ifh Working Paper No. 12[1]/2018

Energy Efficiency of Residential Buildings in the European Union – An Exploratory Analysis of Cross-Country Consumption Patterns[2]

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Abstract

Despite a common EU directive on energy efficiency in residential buildings, levels of energy efficiency differ vastly across European countries. This article analyses these differences and investigates the effectiveness of different energy efficiency policies in place in those countries. We firstly use panel data to explain average yearly energy consumption per dwelling and country by observable characteristics such as climatic conditions, energy prices, income, and floor area. We then use the unexplained variation by sorting between-country differences as well as plotting within-country changes over time to identify better performing countries. These countries are analysed qualitatively in a second step. We conduct expert interviews and examine the legal rules regarding building energy efficiency. Based on our exploratory analysis we generate a number of hypotheses. First, we suggest that regulatory standards, in conjunction with increased construction activity, can be effective in the long run. Second, the results suggest that carbon taxation represents an effective means for energy efficiency.

Keywords: carbon-taxation, energy efficiency, energy conservation, climate policy, residential buildings
JEL codes: H23, K32, P18, Q58

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[1] First version published in 2017 with former title "Energy Conservation of Residential Buildings in the European Union – An Exploratory Analysis of Cross-Country Consumption Patterns"

[2] This research is based on a project on the effectiveness of a carbon tax funded by the Federal Ministry of Education and Research (BMBF).

1. Introduction

As a means of addressing climate change, energy efficiency[3] of residential buildings is becoming increasingly singled out by EU environmental policy. Residential buildings are particularly important to focus on, since, according to Eurostat, they account for around 25% of total energy consumption as well as around 20% of greenhouse gas emissions. EU directives such as the directives 2002/91/EC, 2010/31/EU, and 2012/27/EU of the European Parliament and the Council set minimum standards for all countries of the European Union to improve energy efficiency in residential buildings. More importantly, specific goals are set for the years 2020 and 2030 (20% and 30% reduction in energy consumption compared to projections).

While there are common goals, different governments employ different tools in order to reach these target values. Moreover, energy efficiency levels differ vastly across European countries (Filippini et al. 2014). This gives us the opportunity to study the effectiveness of various tools for increasing energy efficiency levels.

Former research has primarily focused on quantifying energy efficiency policies (Ó Broin et al (2015), Filippini et al. (2014)) or focused on the evaluation of only one energy policy instrument such as regulations (Levinson 2014; Levinson 2016)). This, however, went along with a number of limitations such as homogenizing heterogeneous policy instruments, or excluding important policy instrument which are not quantifiable.

Therefore, we take on a different approach in order explore which factors of energy policy are effective and are able to explain differences in energy efficiency across European countries. By taking on an exploratory and mixed methods approach we shed some light on parts of energy efficiency policies which have earlier been neglected, such as district heating and carbon taxation.

Our analysis is divided into two parts, namely a quantitative and an exploratory qualitative part. In a first step, we use panel data techniques (LSDV) in order to explain residential building energy consumption (from 2000 till 2015) of European countries by a number of observable characteristics. Country dummy coefficients can be regarded as unexplained between-country-deviations from expected consumption levels (where the expectation is contingent on observable characteristics). In a subsequent qualitative analysis, based on the results of our quantitative analysis, we investigate energy efficiency policies (with respect to residential buildings) in selected countries by conducting expert interviews in these countries and examining official policy documents as well as statistics.

Besides evidence on the effectiveness of regulatory (building efficiency) standards, our exploratory hypothesis suggests the hypothesis that energy taxes and carbon taxation represent effective means of energy conservation.

2. Energy Efficiency in Residential Buildings

Literature on the effectiveness of energy policy instruments on energy efficiency is rather scarce. Differences in climatic conditions, levels of income and living area, etc. preclude any simple cross country comparison of energy consumption in the building sector. Some studies circumvent this problem by comparing regulatory standards of new buildings (Schild et. al, 2010) although this also greatly reduces the scope by excluding the great amount of existing buildings which make up most of the overall energy demand. Alternatively one may control for observable characteristics that are known to influence consumption levels. There are only two major studies which analyze and compare the effectiveness of energy policies on energy efficiency in residential buildings across different countries, namely by Filippini et al. (2014) and Ó Broin et al. (2015). Therefore, we will focus mainly on these two studies and explain their approaches fairly detailed since our further analysis is based on these two studies.

The empirical analysis by Filipini et al. (2014) combines an energy demand model which includes climatic conditions, income levels and living area, with a so called frontier analysis. The authors generate six quantitative policy indicators within three main categories. There are (i) regulatory standards (e.g. u-values), (ii) financial/ fiscal incentives, and (iii) informative measures based on the cross country database on energy policies (MURE). This approach has two major limitations: firstly, quite distinct policy measures are treated as if they were identical. To give an example, subsidies for specific types of technologies and broader incentives such as energy taxation are put together in category (ii). Secondly, by simply counting the number of policies there are no weights which signify the relative impact of these measures (i.e. the indicator is equal to 1 if there are two or more regulatory standards in place that prescribe rules for buildings or heating within a country, and 0 otherwise). Many different kinds of standards fall within the precinct of this category. The authors recognize this problem when they state „This is arguably a relatively simplistic approach because [..] the measures are heterogeneous; hence, counting the number of measures introduced in each group could be imprecise“ (Filippini et al., 2014, 78). For example, Filippini et al (2014, 76, table I) list Sweden as one of the countries with relatively few regulatory standards. But as we will show below, the regulatory standards in Sweden should be seen as the strictest across Europe. In summary, the results suggest that regulatory standards and financial/ fiscal incentives

[3] In this paper the term energy efficiency improvement is defined as the reduction in energy consumption whilst holding the temperature level constant. Since we control for prices, income (GDP per capita) as well as average size of apartments and other relevant variables which might affect energy consumption, lower energy consumption indicates higher energy efficiency in a country.

affect energy consumption, whereas informative measures do not. These findings are in accordance with Feser & Runst (2016) who investigate why subsidized information campaigns for home owners do not seem to be effective in increasing the rate of energetic retrofits (and point toward lacking profitability and asymmetric information as reasons).

Ó Broin et al. (2015) pursue a similar strategy as Filipini et al. (2014) but introduce a stronger quantitative element in generating the policy-indicators. The authors use a panel data set of 15 European countries for the time period of 1990 till 2010. They estimate the determinants of heating energy consumption. Instead of simply counting the number of different types of policies (Filipini et al., 2014; also Bertoldi and Mosconi, 2015), Ó Broin et al. (2015) generate what they call a semi-quantitative index, whereby they apply different impact-weights to different policies in order to include a measure of effectiveness (and the effect size) for different policies. The policies recorded in the MURE-database are therefore divided into low, medium and high impact, which correspond to energy savings of 0.1%, 0.1-0.5%, and more than 0.5%. Accordingly, each policy is coded as 1, 10 or 20. The semi-quantitative approach thereby transforms a more or less informal expert consensus on the effectiveness of a policy by mapping tem onto the numbers 1, 10, or 20. The resulting semi-quantitative policy indicators also enter the empirical specification as lags (t-1 until t-7) in order to capture medium run effects. There are three policy categories – financial, informative and regulatory. The authors show that regulatory policies impart the greatest effect on energy consumption. In contrast to Filipini et al. (2014), the results indicate a seven year delay in the effectiveness of informative measures. Information effect sizes are also relatively small. The authors suggest increased implementation of regulatory measures.

A semi-quantitative approach necessarily emphasizes similarities between heterogeneous policies in order to create a feasible number of categories. To be sure, any process of quantification faces this challenge as the counting of entities (variable values) within constructed categories (variables) always entails some degree of artificially introduced homogenization. Another limitation of the study is the exclusion of certain policies (such as carbon-taxation) as they "would already be represented in the energy price time series" (Ó Broin et al., 2015, 220). Yet, the amount of collected energy and carbon-taxes does not necessarily correlate with the size of the tax rate. Individuals will adjust their behavior and substitute taxed sources (e.g. coal and oil) in favor of non-taxed or lightly taxed sources of energy. Thus, for countries in which energy and carbon-taxes have been in effect for many years (e.g. Sweden), the carbon-tax revenue underestimates the full impact of tax based energy policies as oil and coal are no longer in use. In other words, if people have already switched to renewable energy sources a high carbon-tax rate is not necessarily mirrored in a high energy price index.

The studies discussed above (Filipini et al., 2014; Ó Broin et al., 2015) have made valuable contributions to the literature and it is noteworthy that regulatory measures impart effects on building energy consumption in both of these papers. We base our analysis on the contribution of these two studies and extend their approaches in order to solve some methodical limitations and obtain more precise results.

3. Quantitative Analysis

We employ a mixed-methods approach. Our quantitative analysis serves the purpose of explaining energy consumption by country and year by observable characteristics. We pay close attention to country specific effects as they can indicate a higher (or lower) level of energy consumption than what we would expect from the vector of observable characteristics. We also plot the country specific residuals over time. Systematic changes over time may indicate improvements or decline in energy efficiency. We then build upon these quantitative insights by qualitatively investigating certain countries, which stand out due to their better-than-expected energy efficiency, in detail. These case studies identify likely (policy) causes for their high levels of energy efficiency or efficiency improvements.

Having data of the 28 countries of the European Union and Norway for the years from 2000 – 2015, we use panel data methods. The mean energy use per dwelling[4] by country and year (as tons of oil equivalent) represents the dependent variable in our empirical model which takes the following form:

$$Energy_{it} = \beta_0 + \beta_1 \bar{X}_{it} + \beta_2 WAPItax_{it} + \beta_3 longitude_i + \beta_4 latitude_i + \beta_5 country_i + \beta_6 year_t + \varepsilon_{it}$$

In order to capture the country-specific effects a Least Squares (Country) Dummy Variable Model (LSDV) will be run. Therefore, a country dummy variable $country_i$ is included in the model controlling for time-invariant country-fixed effects. These country dummies show whether a country consumed more or less energy than others after having controlled for country-specific conditions. Using a LSDV can also prevent endogeneity caused by omitted variables since it captures all country specific effects. However, in this case we expect that the country specific effects mainly capture public policy differences across countries. It has been shown that cross country analyses often suffer from omitted variable bias (Ranson et al., 2014). Both Filipini et al. (2014) and Ó Broin et al. (2015) include only a small set

[4] Former studies have used consumption per square meter as their dependent variable. We use average consumption per dwelling instead and control for floor area since we believe that consumption only increases until a certain floor area is reached and decreases afterwards.

of controls. Besides the LSDV approach, we consequently add a number of additional variables, represented by $\bar{X}$, which plausibly affect energy consumption.

The vector $\bar{X}$ is composed of the following time-variant explanatory variables: $WAPItax_{it}$ is the weighted average price index which calculates the energy price according to the country's specific energy mix and prices (including taxes and levies). Alternatively, we also used a net weighted average price index (excluding taxes and levies). However, due to a large number of missing values in the time-line and across countries, we did not include WAPInet in the model specifications.

Furthermore, the median age of the population, mean floor area and GDP per capita are included. All three are expected to have a positive impact on energy use. Their squared terms are included as well since we do not expect further positive impact on energy use from a certain floor area or GDP per capita onwards. Share of homes that are owned (as opposed to being rented) is included in the model in order to test for the existence of the owner-tenant dilemma. Moreover, the share of apartments (as opposed to free standing houses) is an important explanatory variable as apartments are more energy efficient due to the lower number of outer walls. In order to control for climatic differences we use HDD_{it}, $longitude_i$ and $latitude_i$ as additional variables. HDD_{it} are heating degree days which is a proxy variable for the country's specific climate, whereas $longitude$ captures possible effects related to continental climates in eastern European countries. The thermal properties of the building stock depend on its age. Therefore, we use the share of newly constructed residential buildings each year in conjunction with the share of buildings after 1980 in order to construct the variable $post1980$ for all years and all countries. We also included the country's average household size as an explanatory variable since we expect higher energy consumption with increasing household size. However, the household size does not vary substantially across countries and neither within countries over time. Besides, the variable household size was not significant and the regression output did not change substantially after the inclusion of the variable. Only the variable floor area lost some significance which could mean that the variable floor area partially captures household size. Therefore, the variable household size was dropped from the model. Finally, ε_{it} is the error term in this model.

The results of a Breusch-Pagan Test showed that the model contains heteroscedastic residuals. As often observed in panel data, we also detect autocorrelation. This is due to the country specific effects which are not constant over time. Therefore, heteroscedasticity and autocorrelation robust standard errors are specified in both model specifications.

Furthermore, energy prices are most likely affected by energy demand. In order to address this endogeneity problem Bigano et al. (2006) rely on lagged energy demand and Arellano-Bond dynamic panel-data estimations. Although a robustified Durbin-Wu-Hausman test on endogeneity led us to accept the null hypothesis of exogenous prices (WAPI tax), we nevertheless use an instrumental variable approach in order to safely rule out potential endogeneity.

To that end, the first year lag of the energy prices is used as an instrument for the energy prices. Energy prices were highly correlated with their lags and the lagged energy prices are not endogenous to the demand of energy. We use a two-stage least-squares (2SLS) estimator since it is more efficient than ordinary instrumental variable estimators (Cameron and Trivedi 2010). In the first stage we regress the potentially endogenous variable WAPItax on the instrument and all exogenous variables. The first stage regression output shows that the instrument (L1.WAPItax) is statistically highly significant and its t statistic is relatively high. This confirms the use of our instrument. The second stage replaces WAPItax in the structural regression by the predicted values from the first stage regression.

The results of the second stage regression show that the negative coefficient is larger. This suggests that the negative effect of prices on energy consumption was underestimated by 6 percent in the original regression. As the standard errors are not substantially larger and the t statistics did not become smaller compared to the original model we can conclude that L1.wapitax is a strong instrument. The strong association between WAPItax and its first year lag emphasizes this. Furthermore, a Stock-Yogo weak ID F test defines the critical value to be 16.38 at a 10% maximal relative bias toleration. Since we have a minimum eigenvalue statistic of 90.86 and an F statistic of 25.77 (due to robust standard errors) we exceed the critical value of 16.38 and therefore, can reject the null hypothesis of weak instruments. By including exactly one instrument for one potentially endogenous regressor our model is just-identified. This is also proved by the Kleibergen-Paap rk LM statistic which shows that our model is identified. Although WAPItax was not found to be endogenous, the estimates are still consistent.

Consequently, by conducting a Two-Stage Least Squares (2SLS) Regression in the second model specification, reverse causality can be circumvented. With the inclusion of the instrumental variables the model takes the following form:

$$Energy_{it} = \beta_0 + \beta_1 \bar{X}_{it} + \beta_2 \widehat{Wapitax}_{it} + \beta_3 longitude_i + \beta_4 latitude_i + \beta_5 country_i + \beta_6 year_t + \varepsilon_{it}$$

Where:

$$\widehat{Wapitax}_{it} = \gamma_0 + \gamma_1 Wapitax_{it-1} + \gamma_2 exogenous\ regressors_{i(t)} + \varepsilon_{it}$$

Where:

$$\gamma_2 = 0$$

3.1. Data Sources

All variables, their sources, and basic descriptive statistics are displayed in table 1. The data for energy consumption per dwelling in tons of oil equivalent was obtained by the ODYSSEE-MURE website, which represents a collaborative effort by several European national energy agencies. The data is normalized to account for varying severity of winter weather conditions from year to year. ODYSSEE-MURE further provided the data on home floor space and heating degree days (HDD). The latter variable is defined as the distance between Temperature Tm and 18 degrees Celsius (weighted by the number of days), if outdoor temperature is 15 degrees or less and zero otherwise:

$$HDD = \begin{cases} (18\,°C - Tm)\ x\ days, & Tm \leq 15° \\ 0, & Tm > 15° \end{cases}$$

where: $Tm = \frac{\sum(Tmin\ + Tmax\ /\ 2)}{\#days}$

We use both latitude and longitude as additional climate controls, whereby longitude controls for continental climates of eastern European countries. These variables were taken from the CIA fact book and verified with additional online sources. The median age is available at Eurostat. Home ownership and the fraction of the population living in apartments (for each country and year) are also available at Eurostat. However, these two variables do not contain values for each year, especially between 2000 and 2006. We graphically inspected the existence of a time trend in each country. If the slope is close to zero, it can be assumed that no systematic trend exists and the last available value was used for imputation. No more than three years of missing data was filled in in this manner.

The weighted average price index represents energy prices according to the country specific energy mix as well as country specific prices and taxes on each energy carrier. Therefore, the share of the main energy carriers (oil, coal, gas and electricity)[5] of the country's energy mix was calculated. Thereafter, prices of each energy carrier for each year were deflated to the prices of the year 2010 and denoted in USD. If the prices were only available in other currencies, the prices were converted into USD using the exchange rate of the respective year. To have a common base of measurement consumption of oil, coal, gas and electricity was converted into the unit tons of oil-equivalents using the IEA unit converter. In addition to this, different conversion efficiencies of the energy sources were considered, too. Therefore, the prices were multiplied by the energy carrier's conversion efficiency factor (NCV). Finally, the prices per ton of oil equivalent in USD and in NCV of one energy carrier (in one year) were multiplied by the carrier's share of the energy mix. Adding up these prices of each energy carrier yields the country and year specific weighted average price index. The data to construct this weighted average price index was drawn from ODYSSEE-MURE, Eurostat, IEA, OECD and Statista.[6]

Data for GDP per capita and floor area were both drawn from Eurostat. In order to construct the variable share_post80 we use data on newly constructed residential buildings in each year and those constructed after 1980 drawn from the European Commission, ODYSSEE-MURE and Norway Statistical Offices. Table 1 presents the descriptive statistics and data sources.

[5] Some country's energy mix includes biomass, wood as well as district heating as energy carriers. Due to a lack of data on prices of these energy carriers in most of the respective countries, we did not include these energy carriers in the WAPItax calculation. Instead, we subdivided the cumulated share of these three energy carries onto the other main energy carriers according to their share.

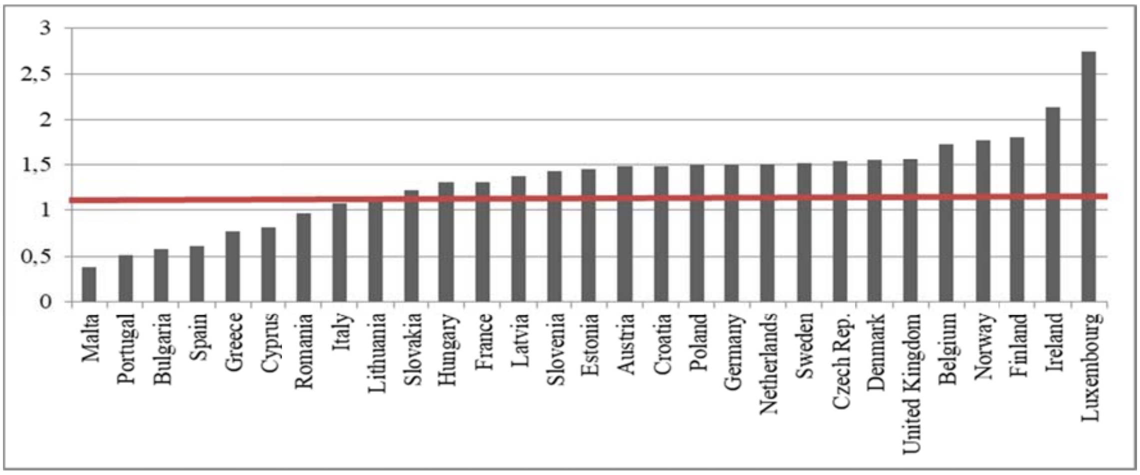
[6] Missing values were carefully imputed up to three years. If a systematic trend was observable, the value was adapted to the trend otherwise the value of the last year available was adopted or the mean between two years' value was chosen.

Table 1: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max	Data Source
consumption (in toe_dw)	406	1.336	0.516	0.300	3.277	ODYSSEE
wapitax	444	1368.910	606.238	229.616	3334.713	based on: ODYSSEE, IEA, OECD, Eurostat, Statista
age	434	39.280	2.344	32.400	45.600	Eurostat
hdd	435	2942.892	1221.309	306.604	6058.319	ODYSSEE
latitude	464	49.136	7.239	35.126	61.924	CIA Fact Book
longitude	464	14.947	13.657	-8.244	60.128	CIA Fact Book
floor_area	417	90.415	22.081	34.360	145.771	Eurostat
gdp_capita	435	29430.310	21918.140	1609.281	116612.900	Eurostat
home-ownership	358	75.861	10.545	51.600	97.600	Eurostat
aprtmt_share	365	38.009	16.860	2.500	69.700	ODYSSEE
share_post80	464	31.749	10.808	2.030	74.230	based on: European Commission, ODYSSEE, Norway Statistical Offices

Figure 1 depicts the average annual energy consumption per dwelling and country sorted from least consuming to most consuming. One can see that southern countries consume, on average, less energy than central or northern European countries. The countries with the highest average consumption per dwelling are Luxembourg, Ireland, Finland and Norway.

Figure 1: Average annual energy consumption per dwelling and country



3.2. Quantitative Results

Regression results are presented in table 2. Model specification 1 are the results of an LSDV estimation including the heteroscedasticity- and autocorrelation robust standard errors, whereas model specification 2 shows the results of the 2SLS regression using an instrumental variable (IV) for the energy prices. As expected the weighted average price index has a negative impact on energy use in both specifications. The 2SLS regression shows that the original model underestimated the negative effect of prices on consumption by almost 6%. The climate control variables HDD, longitude and latitude are jointly significant in both model specifications. As expected, energy consumption increases with more heating degree days and with increasing latitude. Longitude has a positive impact on energy consumption as well, which suggests that continental climate has a positive impact on energy consumption.

Age is only significant in model 2 and has, unexpectedly, a negative impact; its squared terms are not significant in either model. Floor area and GDP per capita and their squared terms are significant in both models. As expected, GDP per capita has a positive impact on energy consumption. However, a reverse trend is observable once a certain income is reached and less energy is consumed. Equally, increasing floor area leads to higher energy consumption up to the point at which floor area exceeds about 100 square meters after which consumption is decreasing again. This is most probably due to selective heating of rooms within a large dwelling. The share of owned homes does not affect the dependent variable. The tenant-owner-dilemma does not seem to be a major hurdle for the implementation of energy efficiency measures. The share of apartments affects energy demand negatively in both models. Similarly, the share of dwellings built after 1980 has a negative impact on energy use, albeit only in model 2.

Overall, our model's explanatory power is very high with an R^2 of around 0.983. This is due to the fact that the Least Squares Dummy Variable Models capture the effects of otherwise omitted variables. Coefficients of year and country dummies are not listed in table 2. A negative time trend is observable, which can be explained by technological progress as well as increasingly stringent European energy efficiency policies. Figure 2 depicts the country fixed effects sorted from least consuming to most consuming country. Country effects which were not significant have a coefficient of 0. Germany and France are left out as a control group and therefore have a coefficient of 0 as well. The country which displays by far the lowest energy demand is Sweden. The two countries which display the highest energy demand are Ireland and Luxembourg.

Our model results coincide with additional evidence. According to data by the International Energy Agency[7], Bulgaria's residential energy consumption per capita is only about one third of Germany's, whereas Luxembourg requires 35% more energy than Germany. A study by the University of Luxembourg (Maas and Zürbes, 2007) also concludes that residential energy requirements are 30% to 40% above German and Swiss ones.

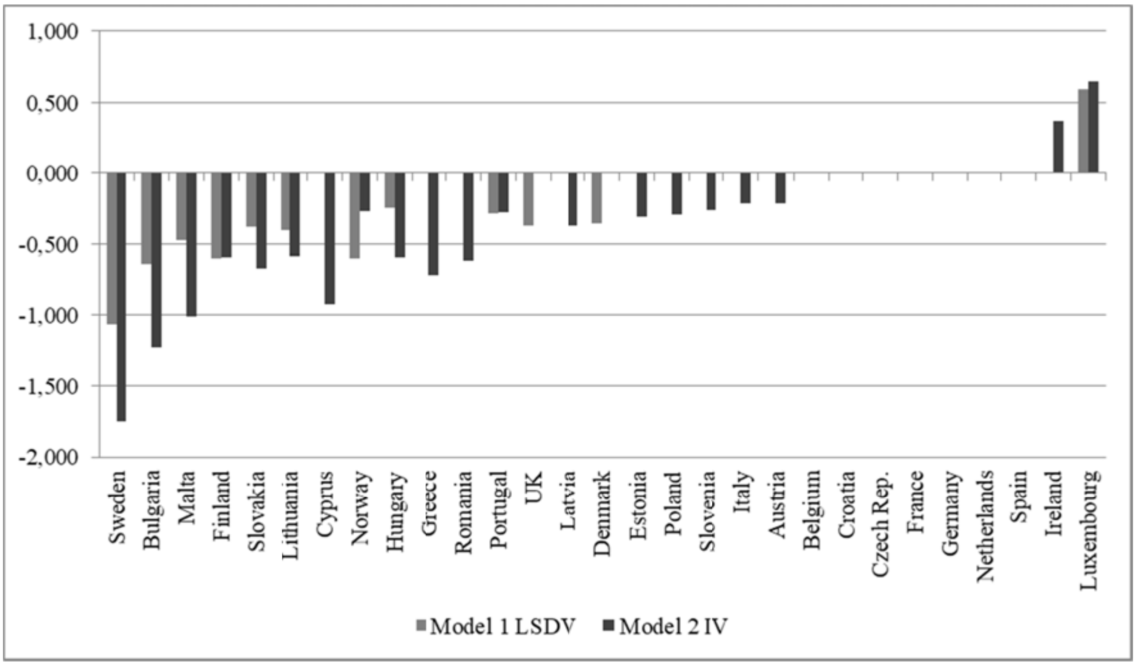
Table 2: Regression Results$_1$

	Model 1 **LSDV**	**Model 2** **IV**
log_wapitax	-0.109**	-0.163*
	(0.043)	(0.052)
log_hdd	0.162*	0.160*
	(0.086)	(0.06)
Longitude	0.0102***	0.0297***
	(0.003)	(0)
Latitude	0.0378**	0.00846*
	(0.018)	(-0.076)
Age	-0.133	-0.145*
	(0.149)	(0.08)
age2	0.00146	0.00161
	(0.206)	(0.119)
floor_area	0.0230***	0.0235***
	(0.008)	(0.002)
floor_area^2	-0.000115***	-0.000119***
	(0.007	(0.002)
gdp_capita (x1,000)	0.00676*	0.00613*
	(0.082	(0.083)
gdp_capita^2	-4.86e-11**	-4.72e-11**
	(3.00E-02)	(1.90E-02)
home_ownership	0.00114	0.00139
	(0.424)	(0.291)
apartment_share	-0.00751***	-0.00751***
	(0.002)	(0.001)
share_post80_	-0.00348*	-0.00299*
	(0.059)	(0.083)
N	276	275
R2	0.983	0.983

$_1$Country and time fixed effects are included in both models. P-values are displayed in parentheses.

[7] https://www.iea.org/statistics/ (referred 01.02.2018)

Figure 2: Country fixed effects after panel regression



Finally, figure 3 depicts the residuals of the model by country over time. While the country dummies have removed mean deviations from the overall energy demands, these graphs can be interpreted as within-country changes over time that are not explained by observable characteristics. The countries which display a clear negative trend over time are Latvia and Hungary as well as France, and Luxembourg to a minor extent.

Falling country specific effects over time are an indicator for the implementation of energy efficiency measures within a country.

In our qualitative and exploratory analysis we will focus on the analysis of Swedish energy policy due to its high performance. Furthermore, the quantitative analysis showed that Finland has consumed on average less energy than we would have expected given the country specific conditions. However, compared to Sweden, Finland's energy consumption savings are not as high. Being geographic neighbors, Finland and Sweden are situated in a similar climatic and cultural zone and are thus, ideally suited for a direct policy comparison. Considering the similarities of the both countries, begs the question, what explains the difference in energy efficiency between both countries. Therefore, Finland will be analyzed additionally. We will, furthermore, analyze Ireland because of its relatively high energy demand as well as Latvia and Hungary due to their decreasing trend found in the plotted residuals.

Figure 3: Residuals after panel regression by country over time

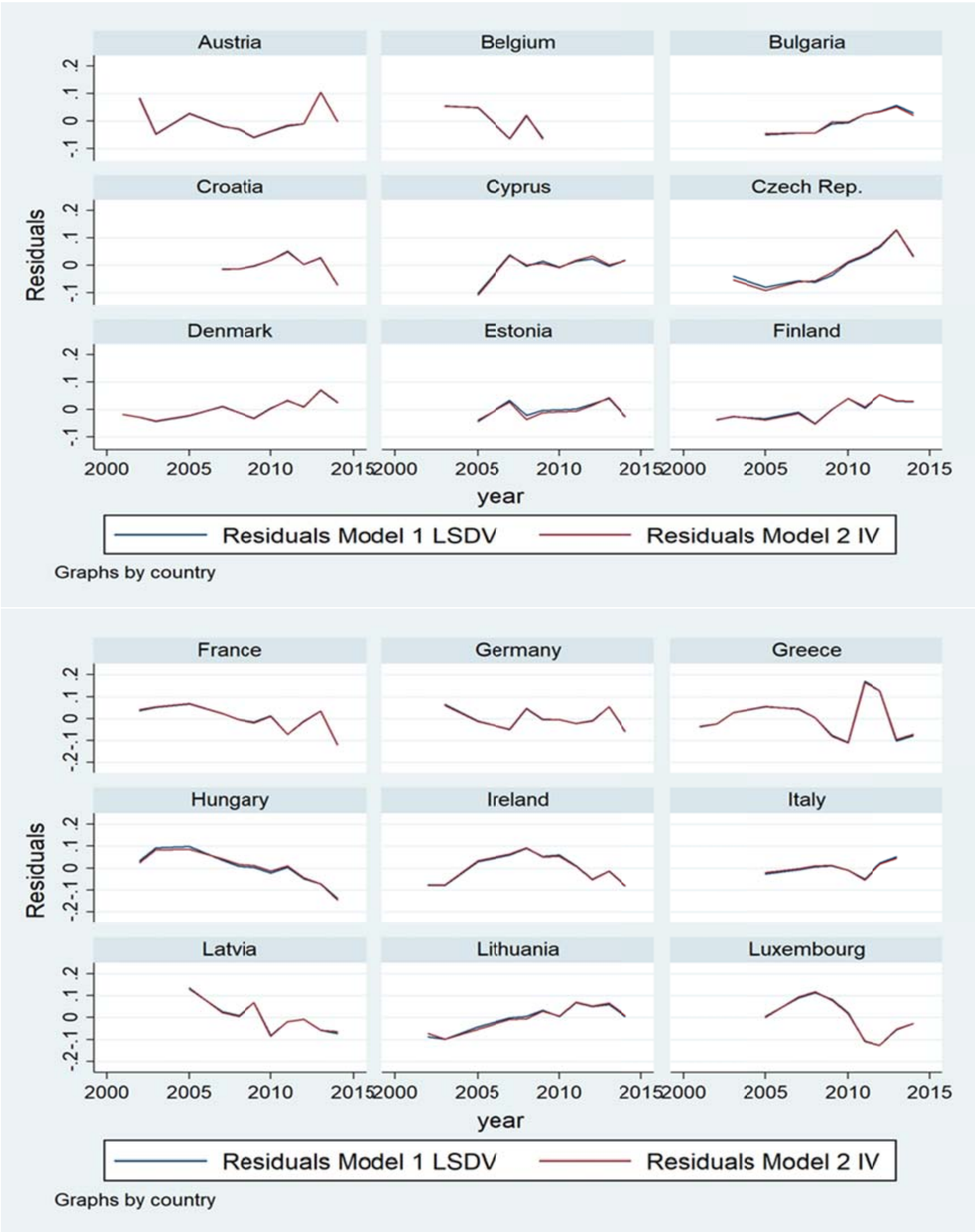
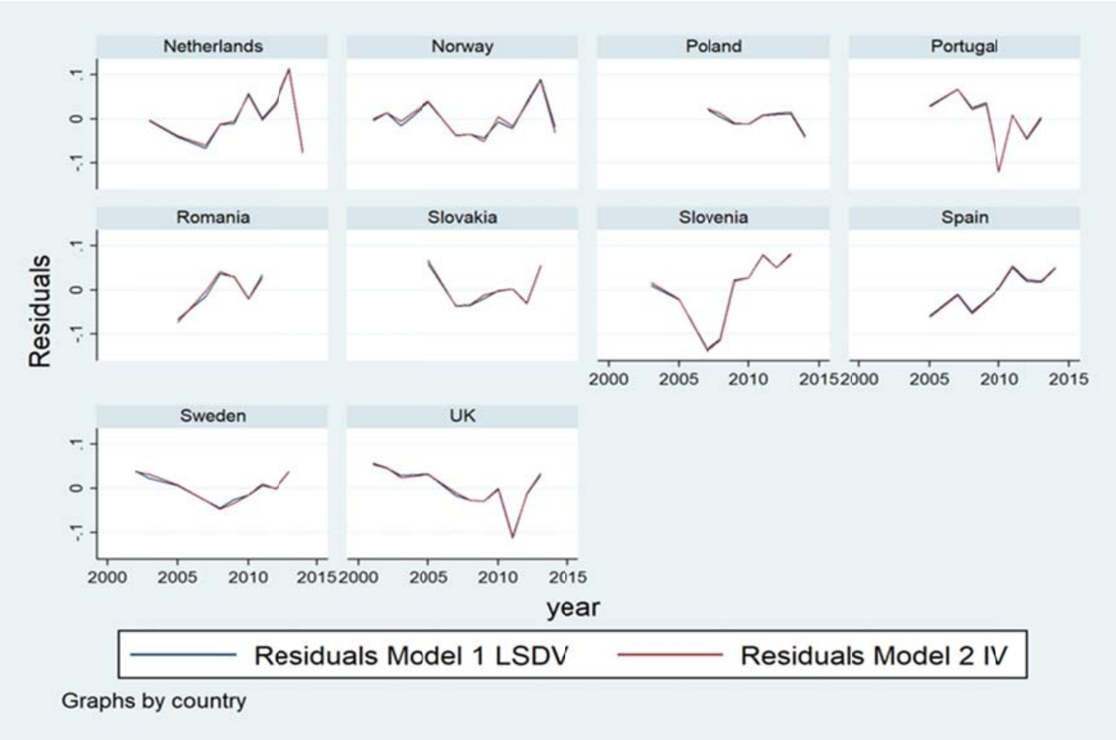


Figure 3 (continued): Residuals after panel regression by country over time



4. Exploratory Policy Analysis

Qualitative methods are known to generate more detailed information. Therefore we use qualitative methods in order to explore the countries' energy policies. The qualitative analysis is based on semi-structured in depth expert interviews and extended by an examination of original policy documents as well as research articles, as table A in the appendix summarizes. The gathered material was evaluated with regard to our research question, i.e. are there any distinct policies that may explain the country's low energy consumption level. This analysis is meant to be explorative, whereby we aim to formulate plausible hypotheses based upon qualitative evidence, not to test them.

4.1. Sweden

Sweden is an interesting case for our policy analysis because once we take all observable characteristics into account, the Swedish residential sector uses the least amount of energy per dwelling. Descriptive data by the Swedish Energy Agency display a falling total consumption between 1995 and 2008 (see figure 4). According to the conducted interviews, three characteristics of Swedish energy policy turn out to be noteworthy: regulatory energy standards for new buildings, the energy and carbon-taxation systems as well as district heating.

4.1.1. Energy regulation standards for new buildings

Swedish energy regulation is quite rigorous, compared with other European countries (see table 3). This is not only the case for the timespan of our quantitative analysis (2000-2015). The regulation from 1978 (SBN 75, Supplement 1) comprises energy requirements that are equal to, or even stricter than those in Germany in 2014 (ENEV 2014). In the meantime, the computational basis for u-values has been altered (BFS 1993; BFS 2002:6) and standards were tightened in 2007 (compare BFS 2006:12 of 2007 as well as BFS 2008:20 BBR 16). 2007's tightening of building part regulation was accompanied by the introduction of a preliminary 2-year license and periodical consumption metering. In the case of non-compliance, owners are fined and buildings have to be modified.

Figure 4 depicts Swedish total residential energy consumption over time. As the regulations have been strict since the 1970s and as they have been tightened further in 2007, they cannot be regarded as the main explanatory factor for the decline of Swedish energy consumption between 1995 and 2007 without further qualification. If we put aside the oil price shocks of the 1970s, we can observe that energy demand is on decline since 1995, or, perhaps 1990, whereas it showed no further reaction to the tightening regulation in 2007.

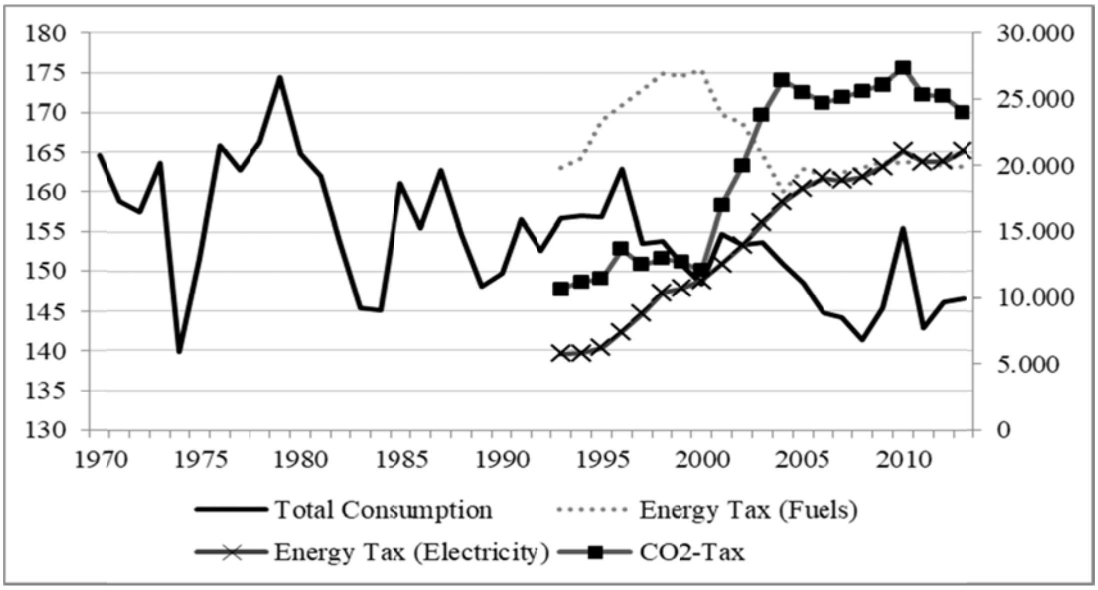
Furthermore, tighter building part regulations may not have been introduced for environmental purposes. They could, perhaps, simply be explained by utility maximizing decisions in colder climate zones. If house owners invest without being forced by regulation, in order to gain more energy efficiency, a law that codifies this practice will not encounter much opposition. Legal codification, in this case, would only translate a common practice into formal law. Thus, the causal relationship is not necessarily running from law to energy consumption.

4.1.2. Energy and Carbon Taxation

Figure 4 shows that a major proportion of energy conservation was achieved from 1995 on and this decline cannot be explained by regulatory reforms or the tightening of building part regulation in 2007 because it was introduced after the major part of conservation had already been achieved. Instead, as we found out in the expert interviews the introduction, and more importantly, the upward adjustment of the carbon-tax play a significant role. In 1991, Sweden was one of the first countries to introduce a carbon tax, right after Finland and Poland did so in 1990. In current prices the tax rate was at 20 €/ton of CO_2, but in subsequent years it was subject to continuous increases. The highest raise occurred in between 2000 and 2004 where the price per ton grew up to 100€. The energy- and electricity- as well as the carbon-tax revenues are also shown in figure 4. The continuous increase of the electricity tax revenue after 1993 and the increase of the carbon tax rate after 2000 mirror the declining energy consumption trend. The reduction of fuel energy taxation is strongly overcompensated by the increase of electricity and carbon taxation.

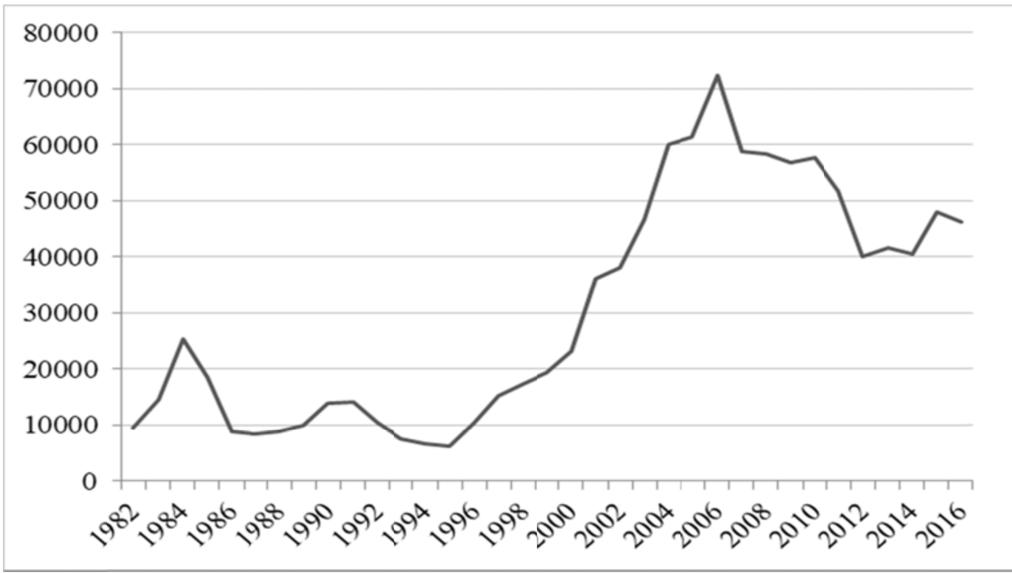
Based on our findings we hypothesize that the carbon tax had two major effects: (1) a general reduction in energy consumption and (2) changes of the energy-mix. Especially intensified use of heat pumps (figure 5) and the reduction of oil consumption (figure 6) are presumably caused by the tax increase, which is supported by their co-varying time trends. Interestingly, the spread of heat pumps caused only a very slight increase in electricity consumption after the year 2000. Furthermore, the oil consumption reduction is partly compensated by an increase in biomass consumption. The actual increase in biomass consumption is underestimated in figure 6, as a large portion of district heat (which is listed separately) is fueled by biomass as well.

Figure 4: Total residential energy consumption (1970-2013, in TWh) and environmental tax revenues in Sweden (1993-2013, in Mio. SEK)



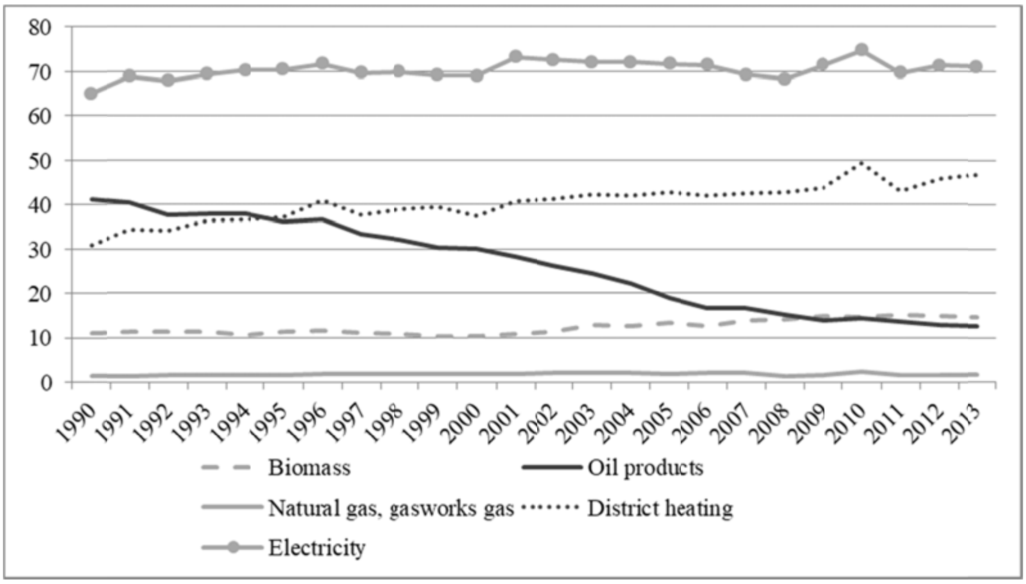
Source: Swedish Energy Agency, Statistics Sweden

Figure 5: Sales of heatpumps in Sweden between 1982 and 2016



Source: Svenska Kyl & Värmepump Föreningen

Figure 6: Energy consumption (households) by energy carrier (Sweden, in TWh)



Source: Swedish Energy Agency

4.1.3. District Heating

District heating was mentioned by our interviewees as another factor having improved energy efficiency in Swedish residential buildings. As a reaction to the oil price shocks in the 1970s, a political promotion of municipal district heating occurred. District heating in Scandinavian countries is relatively energy efficient (Joelsson and Gustavsson, 2009). Due to high energy taxation, the district heat production was incrementally adjusted to include a greater share of renewable energies instead of fossil fuels since the 1990s, which may have been partly caused by higher fossil fuel prices. District heating had a market share of around 55% in 2014 (Werner, 2017).[8]

Hypothesis 1: *Strict regulations are effective in lowering energy consumption.*

Hypothesis 2: *Carbon and energy taxes are effective in improving energy efficiency by lowering consumption and causing fuel substitution.*

Hypothesis 3: *The prevalence of relatively efficient district heat systems has caused lower energy use.*

[8] However, district heating is not per se an energy efficient energy carrier. In cases in which pipes are outdated and badly insulated districting heating can lead to an enormous loss of energy."

Table 3: Building part regulation across chosen countries (u-values)[2]

	Finland			**Germany**		**Sweden**		**Latvia**			**Hungary**		
Year	***1978***	***1985***	***2010***	***1977***	***2014***	***1978***	***2008***	***< 1991***	***1991***	***2003***	***< 1991***	***1991***	***2006***
Wall	0,29 - 0,35	0,28	0,17	1,45 - 1,75	0,28	0,25 - 0,30	0,18	1.1	0.36	0.25-0.3	1.2	0.7	0.45
Roof	0,23 - 0,29	0,22	0,09	0,45	0,2	0,17 - 0,20	0,13	1.3	0.31	0.2 -0.25	0.9	0.4	0.25
Windows	2,1 - 3,1	2,1 - 3,1	1,00	1,6 - 3,5	1,3	1,0 - 2,0	1,3	5.9	2.0	1.8	-	3.00	1.6
Ground Floor	0,23 - 0,4	0,22 - 0,36	0,16	0,9	0,35	0,17 - 0,30	0,15			0.25	-	0.85	0.25

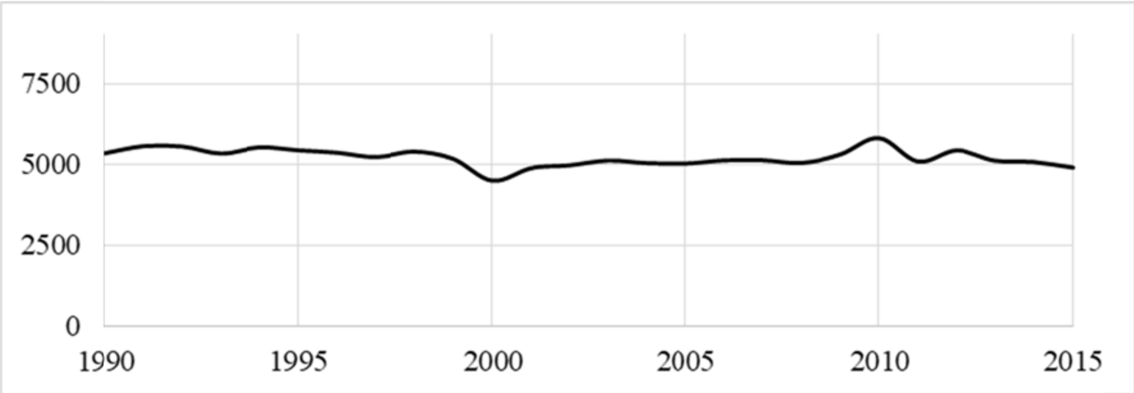
[2]The table displays u-values: $\frac{W}{m^2K}$

Sources: *Finland* – ODYSSEE-Mure Policy Data Base
Germany - Wärmeschutzverordnung 1977, nichtamtliche Fassung S. 9-12; Energieeinsparverordnung 2014 nichtamtliche Fassung S. 41f.
Sweden - SBN 1975 Supplement 1 S. 17, BFS 2008:20 BBR 16 S. 10.
Latvia – Cabinet Regulation No 495 Adopted 27 November 2001, "Implementation of the EPBD in Latvia Status in November 2010" by Dzintars Grasmanis
Hungary - before 1991: ME-30-65; 1991: BS-04-140/2-79; BS-04-140 2-85; DIN-04-140-2; 2006: 7/2006. (V. 24.) TNM

4.2. Finland

Finnish residential energy consumption is higher than the one in Sweden in both descriptive statistics, as well as in our regression analysis (see figure 2). Descriptive statistics by the IEA (figure 7) as well as the residuals in our quantitative analysis above (figure 3) show hardly any change in total residential energy consumption over time. In the following paragraph we will outline the reasons for Finland's lower, yet, by European comparison still quite satisfactory, energy performance.

Figure 7: Total Residential Consumption Finland 1990-2015 (in ktoe)



Source: International Energy Agency (IEA)

Besides strict regulatory building part energy efficiency regulations (see table 3), Finnish energy efficiency policy incorporates a range of economic incentives such as energy audits for households or industrial production as well as energy grants for households in order to promote energy efficiency in the old building stock. Like Sweden, Finland also makes extensive use of district heating which has a market share of about 45% (Sweden: 55%, see above; Vainio et. al. 2015). Alternatively, country statistics provided by Euroheat & Power (2013) estimate that about 50% and 52% of all customers are served by district heat in Finland and Sweden respectively. The fossil fuel intensity within the district heating energy mix and the overall residential energy mix has been declining over the last decade. It is being mostly substituted by renewable and carbon neutral energy sources.

Thus, Finland makes use of a policy mix that displays remarkable similarities to Sweden's regarding regulations, use of subsidies, and the prevalence of district heating. Therefore, it seems appropriate to expect Finland's residential energy conservation level to be roughly similar to the one in Sweden. Since this is not the case, the discrepancy in energy efficiency performance calls for another explanation.

The expert interviews and our analysis of policies suggests that the main difference between the two countries energy policy lies in the more stringent carbon taxation in Sweden.

Being the first country to do so, Finland enacted a carbon tax in 1990. This tax has been subject to major reforms (e.g. in 1997, 2007, 2011) of which the merging with the energy tax is of particular importance. Since 1997 the carbon tax also applies to traffic and heating fuels.

In Finland, different energy carriers are subject to different carbon-tax rates, either expressed in c/l (light/heavy heating fuels) or c/kg (coal). Heavy fuel oil and coal make up only an insignificantly small share of the heating energy mix, whereas light fuel oil is the most important fossil energy carrier after wood. If we project the 2015 tax rate for light fuel oil (9,94c/l) to tons of CO2 (Statistics Finland, 2017), it can be concluded that the current carbon tax rate in Finland is set at around €30 per ton of CO_2 for light fuel oil. This is, as a World Bank study shows, rather high in international comparison, although the Swedish carbon tax rate is much higher (World Bank, 2015: 15). Lower tax rates are imposed on natural gas, certain biofuels, and peat. The relatively lower tax rate, can be regarded as the main factor that distinguishes Finland from Sweden.

In summary, both Finland and Sweden display energy performance levels above what we would predict based on observable characteristics. Their relative position can be explained by tight regulatory standards. Finally, more stringent carbon-taxation seems to explain Sweden's more advanced position when we compare the two.

Hypothesis 4: The effectiveness of a carbon tax is dependent on its magnitude. A tax of 30 € and a tax of 100 € per ton of CO_2 cause markedly different reductions in energy consumption.

4.3. Ireland

In comparison to Sweden and Finland, Ireland is underperforming when it comes to energy conservation in the residential sector. However, the descriptive data shows a 25% decline in residential energy use between 2000 and 2015. Thus, while Ireland displays poor energy performance on average, there have been considerable improvements during the last two decades. A rough calculation based on our regression coefficients suggests that at least one quarter of the overall decline in energy use between 2000 and 2015 can be traced back to the construction of new buildings.[9] The single most important policy measure seems to be the building part regulation in Ireland, which is currently comparatively strict.

The building part regulation was drastically tightened between 2000 and 2014. Table 4 shows its development over time. It applies to new buildings as well as to renovation for existent buildings, although in the former case, it is more demanding. Between 2000 and 2015, the building stock grew from 1.2 Mio. to 1.7 Mio. permanently occupied buildings. Therefore, a large portion of buildings is subject to the tightened regulations of 2002 and 2007. The average area per building grew during that period, but energy demand per dwelling declined (Irish Energy Agency, 2016). The Irish Energy Agency explains this improvement by the increasing spread of central heating which is more energy efficient than space heating systems.

Table 4: Building part regulations (u-values) for existent and new buildings in Ireland[3]

	New Buildings					
Year	**1991**	**1997**	**2002**	**2007**	**2011**	**2017**
Wall	0,45 - 0,6	0,45 - 0,6	0,27	0,27	0,21	0,21
Roof	0,25 - 0,35	0,25 - 0,35	0,16 - 0,22	0,16 - 0,22	0,16 - 0,2	0,16 - 0,2
Windows	--	3,30	2,2	2	1,60	1,60
Ground Floor	0,45 - 0,6	0,45	0,25	0,25	0,21	0,21
Source:	BRTGDL[4], 1991, p. 8	BRTGDL, 1997, p. 8	BRTGDL, 2002 (Reprint 2005) , p. 9	BRTGDL, 2007 (Reprint 2008), p.17	BRTGDL, 2011, p.17	BRTGDL, 2017, p.18
	Existent Buildings / Renovation					
Year	**1991**	**1997**	**2002**	**2007**	**2011**	**2017**
Wall	0,60	0,45 - 0,6	0,6	0,27	0,35 - 0,55	0,35 - 0,55
Roof	0,35 - 0,6	0,35 - 0,6	0,35	0,16 - 0,22	0,16 - 0,25	0,16 - 0,25
Windows	--	3,30	2,2	2	1,6	1,6
Ground Floor	--	--	--	0,25	0,45	0,45
Source:	BRTGDL, 1991, p. 8	BRTGDL, 1997, p. 8	BRTGDL, 2002 (Reprint 2005) , p.9	BRTGDL, 2007 (Reprint 2008), p. 28	BRTGDL, 2011, p. 26	BRTGDL, 2017, p. 27

[3] All values are u-values. The unit is $\frac{W}{m^2K}$

[4] BRTGDL = Building Regulations Technical Guidance Document L

Carbon-taxation was introduced for heating and motor fuels in 2010. Its original rate was set at 15€ per ton of CO2, which was raised to 20€ per ton in 2012. Descriptive statistics show a marked decline in total energy use after 2010 despite the general increase in living space (Irish Energy Authority, 2016, 65-66). While this may indicate an impact of carbon-taxation, the intervention is too recent in order to draw more definite conclusions.

The case of Ireland illustrates that hard building regulations are only effective in the long run. Because of the building boom, about a third of the Irish building stock was built after the year 2000, thereby being subject to current energy efficiency standards. Nevertheless, the average Irish energy consumption level is still higher than in most European countries.

Hypothesis 5: Stringent building regulations are only effective in the long run.

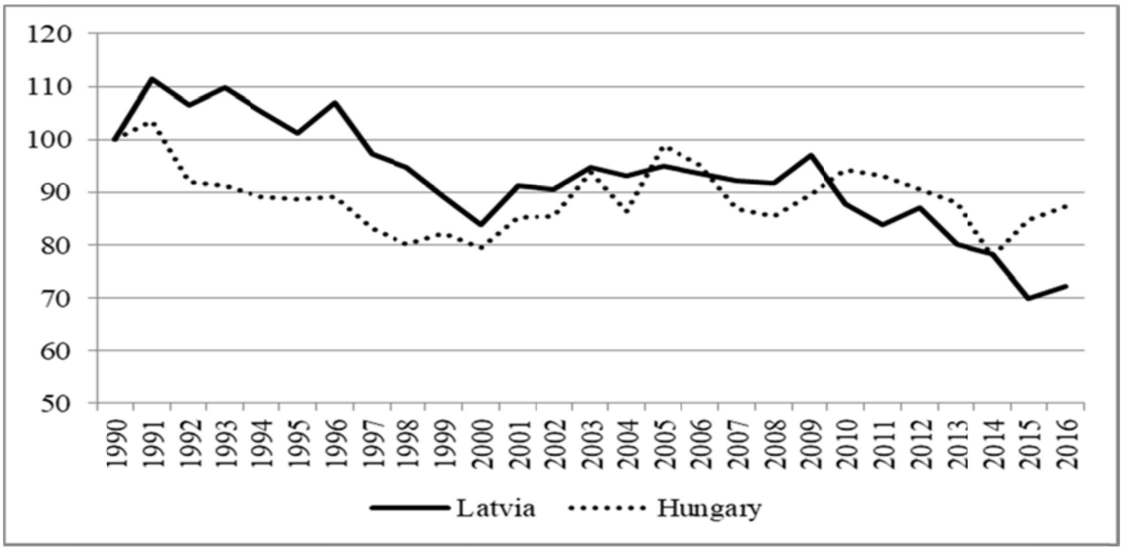
[9] We assume the share of new buildings to be 33%, whereas the coefficient for the variable 'post_80' is 0.0035. The latter number signifies the reduction in energy consumption (measured in toe) caused by a 1 percent increase of new buildings. Multiplying 0.0035% with 33 yields 0.12, which represents about a quarter of the total reduction of the Irish energy consumption.

4.4. Latvia and Hungary

Our quantitative analysis has shown that among all countries Latvia and Hungary both occupy middle positions with regard to their energy consumption level. Yet, both countries show the strongest improvements in energy efficiency over the years. The residential energy consumption pattern in both countries moves almost parallel. Overall, Latvia's as well as Hungary's total residential energy consumption fell between 1990 and 2016 (figure 8). In our regression analysis above, after having controlled for a number of key observable characteristics, we can see that energy efficiency has improved in the years from 2000 onwards (see figure 3).

From 1980-1991 buildings in Latvia and Hungary were built according to USSR Standards (for u-values see table 3). After their independence, the Ministry of Architecture and Construction imposed considerably stricter energy efficiency standards in Latvia in 1991 which were again tightened by the Cabinet Regulation No 495 (LBN 002-01). The latter regulation came into force in 2003 and set construction standards for new buildings, as well as reconstructed and renovated buildings. The u-values from 2003 are not as strict as in Sweden or Finland but roughly correspond to standards in Germany in 2014. Similarly, building regulation in Hungary was tightened in 1991, and again in 2006. Hungary's regulatory demands are slightly weaker than the ones in Latvia.

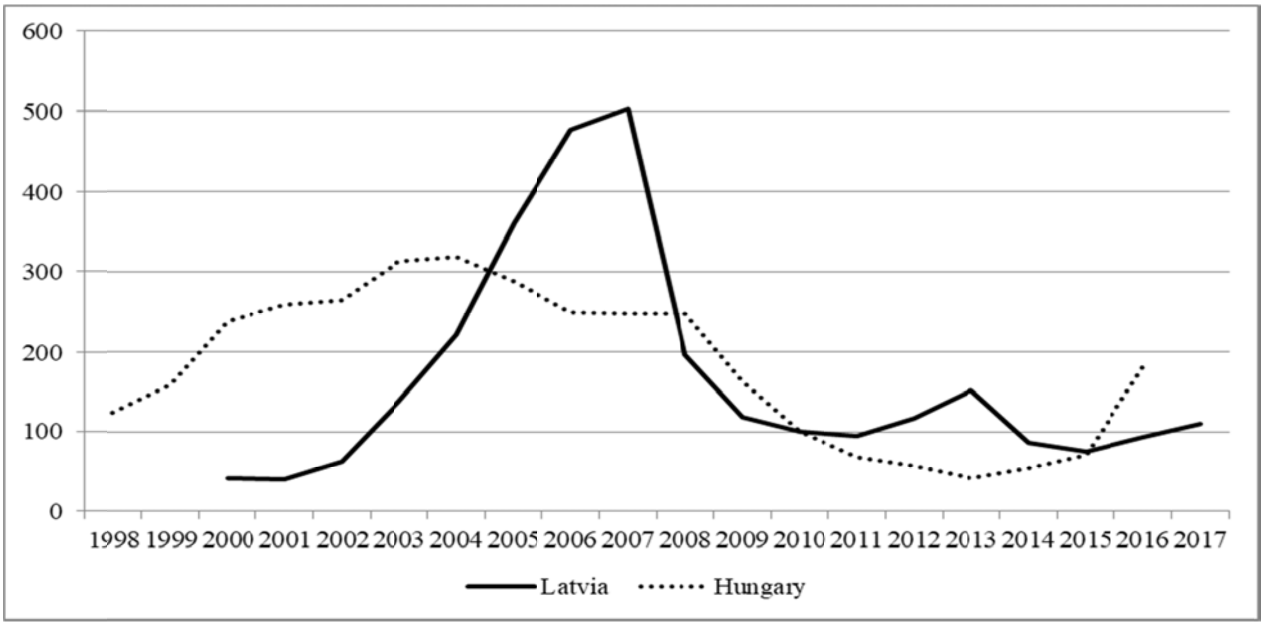
Figure 8: Residential Energy Consumption in Latvia and Hungary (1990-2016, Index: 1990=100)



Source: Eurostat

As figure 8 depicts, total energy consumption in Latvia and Hungary already had a decreasing trend in the 1990s which could be due to the introduction of stricter standards in both countries at that time in 1991 (see table 3). However, construction activity was low in the 1990s (see figure 9) and thereby regulatory building standards do not translate into improved efficiency performance. Instead there was a massive post-socialist GDP slump per capita in the early 1990s followed by a gradual recovery. Thus, the reduction in energy consumption can most probably be explained by low incomes.

Figure 9: Total number of new residential dwellings in Latvia and Hungary over time (Index: 2010=100)



Source: Eurostat, Centralas statistikas parvaldes datubazes

In the year 2003, when construction standards LBN 002-01 came into force in Latvia, the number of new dwellings skyrocketed till the financial crisis in 2008 (figure 9). The sudden increase in construction activity correlates with the steady and strong GDP growth starting in 2003. Similarly, Hungary experienced a building boom starting in 1999 as GDP per capita increased continuously. The building boom coincides with a temporary increase in energy demand, which plateaus in 2004 and then gradually declines. Interestingly, energy consumption seems to decline in both countries around 7 years after the country's tighter regulatory standards were implemented.

In conclusion, similar to Ireland, tighter building regulations in conjunction with increased building activity are likely to explain the falling energy consumption levels in Latvia and Hungary over time (see figure 8). However the effects are lagged by around 7 years after the country's implementation of tighter building standards.

Hypothesis 6: Tighter regulations are most effective when accompanied by high construction activities in the residential sector.

5. Conclusion and Policy Implications

In this paper, we examine the effectiveness of environmental policies in reducing residential energy consumption. In contrast to former studies, we use an exploratory approach in order to find out which policies explain differences in energy efficiency between countries and to generate hypotheses.

In our quantitative analysis we regress the mean annual energy use per dwelling in 29 European countries on a number of observable characteristics. We then plot country dummy coefficients in order to identify countries that exhibit inexplicably low or high energy consumption. Sweden and Finland stand out because of their low energy consumption, whereas Ireland can be found on the other end of the spectrum. We also plot residuals by country over time in order to spot improvements in energy efficiency. Latvia and Hungary display a falling time trend. We then analyze these countries' policy environments qualitatively.

We find that building part regulations are an effective policy instrument for reducing the consumption of energy in residential buildings. However, the impact of regulatory standards becomes only visible over longer time periods, as for example in Sweden and Finland, unless the tightened regulation is accompanied by a building boom, as for example in Ireland, Latvia and Hungary. While regulations have markedly contributed to the reduction of overall energy consumption in Latvia, Hungary and Ireland, these three countries are still positioned in the lower half of our energy performance ranking, which, again, speaks to the longer time periods required for regulation to affect energy performance.

Our results also point toward an additional policy instrument: carbon-taxation. As regulatory standards as well as other factors (such as the performance and the share of district heating) are almost identical in the case of Sweden and Finland, another explanation is required in order to understand the relatively advanced performance of Sweden in comparison to Finland when it comes to energy consumption. We argue that this crucial difference can be found in high carbon-taxation rates that have existed in Sweden. The decline in the energy consumption pattern over time is consistent with such an explanation as the increases in taxation coincide with the decline but cannot be explained by the timing of building code reforms. In this regard the scope of carbon taxation plays a crucial role for its effectiveness. A carbon tax of only 4,50 € per ton of CO2 as in Latvia or 30 € per ton of CO2 in Finland cannot show the far-reaching effects as observed in Sweden (with a carbon tax of 120 € per ton of CO2).

From our research, the following policy implications and hypotheses can be derived, which should be tested in future studies:

1. Strict regulations are effective in lowering energy consumption.
2. Carbon and energy taxes are highly effective in improving energy efficiency.
3. The prevalence of relatively efficient district heat systems has caused lower energy use.
4. The effectiveness of carbon taxation is highly dependent on its scope. A tax of 30 € and a tax of 120 per ton of CO2 cause markedly different reductions in energy consumption.
5. Stringent building regulations are only effective in the long run.
6. Tighter regulations are most effective when followed by high construction activities in the residential sector.

There are certain limitations to our approach. Most importantly, we have focused on generating hypotheses, not hypothesis testing. While our qualitative analysis leads us to argue that carbon-taxation can be an effective policy instrument for reducing energy consumption, quantitative efforts should test this assertion. As more and more countries introduce carbon-taxes, more data for such an endeavor will be available in the near future. In this regard, Lin and Li (2011) have already provided a valuable first contribution by examining the impact of carbon-taxation on overall CO2-emissions. Future studies should be careful to include the varying tax rates as our results indicate that the difference between a tax of 30 € and a tax of 120 € per ton of CO2 causes markedly different outcomes.

Furthermore, the use of the country specific effects as an energy policy indicator has two major limitations, one of which is the omitted variable bias. As above mentioned, the country dummies absorb the effects of omitted variables. Moreover, the country dummies could include cultural factors or habits in what concerns energy consumption. Further research could take upon these limitations.

Finally, while we cautiously suggest that both regulatory building standards as well as carbon-taxation can be effective policy approaches for reducing energy consumption, we have not addressed the cost-benefit aspects of these policies. There are strong theoretic reasons to believe that a taxation scheme will cause market actors to discover the most cost-efficient means of lowering CO2-emissions. If the cost of CO2-reduction exceeds a certain level, the likelihood of losing public support for further climate policies will increase, thereby jeopardizing global efforts to mitigating climate risks.

However, since we used an exploratory analysis we were able to shed some light on energy policies which were earlier neglected due to homogenization by quantification of energy policies. Therefore, our analysis provides useful policy implications for further enhancement of energy efficiency policies in the European Union

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Appendix

A. Overview on documents and interviewees

Country	**Policy documents and interviews**
Sweden	Boverket (National Housing Board) building part regulation: www.boverket.de SBN 1975 Supplement 1, BFS 1993; BFS 2002:6; BFS 2008:20 Economist: 1 Swedish Energy Agency: 2 Boverket: 1 Swedish Green Building Council: 1
Ireland	Building Regulations Technical Guidance Document L 1991, 1997, 2002 (Reprint 2005), 2007 (Reprint 2008), 2011 Economists: 1
Finland	ODYSSEE-Mure Policy Database Ministry of the Environment: 1 Energy Authority: 1
Hungary	ME-30-65; BS-04-140/2-79; BS-04-140 2-85; DIN-04-140-2; 7/2006. (V. 24.) TNM
Latvia	Cabinet Regulation No 495 (Regulations Regarding Latvian Construction Standard LBN 002-01 Thermotechnics of Building Envelopes Ministry of Finance Republic of Latvia 2007: Operational Programme "Infrastructure and Services" (3.5.2 Energy) Energy Efficiency Law Energy Law Centralas statistikas parvaldes datubazes
Other	*Germany* – Wärmeschutzverordnung (WSchVO) 1977; Energieeinsparverordnung (EnEV) 2014 UK – National Audit Office, 2016.