368	0.05	0.1	0.0	0.4
No. flats	Average of number of flats per building	368	13.4	9.8	3.0	118.3
Living space	Average living space in m^2 per building	368	929.4	578.5	187.6	6152.1
Commercial	Share of buildings which are partly in commercial use	368	0.2	0.1	0.0	0.7
City	Share of buildings located in the core of a city > 50,000 inhabitants	368	0.5	0.3	0.0	1.0
Oil price	log oil price in US \$	368	0.05	0.2	-0.6	1.0
No oil price	missing data of oil price expectations (dummy)	368	0.2	0.4	0.0	1.0
Green attitudes	Share of supporters of the green party	368	0.05	0.05	0.0	0.2

Building characteristics The building size affects housing’s “natural” energy efficiency due to differences in the ratio between interior space and the outer shell of a building. As for example demonstrated by Leth-Petersen & Togeby (2001) for Danish apartment blocks, the smaller the house, the higher are energy requirements. We control for size including the average living space in m^2 and the average number of flats per building. Further, we include the share of buildings used for residential as well as commercial purposes.

4 Model and methods

4.1 Estimation

Model setup Our panel setup essentially is an error correction type model taking the form:

$$\begin{aligned} \Delta q_{j,t}^{90} = & \alpha_1 + \alpha_2(q_{t-1}^{90} - q_{t-1}^{10}) + \alpha_3\Delta q_{j,t-1}^{90} + \alpha_4\Delta q_{j,t-1}^{10} \\ & + \alpha_5 r_t + \sum_{m=1}^M \psi_m \bar{c}_{j,t}^m + \sum_{k=1}^M \phi_k C_k \end{aligned} \quad (2)$$

$$\begin{aligned} \Delta q_{j,t}^{10} = & \beta_1 + \beta_2(q_{t-1}^{90} - q_{t-1}^{10}) + \beta_3\Delta q_{j,t-1}^{90} + \beta_4\Delta q_{j,t-1}^{10} \\ & + \beta_5 r_t + \sum_{m=1}^M \xi_m \bar{c}_{j,t}^m + \sum_{k=1}^M \chi_k C_k, \end{aligned} \quad (3)$$

where $q_{j,t}^p$ is the natural logarithm of the p^{th} percentile of the energy performance measures of buildings in region j constructed in year t , $\bar{c}_{j,t}^m$ is the mean of the building specific control variable c^m for region j and year of construction t , and C_k are non construction specific control variables. Essentially, this model is a version of a panel cointegration model, where the cointegration relation is restricted to one. An unrestricted version of the model has been tested and yields similar results. The key difference between our approach and conventional panel cointegration models is the use of an error correction term relying on the entire sample rather than the specific region. Thereby, we avoid carrying the uncertainty in the quantile estimates in regions with few observations into the error correction term.

The wild bootstrap To account for heteroscedasticity, the estimation is made using an adjusted wild bootstrap (Wu 1986). When resampling for a wild bootstrap, the original residuals are multiplied with a factor v drawn from a distribution that guarantees that the moments of the distributions of ε and εv resemble each other. Most importantly, mean and variance should be identical for ε and εv . Contrary to the residual bootstrap the wild bootstrap maintains fluctuations of variance over time from the original sample.

Following Davidson & MacKinnon (2010), we apply the same multiplier v to residuals from both equations, allowing cross equation correlation similar to SUR estimation approaches. Similarly, we apply the same v to observations in the same period, thereby accounting for cross sectional correlation in the residuals. This leaves us with a fairly low number of possibilities to resample. To allow a large number of distinct bootstrap samples (and thereby prevent

statistical artifacts in the results), we draw the multipliers from Webb’s six point distribution (Webb 2013) instead of the more commonly used two-point distributions proposed by Mammen (1993) and Davidson & Flachaire (2008).

Generated regressor problem An additional advantage of using a bootstrap in our application is that it simultaneously accounts for the generated regressor problem that occurs since our measures for adaptation and innovation are quantile estimates based on the available subsample. Since the entire process is simulated in our bootstrap, resampling the endogenous variable implies resampling the lagged endogenous that is used as predetermined explanatory variable at the same time. Since the measurement error in the left hand side variable is a (substantial) part of the error term, this measurement error is automatically considered by the bootstrap with respect to the lagged endogenous, which is our only variable where a generated regressor problem matters.

However, as a robustness test, we also apply a two step bootstrap where we explicitly consider the uncertainty in the quantile estimates. To do so, we resample the micro-data before aggregating to the panel level before each iteration of our wild bootstrap. For each state and year specific subsample we draw (with replacement) $N_{i,t}$ buildings from the original corresponding subset of the micro-data. This resampled micro-data is used to create a new panel dataset. Equation 3 is estimated based on that data. The coefficients and residuals obtained thereby are then used for a single wild bootstrap iteration. Since the uncertainty coming from the estimation of quantiles from our sample is accounted for twice in this procedure, the standard errors of the coefficients are larger when applying the double bootstrap by construction. However, all results remain stable quantitatively and mostly significant, also at lower significance level.

4.2 Deriving impulse response functions

Since our sample includes periods without regulation, we cannot capture the impact of regulation through the level of regulation itself but instead rely on the regulation index proposed in Section 3.2. Contrary to regulation that might be treated as exogenous, the regulation index is merely predetermined since it includes past information on the distribution of energy coefficients. While this is sufficient for the estimation of unbiased regression coefficients, it poses a problem when computing impulse response functions where changes of the regulation index due to changes in energy efficiency have to be treated as endogenous.

For the impulse responses presented in Section 5 we assume that energy coefficients at any point in time are normally distributed. If this assumption holds, the two points of the distribution considered in our estimation, i.e. the 10th and the 90th percentile, describe the entire distribution of energy coefficients for a given year. That is, we can compute share of houses affected by the regulation for any given period endogenously.

Following Fry & Pagan (2007) we do not report the median impulse response function, but the individual impulse response (generated by the bootstrap) that is closest to the median. This guarantees that the IRF as reported is actually consistent with a potential parameter constellation.

5 Results

Our estimations confirm the general finding of the previous literature that regulation successfully affects energy efficiency rather than merely reinforcing developments already initiated by private actors. However, it sheds some new light on the propagation of regulation throughout the economy. We find that regulation strongly affects the adoption of existing technologies in the low quality housing market segment (see table 6). This result is not surprising since in general regulatory compliance is high in Germany, indicated for example by Transparency International’s “Corruption Perceptions Index.”

Table 5: Model diagnostics

	F-Statistic	R-Squared
Model 1: Adoption of energy efficiency (90 th percentile)	13.44*** (N=352, DF=18, 333)	0.4209
Model 2: Innovations in energy efficiency (10 th Percentile)	8.203*** (N=352, DF=18, 333)	0.3072

However, the results for the 10th percentile show an entirely different picture: we find no direct impact of regulation on the energy performance of innovators. At the same time, we find a strongly positive impact of the error correction term, i.e. the spread between the considered time series. That is, the impact of regulation on innovation that has been found in the micro-data, is entirely of an indirect nature. Regulation reinforces the incentive to adopt existing technologies, thereby reducing the spread between adopters and innovators. The reduction of the spread – or in other words: the shrinking technological advantage of the innovators over adopters – is, in turn, fostering innovation.

Figure 5 shows the joint dynamics of innovation and adaption in both percentage changes and accumulated level changes after the introduction of higher energy standards that affect 50% of the current construction. While the effect on adaption is spread over several years (with a significantly negative impulse response function over almost a decade) the vast majority of the impact happens right after the introduction of the regulation. Surprisingly innovators do not react at all in the first year. Starting two years after the new energy standards were established, the energy coefficients of the innovators start to decrease, maintaining a highly improved speed of innovation for two decades. After 20 years, energy consumption in both the low and high quality housing market segments is almost 20% below the level where it would have been without the new energy standard.

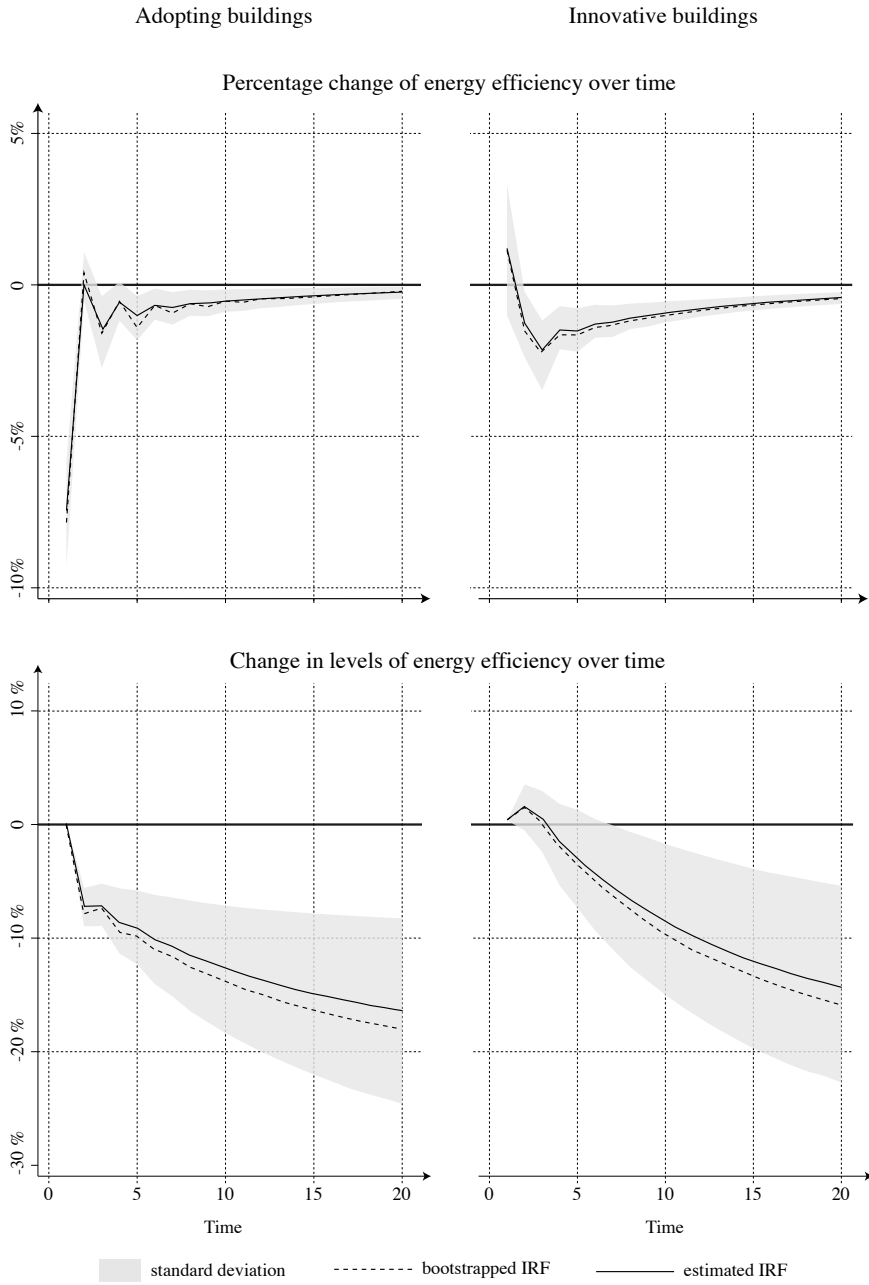


Figure 5: Impulse response to regulation

Table 6: Model 1: Adoption of energy efficiency

	double-bs innovation		single-bs innovation		orig. estimates innovation	
	coefficient	p-val.	coefficient	p-val.	coefficient	Pr(> t)
Constant	0.37167	***	0.38902	***	0.38682	***
$q_{t-1}^{90} - q_{t-1}^{10}$	-0.56644	***	-0.58894	***	-0.58896	***
Δq_{t-1}^{90}	-0.24082	***	-0.22947	***	-0.23142	***
Δq_{t-1}^{10}	-0.24136	***	-0.26269	***	-0.25860	***
Regulation r_t	-0.15949	**	-0.16006	**	-0.15896	**
Δ Green attitude	-0.23905		-0.23424		-0.22574	
Δ oil price $_{t-1}$	0.01202		0.01229		0.01282	
No oil price $_{t-1}$	-0.00266		-0.00317		-0.00266	
No. flats	0.00322		0.00318		0.00322	
Living space	-0.00006		-0.00006		-0.00006	
Commercial	0.13735	**	0.13552		0.13863	
City	0.01034		0.00389		0.01221	
North Rhine-Westphalia	0.00912		0.01248		0.00858	
Baden-Wrttemberg	-0.03284		-0.03372		-0.03464	
Bavaria	-0.03940		-0.04149		-0.04166	
Berlin	0.00320		0.00762		0.00111	
North	-0.00458		-0.00028		-0.00703	
Rhine-Hesse	0.00154		0.00203		0.00073	
East	0.01761		0.01960		0.01721	

***, **, * indicate significance at 1%, 5% or 10% level of confidence

Table 7: Model 2: Innovations in energy efficiency

	double-bs innovation		single-bs innovation		orig. estimates innovation	
	coefficient	p-val.	coefficient	p-val.	coefficient	Pr(> t)
Constant	-0.24027	***	-0.26054	***	-0.25988	***
$q_{t-1}^{90} - q_{t-1}^{10}$	0.43613	***	0.46750	***	0.46463	***
Δq_{t-1}^{90}	-0.23502	***	-0.25316	***	-0.25784	***
Δq_{t-1}^{10}	-0.16824	***	-0.15325	*	-0.15218	*
Regulation r_t	0.02611	0.760	0.02642	0.601	0.02779	0.617
Δ Green attitude	-0.29874	0.137	-0.28909	*	-0.28781	*
Δ oil price $_{t-1}$	0.00052	0.988	-0.00086	0.925	0.00091	0.971
No oil price $_{t-1}$	-0.01650	0.464	-0.01877	0.569	-0.01837	0.543
No. flats	0.00675	**	0.00665	**	0.00672	***
Living space	-0.00012	**	-0.00012	***	-0.00012	***
Commercial	-0.17578	**	-0.17729	**	-0.17967	**
City	-0.04672	0.439	-0.04323	0.649	-0.04489	0.627
North Rhine-Westphalia	-0.00463	0.898	-0.00552	0.913	-0.00541	0.911
Baden-Wrttemberg	0.02814	0.363	0.02873	0.430	0.02989	0.408
Bavaria	0.03169	0.290	0.03326	0.302	0.03326	0.292
Berlin	0.07069	0.288	0.06910	0.446	0.07291	0.380
North	0.03476	0.437	0.03497	0.613	0.03453	0.639
Rhine-Hesse	-0.01186	0.675	-0.01220	0.753	-0.01217	0.747
East	-0.02717	0.543	-0.02685	0.464	-0.02762	0.440

***, **, * indicate significance at 1%, 5% or 10% level of confidence

Since the regulation considered in our study works through fixed limits rather than incentives that scale with the energy efficiency, the results meet the theoretical expectations. Only investors who build less energy inefficient housing have an immediate incentive to adapt their behavior, thus reducing the risk of an apartment house construction permit not being approved by the authorities. This stimulates the market diffusion of construction techniques, building designs and materials fostering energy efficiency. The indirect effect on innovation is also intuitively traceable. As “innovators” are not directly affected by regulation, they most likely respond to market signals - thus after the introduction of new energy efficiency standards. This is also consistent with the “*Porter Hypothesis*” that states that a more favorable environment for innovation is created by new regulation.

All our results hold when controlling for oil price changes or lagged oil price changes as a proxy of energy price movements and green attitude. Oil prices are not significant in neither the adaptation nor the innovation equations, which contrasts with the findings of previous studies on housing quality in the USA. In this context, it must be noted that residential real estate in the US is, in most cases, owner occupied. We analyze apartment housing in Germany, of which roughly 80% are rental segment. There is an ongoing discussion about the incentives to invest in energy efficiency, since landlords bear the costs of investment but cannot typically pass the costs on to the tenants who benefit from reduced energy bills. In the literature this is referred to as the so-called “*landlord tenant dilemma*” (Stull 1978, Rehdanz 2007) and might serve as an explanation for the observations in this study.

The share of green voters, albeit having a sizable coefficient, is only significant in the innovation equation and even there only at the 10% level. Quantitatively the coefficients of green attitude in both equations are very similar. The coefficients bear the expected negative sign. However, these estimates might downplay the role of green attitudes in the change of energy efficiency. The volatility of green voting might be much higher than the volatility of the underlying attitudes.

6 Conclusions

The present paper evaluates the effects of building energy codes in the German apartment housing sector. Based on our analysis, we can draw two main conclusions:

- i) In line with previous studies, we find that energy building codes effectively decrease energy requirements in residential real estate. More precisely, energy efficiency standards successfully affect technology adoption in the low quality housing market segment. Our results show that regulatory intensity is important in this context; the tighter the regulation, the higher the technology adoption and the faster the diffusion of existing technologies in the low quality housing market segment.
- ii) Regulation has no direct impact on “innovators.” However, there is a strong indirect effect of regulation on innovation. Investors in the high end housing market segment strongly react to a narrowing technology gap compared to adopters, even if their own performance is far from being in risk of

being affected by regulation in the near future. Although this effect is merely indirect, the strong overall importance of regulation for innovation essentially constitutes an empirical validation of the “weak” form of the “Porter hypothesis.”

Unfortunately, the methodology applied does not allow for exact conclusions about the communication channels between the housing market segments. But the indirect link between regulation and innovation favors explanations that emphasize shifts in production technology or the importance of market trends. A new energy efficiency framework might motivate real estate investors in the high quality segment to readjust their ‘signaling’ of outstanding quality to tenants; for example by developing less heating energy demanding buildings. At the same time, the improvement in general energy efficiency increases the credibility of the imminent threat of more rigid future regulation. Both aspects are associated with a higher demand for energy efficiency innovations. Alternatively, the manufacturing processes might increase efficiency as a result of scale economies in production; cost reductions potentially allow for the market-uptake of previously economically non-feasible inventions. Altogether these factors increase the incentives for innovation. However, a detailed analysis should be subject to future research.

At first glance, our results seem to encourage the application of building energy codes in general. Policy makers, however, should read the presented insights carefully. Although we find that past policy has been effective, this does not necessarily imply that this success can be improved upon with future rounds of regulation. In the German case, for example, regulation is already very tight, narrowing the room for future regulatory interventions. Applying our results to the announced regulatory steps in 2014 and 2016 an - in terms of $kWh/(m^2 \cdot a)$ - only small indirect impact on energy efficiency in the innovative segment can be expected. Moreover, it must be noted that our analysis did not evaluate the “optimal” level of regulatory intensity. Thus, policy makers should take into account drawbacks on aggregate construction activity. This potentially decelerates technology diffusion and innovation, which in turn might offset the positive effects from regulation.

Over all regulation seems to be a valid policy option in countries with relatively poor housing quality, i.e. high energy requirements. For countries like Germany, the impact of regulation is less important. Especially against the background of the targeted NZEB housing standard by 2020, other activities to stimulate energy efficiency investments and energy efficiency innovations must supplement the legal setting. In this context, the results on “green attitude” provide an alternative option to speed up innovation. Rising awareness for energy saving technologies and communicating the positive effects of energy efficiency can be one such supplemental strategy.

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