ENERGY EFFICIENY AND THE BEHAVIOURAL RESPONSE OF OCCUPANTS – EVIDENCE FROM EUROPEAN OFFICE BUILDINGS

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ABSTRACT

Energy consumption in office buildings is determined by the fixed building characteristics such as location, size, building fabric and age, but also to a great extent by the behavioural response of their occupants. Within the European Union office buildings became subject to more stringent energy efficiency regulation for new construction or major refurbishment over the last years – expected to reduce energy consumption and carbon emissions significantly. This research study determines the influence of physical building characteristics and the behavioural response by occupants on the actual energy consumption. The authors hypothesise a behavioural response of occupants being negatively related to energy savings. A unique data sample of the Green Rating Alliance (GRA) is tested to provide empirical evidence when applying hedonic regression models for actual energy consumption and intrinsic energy assessment. The results highlight the behavioural response by occupants accounting for a tremendous gap in the energy consumption between single and multi-tenant office buildings. Furthermore, a higher consumption associated with total or major refurbishment in a margin between 17.5% up to 21.7% is investigated. The study proves the existence of a "rebound effect" inherent in the European office markets for total or major refurbishment, thus contradicting the expectation of potential energy saving associated with refurbishment. All above, for the tested portfolio total or major refurbishment is identified to contribute to a negative impact on climate change.

Keywords: Sustainable Real Estate, Energy Efficiency, Behavioural Real Estate, Carbon Emissions, Hedonic Effects.

I. INTRODUCTION

In the European Union (EU) the energy consumption from the building sector accounts for 40% of the total final energy use. Over the past decade the EU policy required all member states to implement increased energy efficiency regulation for new construction in order to reduce energy consumption in the building sector. As a consequence, office buildings became subject to more stringent energy efficiency regulation for new construction or major refurbishment[i]. In a theoretical framework, they are expected to reflect higher levels of energy savings, whenever both the technical operability as well as the behaviour of the occupants reflect a stable balance.

The energy consumption of office buildings is mainly determined by core operations referring to physical building characteristics (heating, cooling, lighting, ventilation and elevators) and consumption from applied technical equipment depending on occupants' behaviour in the buildings. Beside the fixed building characteristics such as location, size, building fabric and age, energy consumption in office buildings is also to a great extent dependent on the behavioural response of their occupants.

While more stringent energy efficiency regulation is intended to reduce carbon emissions from the durable building stock, the question arises if this could be achieved essentially by focusing on the physical building characteristics comprehending the technological progress. Growing evidence has shown a latent "rebound effect", implying a deterioration in the behavioural response of the occupants when they are confronted with a modern building quality.

In this context, the study investigates the relationship between actual energy consumption, physical building characteristics and behavioural attributes of occupants under control of outdoor climate conditions to identify the factors affecting the energy consumption in office buildings.

Our research provides empirical evidence that the behavioural response of occupants in office buildings is negatively related to energy savings, leading to a spurious rebound effect in European office building markets. Although newer buildings are subject to more stringent energy efficiency regulation confronted with new construction or major refurbishment, our study reveals that office buildings of lower age do not consume less energy.

While the applied dataset contains an assessment of intrinsic energy consumption in addition to the actual consumption, the authors try to identify the most significant explanations for the deviance between the two.

The remainder of this paper is as follows: Section II provides the background for our study and catches up with some related research. In section III, we explain the characteristics of the applied data sample and discuss the econometric methodology. Section IV will present the results of the regression model, while section V highlights some major conclusions and recommendations for further research.

II. BACKGROUND AND EMPIRICAL FRAMEWORK

Background

Due to a significant greenhouse gas externality associated with energy consumption, the building sector was attributed to have a tremendous potential in reducing carbon emissions from the durable building stock. In the absence of any carbon pricing, increment in energy consumption of commercial buildings is contributing to a negative impact on climate change.

However, over the past decade, research insights about energy consumption and potential carbon emission savings in the commercial building sector of Europe were still limited. This corresponds to the experience from the US, where Kahn et al. 2014 found that research about commercial buildings energy consumption is limited and most of it has been provided by explorations of engineers. A research study by Guerra Santin et al. 2009 argues that empirical evidence for the extent of influence from occupants in the commercial or office building sector of Europe is still poor.

The energy consumption of office buildings is determined through the combination and interaction of multiple parameters. The physical building characteristics include location, building envelope referring to building size, fabric and age, technical equipment, such as heating, cooling, ventilation, lighting, elevators and IT equipment. With different energy efficiency measures these characteristics inherently place disparities in the energy consumption compared between office buildings. An enormous influence on energy consumption has been attributed to the building size since a one standard deviation increase in the log of building size is associated with an increase in energy consumption by 1.7% (see Kahn et al. 2014).

In the course of a recent research project[ii] the actual energy consumption of non-residential buildings within the EU was investigated in depth on country level. The results at normal climate provide significant differences between European countries with regard to the influence of the physical – mainly thermal – building characteristics and behavioural response on the non-residential building stock (see ENTRANZE Project 2014).

Table I: Total energy consumption of non-residential buildings in EU-countries

Total consumption (at normal climate)	kWh/sqm/a
Austria	345.5
Belgium	553.9
Bulgaria	171.1
Czech Republic	423.8
Denmark	195.7
Estonia	443.2
Finland	298.8
France	238.5
Germany	254.6
Greece	198.1
Hungary	347.5
Ireland	468.6
Italy	590.1
Latvia	444.8
Lithuania	244.2
Netherlands	326.4
Poland	230.0
Portugal	237.1
Romania	401.5
Slovakia	623.4
Slovenia	220.6
Spain	310.8
Sweden	304.1
UK	277.2

excl. Croatia, Cyprus, Luxembourg, Malta

ENTRANZE Project 2014

The spread between actual and engineering predicted intrinsic energy consumption depends on the final realisation of the construction with the installed technical systems, but also the utilisation of such systems for example in response to the indoor temperature by occupants. The most relevant parameters influencing the energy consumption for heating and cooling are the thermal characteristics and related technical systems, the building type with regard to the surface to cubic volume ratio, occupant behaviour and the outdoor climate conditions.

Within the EU, the European Performance of Buildings Directive (EPBD)[iii] required all member states to implement increased energy efficiency regulation for new construction in order to reduce energy consumption in the building sector, resulting from heating, cooling, ventilation, lighting, elevators and IT-applications. The more stringent regulation was implemented based on the theoretical framework to achieve higher energy efficiency with reduced energy consumption measures, affected by stricter building codes to be applied to new office construction or to existent structures undergoing a major refurbishment. In this regard, buildings of lower age are hypothesised to be associated with remarkable energy conservation potentials.

When analysing the effects of policy measures aiming to reduce the energy consumption for space heating, an early study for residential buildings in Denmark found evidence for an important role of building regulation on energy conservation in new buildings (see. Leth-Petersen and Togeby 2001).

In consideration of the increasing energy efficiency regulation for new construction over the last decade, the aim of the underlying policy is to contribute to a reduction in the total energy consumption based on the physical building potentials – what draws even more attention to the behavioural response of occupants.

Behavioural response of office occupants

Beside the fixed influence of applied technical equipment in buildings the response of occupants on heating, ventilation and air-condition (HVAC) to the outdoor climate conditions is very dynamic. When focusing on the energy consumption for space heating only, the actual consumption depends on the heat gains and losses determined by the physical building characteristics and the behavioural response of occupants. Individual heating or cooling systems instead of a centralised control system, account for a different behavioural response from occupants between office buildings.

With regard to improved thermal building features the influence of occupant behaviour in comparison to the physical building characteristics in relation to energy consumption was analysed by Guerra Santin et al. 2009 for the residential sector in the Netherlands. Their study results revealed a significant effect of occupants' influence on energy consumption by 4.2%. However, the investigation indicated that occupants' behaviour is determined by the type of residential unit as well as the HVAC system in the building, whereas physical building characteristics are responsible for a large portion of 42% of energy consumption within the tested Dutch residential observations.

The same appears for office buildings, where the behavioural response by occupants is strongly affecting the energy consumption in different ways and with different intensities. Technical equipment in office buildings is prone to be highly influenced through the behavioural patterns of occupants. Another influencing factor is whether the building is rented to a single tenant or multiple tenants. The allocated office space per occupant implies an important effect as well as the overall occupancy rate. Kahn et al. 2014 found out that energy consumption in office buildings is for the largest part determined by whole building heating, cooling and ventilation, when a one standard deviation increase in the occupancy rate increases electricity consumption by 2.6 percent. Depending on the business industry and related equipment, such as IT, building occupants' activities and behavioural patterns result to a different intensity of energy consumption. Beside the use intensity of occupants also the energy efficiency of the technical equipment applied determines the energy consumption on the office floor area.

Moreover, the individual awareness and behavioural attitude of occupants towards energy consumption and potential energy (cost) savings is assumed to play an overall important role in the dynamic dimension of energy consumption. Experience from the USA (California) demonstrates that the presence of a building engineer is a factor significantly lowering the consumption when compared to buildings without an engineer (see Kahn et al. 2014). With regard to the behavioural response, Allcott 2011 investigates a decrement in electricity consumption of residential occupants who were confronted with a comparison about how their individual energy consumption relates to their geographic neighbours.

Recent research results from the US investigated – somewhat surprisingly – that office buildings of younger age and of higher quality are responsible for higher electricity consumption (see Kahn et al. 2014). These results emphasise the significant influence of occupants' behaviour on the energy consumption dynamics and provide empirical evidence for the existence of the rebound effect in the commercial building sector.

Rebound effect

Experience from the automobile industry shows that a conservation of fuel consumption was achieved while the safety and comfort attributes of cars had been enhanced remarkably. However, the progress in fuel technology has partially been offset by increased vehicle weight and engine power (see Knittel 2012). Similar observations were expected from the commercial building sector in the past. However, the investigated results for commercial buildings of lower building age or recent refurbishment indicate higher energy consumption when compared to their older peers. Even contradicting the accelerated energy efficiency regulation over the last years, these observations were followed by the rebound hypothesis in the building sector. The rebound effect has been investigated and described for commercial buildings by Greening et al. 2000. For a brighter discussion on the rebound effect within economics we refer to Gillingham et al. 2013 and related literature.

Research on the rebound effect in the residential sector leads to the conclusion that energy savings due to energy conservation measures will be of less potential in reality than predicted in engineering conservation studies. For instance within the residential sector of Austria, evidence for a rebound effect with margin between 15% up to 30% due to refurbishment has been investigated by Haas et al. 1998. They argue that increasing energy efficiency will lead to cheaper prices for the services provided and a substantial increase in energy demand.

Based on the empirical observation that more energy efficient technology (e.g. HVAC systems) is used more because of the substitution effect, Kahn et al. 2014 argue that the behavioural response of occupants to more efficient technology is consistent with a rebound effect for commercial real estate. They state that energy consumption and building quality are complements – not substitutes. Even when technological progress reduces the theoretical energy demand from HVAC and lighting the building, the increase of quality attributes (such as more representative lobby and office space, more elevators and individual adaption of comfort temperature by occupants) has the potential to actually increase energy consumption. This argumentation coincides with the explored lower temperature-elasticity of new or refurbished office buildings compared to older buildings.

Results for a refurbishment variable included in the elaborations of Kahn et al. 2014 documented that refurbished observations feature a higher energy consumption of 19% when compared to similar sized observations without refurbishment. Again, the interpretation is that an improvement in the building quality which provides better HVAC and lighting systems may induce greater use.

With regard to the discussed empirical findings our study is intended to investigate the relationship between actual energy consumption, physical building characteristics and behavioural attributes of occupants. Since energy efficiency regulation within the EU has become more rigorously, we test if higher energy efficiency is applicable for office buildings of lower age. We expect that large office buildings are consuming less energy due to economies of scale in heating and cooling buildings. Furthermore, we hypothesise a behavioural response of occupants in office buildings being negatively related to energy savings in order to show a potential rebound effect existing in European office markets. We suppose the behavioural response turns out in the effect of refurbishment providing applications that increase energy consumption by occupants.

III. DATA SAMPLE

In order to answer our research questions we applied the data sample of GRA providing physical building characteristics and behavioural attributes in detail on building level. The database includes two main sources for energy consumption, first the actual measured energy consumption and second the intrinsic energy consumption as the result of the Green Rating Auditing.

The intrinsic energy measure of GRA is based on an individual assessment of the physical building characteristics with estimation of the thermal qualities of different construction and fit-out elements – inherent in each single building. To contribute to the influence of occupants, a fixed standard formula for the influence of the user on the office space is introduced to the assessment. While this fixed standard formula is equal for each building in the intrinsic energy assessment, the intrinsic energy is to be seen as a measure for the potential energy consumption without a differing behavioural response from the occupants between different office buildings. For the objective to identify the most significant explanations for the deviance between actual and intrinsic energy consumption measures, we calculated the difference between the two as a spread to be introduced to our hedonic regression approach.

To control for the dynamic attributes of outdoor climate conditions and temperature-elasticity of energy consumption, the heating degree days (HDD) and cooling degree days (CDD) of the respective auditing year have been implicated for the study. While the auditing process of GRA with actual measurement is assessed over a time period of eight months, we applied the HDD and CDD[iv] taken from the Weather Underground Website (wunderground.com) respective to the year in which more than four months of the auditing period have been carried out. Our total sample comprises 273 observations combining the GRA sample with the HDD and CDD from Weather Underground. Table II includes the attributes with the three response variables described above and the explanatory variables.

Table II: Attributes from the data sample integrated in hedonic regression model

Attributes
Response Variables:
Actual energy consumption in kWh/sqm/a
Intrinsic energy consumption in kWh/sqm/a
Spread (actual-intrinsic energy consumption) in kWh/sqm/a
Explanatory Variables:
Heating degree days (HDD) in year of Green Rating Audit
Cooling degree days (CDD) in year of Green Rating Audit
Sub-categories for actual energy consumption in kWh/sqm/a
Actual energy consumption for heating
Actual energy consumption for cooling
Actual energy consumption for lighting
Actual energy consumption for IT
Actual energy consumption for ventilation
Actual energy consumption for elevator
Actual energy consumption for other
Building age (economic)
Building area in sqm
Building area in sqm per occupant
Ceiling height in meters
Dummy: Single tenant = yes
Dummies: Heating production type
Condensation boiler = yes
Electricity = yes
Heat pump = yes
Low temp. boiler = yes
Normal boiler = yes
Other = yes
District Heating = yes (omitted)
Dummies: Cooling production type
Central cooling towers = yes
Central remote condensers = yes
District cooling network = yes
Groundwater source heatpump = yes
Individual Production = yes
Centralised production = yes (omitted)
Dummies: Refurbishment
Total / major refurbishment = yes
Facade / windows / roof / insolation = yes
Renewal heating / cooling = yes
Partly refurbishment = yes
No / not relevant refurbishment = yes (omitted)
Dummies: Country
Austria = yes
Belgium = yes
Switzerland = yes
Germany = yes
Spain = yes
UK = yes
Hungary = yes
Italy = yes
Luxembourg = yes
Netherlands = yes
Poland = yes
Sweden = yes
France = yes (omitted)
Dummies: Audit year
2008 = yes
2009 = yes
2011 = yes
2012 = yes
2010 = yes (omitted)

In the context of our theoretical considerations with regard to the physical building characteristics, building age and size as well as ceiling height, heating and cooling production type and the dimension of refurbishment are of a major research interest. To investigate the behavioural response of occupants we focus on the attributes building area per office occupant and differentiation between single and multi-tenant occupied buildings. We expect a significant difference between buildings rented on single tenant basis compared to those on multi-tenant basis. Our supposition is that multi-tenant buildings face more – meanwhile contradictory – decisions regarding the heating, cooling and lighting of the controlled office space.

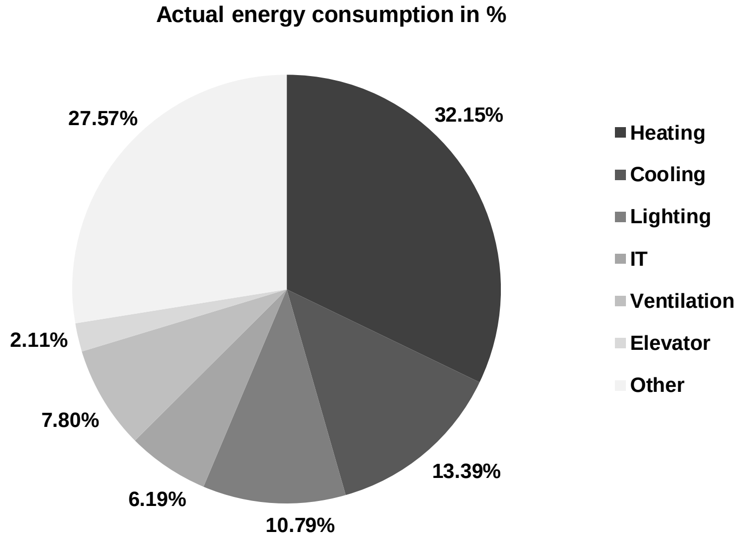
The sub-categories of the total actual energy consumption applicable from the data sample provide the possibility to distinguish between each energy consuming sub-category. Due to the fact that the data does not include any reference to the business industry occupying the office space the actual consumption of the sub-category for IT reveals the only indication on building level whether the office space is occupied by more or less IT-related business industries.

Table III: Descriptive statistics of applied metric attributes

Descriptive Statistics	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Actual energy consumption in kWh/sqm/a	73.5	179.4	238.0	257.1	316.9	696.5
Intrinsic energy consumption in kWh/sqm/a	54.6	104.6	129.5	138.4	163.4	368.7
Δ (actual-intrinsic energy consumption in kWh/sqm/a)	-76.3	50.3	101.2	118.6	163.4	637.1
No. of heating degree days in year of Green Rating Audit	28	38	44	44	48	66
No. of cooling degree days in year of Green Rating Audit	0	14	15	15	16	22
Actual energy consumption heating in kWh/sqm/a)	6.1	49.4	73.6	82.7	101.1	365.7
Actual energy consumption cooling in kWh/sqm/a	0.9	12.4	24.5	34.4	41.7	205.0
Actual energy consumption lighting in kWh/sqm/a	1.0	17.6	24.2	27.7	35.2	115.6
Actual energy consumption IT in kWh/sqm/a	1.1	8.5	12.9	15.9	20.6	77.1
Actual energy consumption ventilation in kWh/sqm/a	1.0	8.8	14.8	20.1	24.6	144.7
Actual energy consumption elevator in kWh/sqm/a	0.4	2.4	4.0	5.4	6.4	61.1
Actual energy consumption other in kWh/sqm/a	0.1	26.8	54.3	70.9	95.3	503.0
Building age (economic)	0	3	9	12	19	50
Building area in sqm	1,340	5,598	9,990	13,990	18,160	108,100
Building area in sqm per occupant	7.5	17.0	21.8	24.7	29.4	94.9
Ceiling height in meters	2.3	2.6	2.7	2.8	2.9	4.3

Comparing the actual with the intrinsic energy consumption a large gap is obvious at first sight. The intrinsic consumption is a measure in relation to the physical building characteristics and a standard factor for occupants' influence assessed in the Green Rating Audit. In this way the difference between the two as spread is turning out to be an explanatory variable of even more interest.

Table IV: Sub-categories of total actual energy consumption



When looking at the share of the sub-categories to the total energy consumption, heating, cooling and ventilation account for more than 53% of the total actual consumption. The sub-category other accounts with a share of 27.6% of the total consumption, incorporating consumption from (underground) car park, canteen and outside lighting. However, the share of these categories summarised under "other" was not applicable from the GRA data sample.

The building area allocated per office occupant offers a large range with a min. of 7.5 up to a max. of 95 square meters and a mean of almost 25 square meters. The economic building age which considers total or major refurbishment in terms of the construction year is of quite a low average of only 12 years. This result draws more attention to the information regarding refurbishment from the data sample.

Table V: Energy consumption and refurbishment sub-samples

Refubishment and Energy Consumption (kWh/sqm/a)	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Total Sample GRA (n = 273)	73.5	179.4	238.0	257.1	316.9	696.5
Refurbishment = yes (n = 164)	73.5	184.0	245.5	266.5	327.3	685.5
Refurbishment < 11 years = yes (n = 136)	73.5	179.6	244.4	261.5	325.8	685.5
Refurbishment < 6 years = yes (n = 93)	73.5	175.9	238.4	261.5	326.9	685.5
Refurbishment Facade/Windows/Roof/Insolation = yes (n = 29)	92.4	164.8	217.2	240.1	291.9	538.8
Potential Energy Conservation			-8.74%			
Refurbish. Facade/Windows/Roof/Insolation				-6.61%		

At first sight we find no verification that refurbishment has a positive impact on the energy efficiency, in such a way resulting to a decrement in actual energy consumption of the tested office buildings. The sub-samples for refurbishment within the last 10 or 5 years indicate all higher actual energy consumption on average and median values compared to the total sample. In comparison to the total sample the observations attributed to have undergone a refurbishment in the past (n = 164) suggest a 3.7% higher energy consumption on average. Analysing a small sub-sample of only 29 observations attributed with refurbishment details such as façade/windows/roof/insolation which are expected to enhance energy efficiency and potentially reduce energy consumption, a very slight decrement in actual energy consumption is observable compared to the total sample. The result denotes a small conservation potential of around -6.6% on average and approx. -8.7% for the median value. This provides some ambivalent result, where general refurbishment accounts for more energy consumption – a prompt indication for the existence of a rebound effect – and a small sample of 29 observations proves a slight decrease of actual consumption in relation to refurbishment of only thermal building characteristics. To consolidate this result while accounting for other effects to be fixed we will include refurbishment details as explanatory variables to our regression analyses.

Table VI: Correlation matrix of metric attributes

Correlation Matrix		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log(actual energy consumption in kWh/sqm/a)	(1)	1								
log(intrinsic energy consumption in kWh/sqm/a)	(2)	0.524	1							
Δ (actual-intrinsic energy consumption in kWh/sqm/a)	(3)	0.845	0.058	1						
No. of heating degree days in year of Green Rating Audit	(4)	-0.027	0.131	-0.132	1					
No. of cooling degree days in year of Green Rating Audit	(5)	-0.297	-0.240	-0.197	-0.040	1				
Building age (economic)	(6)	-0.065	0.038	-0.081	0.028	0.075	1			
log(building area in sqm)	(7)	0.110	-0.063	0.165	0.053	0.000	-0.040	1		
log(building area in sqm per occupant)	(8)	-0.120	-0.008	-0.133	0.045	0.081	-0.002	0.028	1	
Ceiling height in meters	(9)	0.056	0.132	0.020	0.096	-0.066	-0.158	0.016	0.062	1

The correlation matrix for metric attributes shows an orthogonal linear relationship between the response and explanatory variables. Corresponding to our expectations a positive bivariate relationship between intrinsic and actual energy consumption is observable. The same appears to be true for the relationship between the spread (actual-intrinsic) and the actual consumption. HDD and CDD demonstrate a negative bidirectional relation to actual consumption. Somewhat surprisingly at first sight, the energy consumption decreases with increment of HDD and CDD. Furthermore, HDD and intrinsic energy are positively correlated, whereas a negative relationship between intrinsic energy and CDD is observable; for the spread again negative coefficients are resulting.

The negative relationship between building age and actual consumption is an indicator for the existence of a potential rebound effect within the tested portfolio, as observations of higher age turn out to be less energy consuming. The building size was expected to show less energy consumption in large buildings due to economies of scale. This appears not to be true for actual consumption, but for the intrinsic energy assessment. Interestingly, the spread between the two rises when the building area is increasing. The building area allocated per occupant has been calculated from building area and the total number of occupants in the building, both applicable from GRA data. We have no information about the vacancy rate in the observations, so we interpret the negative coefficient on energy consumption with reference to the vacancy rate. More office area allocated per occupant corresponds to some extent to a higher vacancy in the building which is followed by a decrement in actual energy consumption; the same appears for intrinsic consumption. With increasing office area per occupant as a proxy for higher vacancy the spread is reducing.

IV. ECONOMETRIC APPROACH

When applying a hedonic regression, energy consumption is analysed as a function of physical building and behavioural attributes of occupants and the outdoor climate conditions. In order to determine these effects on the response variable, we have to control for all other factors affecting the energy consumption. To address this issue, within a multiple regression model the dependent variable is decomposed into implicit contribution of the building characteristics and behavioural attributes under control of the outdoor climate conditions.

The general hedonic regression model via linear ordinary least squares (OLS) is described in equation (1) with Y as response variable and X as a vector containing the explanatory variables.

$$Y_i = \alpha_i + \beta X_i + \varepsilon_i \tag{1}$$

In our approach the regression model will be applied with three different response variables: 1) actual and 2) intrinsic energy consumption as well as the 3) spread between the two – all metered kWh/sqm/a. The vector containing the explanatory variables includes the physical building and behavioural attributes of occupants as well as the HDD and CDD for control of the local outdoor climate conditions.

As common in hedonic price models (see Malpezzi 2003), we transform the response variables actual and intrinsic consumption logarithmically. However, in the case of the spread between actual and intrinsic we applied not the natural logarithm function due to some negative results when calculating the spread. We transform strictly positive metric variables logarithmically when estimating a log-linear function with the following equation:

$$\begin{bmatrix} \log(\text{actual E cons.})_i \\ \log(\text{intrinsic E cons.})_i \\ \Delta(\text{actual} - \text{intrinsic E cons.})_i \end{bmatrix} = \alpha + \beta_1 \,\text{HDD}_i + \beta_2 \,\text{CDD}_i + \beta_3 \begin{bmatrix} \log(\text{E} - \text{heating})_i \\ \log(\text{E} - \text{cooling})_i \\ \log(\text{E} - \text{lighting})_i \\ \log(\text{E} - \text{IT})_i \\ \log(\text{E} - \text{ventilation})_i \\ \log(\text{E} - \text{elevator})_i \\ \log(\text{E} - \text{other})_i \end{bmatrix} + \beta 4 \begin{bmatrix} \text{building age}_i \\ \log(\text{building area})_i \\ \log(\text{area/occupant})_i \\ \text{ceiling height}_i \end{bmatrix} +$$

$$\beta_5 \,\text{single tenant binary}_i + [\text{heating}_i'\gamma] + [\text{cooling}_i'\delta] + [\text{refurbishment}_i'\eta] + [\text{country}_i'\kappa] + [\text{year}_i'\lambda] + \begin{bmatrix} \varepsilon_i \\ \rho_i \\ \sigma_i \end{bmatrix} \tag{2}$$

The explanatory variables **HDD** and **CDD** control for the local outdoor climate conditions in the relevant year of the Green Rating Audit. The actual energy consumption for the seven sub-categories is introduced in a matrix to the regression equation, e.g. for sub-category heating: log(E – heating) and so forth. Because the integration of all sub-categories for actual energy consumption together when explaining the actual consumption would automatically lead to a selection bias problem in our model, we applied the model for each of the seven sub-categories solely, omitting the other six sub-categories in each single regression of the response variable. This approach is adequate in order to measure the effect of each sub-category on the response variables when in- or decreasing the consumption of the respective sub-category.

The other metric variables have been contained to a matrix. The **building age** is included to test for differences between observations of higher and lower age. It was contemplated under economic considerations, reflecting major refurbishment with improved physical characteristics of the buildings, thus expressing a proxy for depreciation over time. The explanatory **log(building area)** controls for the natural logarithm of the building area in square meters, introduced along with building age and the **ceiling height** in meters as physical building characteristics. The building area allocated per occupant in square meter is put logarithmically into the model with **log(area/occupant)**. In addition, with regard to the behavioural response a dichotomous variable as **single tenant binary** distinguishes between a single or multi-tenant use of the building premises.

Furthermore, a matrix for **heating** production type and for **cooling** production type dummies enters the equation to control for energy consumption related to different technical systems applied in the buildings. To investigate the effect of **refurbishment** on the response variables a matrix of refurbishment details is introduced to the equation. A matrix of **country** dummies was considered to control for spatial heterogeneity, e.g. energy efficiency regulation with regard to local building codes and different pricing of energy between the countries. Due to the introduced HDD and CDD with reference to the location based outdoor climate conditions, we do not append additional location dummies to control for spatial heterogeneity to avoid any selection bias. As mentioned before, the HDD and CDD controlling for outdoor climate conditions have been selected for the year of the GRA audit process. Therefore, a matrix of **year** dummies for the relevant audit year of the buildings is included to the model, in order to control differences between the years of the audit process which are not explained through HDD and CDD as reference for outdoor climate conditions.

The regression intercept is expressed with α. β_1, $\beta_{2,}\ldots$ β_8 are the regression coefficients for physical building characteristics and behavioural attributes as well as for HDD and CDD. The vector for effects from heating production type is captured in $\gamma_,$ for cooling production type in δ, for the refurbishment details in η, for countries in κ and for the audit year in λ. Terms ε, ρ and σ denote iid error terms for the respective equation expected to follow a normal distribution of mean zero and constant variance.

V. RESEARCH RESULTS

Results for actual energy consumption

The results of our log-linear regression model for actual energy consumption are summarised in table VII. Column 1 shows the results for the regression when including all seven sub-categories of actual energy consumption and columns 2-8 present the results when inducing each single sub-category separately from the others.

Table VII: Regression results of log-linear hedonic model on actual energy consumption as response variable in equation (2)

Response Variable: log(actual energy consumption in kWh/sqm/a)

Explanatory Variables	1	2	3	4	5	6	7	8
Parametric Coefficients (t-values)	**Response Variable: log(actual energy consumption in kWh/sqm/a)**							
Intercept	2.457	4.481	5.234	5.056	5.498	6.273	5.732	5.571
	(7.842)***	(8.081)***	(8.463)***	(8.078)***	(7.995)***	(10.791)***	(9.222)***	(10.847)***
No. of heating degree days in audit year (GRA)	-0.006	-0.017	-0.015	-0.016	-0.018	-0.017	-0.016	-0.013
	(-1.724)*	(-2.486)**	(-1.875)*	(-2.074)**	(-2.114)**	(-2.246)**	(-2.035)**	(-1.972)**
No. of cooling degree days in audit year (GRA)	-0.014	-0.017	-0.035	-0.030	-0.034	-0.046	-0.034	-0.029
	(-2.558)**	(-1.616)	(-2.921)***	(-2.538)**	(-2.715)***	(-3.916)***	(-2.745)***	(-2.818)***
Sub-categories energy actual consumption in kWh/sqm/a								
log(actual energy consumption heating in kWh/sqm/a)	0.311	0.359						
	(17.733)***	(10.399)***						
log(actual energy consumption cooling in kWh/sqm/a)	0.094		0.165					
	(7.298)***		(6.000)***					
log(actual energy consumption lighting in kWh/sqm/a)	0.127			0.248				
	(6.624)***			(6.071)***				
log(actual energy consumption IT in kWh/sqm/a)	0.055				0.127			
	(2.770)***				(2.802)***			
log(actual energy consumption ventilation in kWh/sqm/a)	0.102					0.168		
	(8.796)***					(6.834)***		
log(actual energy consumption elevator in kWh/sqm/a)	0.025						0.142	
	(1.811)*						(4.617)***	
log(actual energy consumption other in kWh/sqm/a)	0.184							0.233
	(17.122)***							(11.438)***
Building / occupant response variables								
Building age (economic)	0.000	-0.003	0.001	0.001	0.002	0.002	0.001	0.004
	(0.468)	(-1.282)	(0.465)	(0.634)	(0.755)	(0.869)	(0.419)	(1.912)*
log(building area in sqm)	0.009	0.074	0.044	0.044	0.045	0.007	0.051	-0.013
	(0.669)	(2.902)***	(1.547)	(1.570)	(1.496)	(0.235)	(1.760)*	(-0.527)
log(building area in sqm per occupant)	0.001	-0.079	0.036	0.008	0.051	-0.074	-0.021	-0.061
	(0.026)	(-1.693)*	(0.662)	(0.152)	(0.798)	(-1.426)	(-0.393)	(-1.342)
Ceiling height in meters	0.082	0.038	0.135	0.125	0.141	0.136	0.131	0.115
	(2.320)**	(0.539)	(1.710)	(1.583)	(1.685)*	(1.753)*	(1.612)	(1.690)*
Single tenant (single tenant = 1)	0.048	0.133	0.170	0.176	0.129	0.134	0.148	0.021
	(2.184)**	(3.156)***	(3.572)***	(3.698)***	(2.558)**	(2.870)***	(3.038)***	(0.501)
Heating production type								
Condensation boiler	-0.017	-0.015	0.021	0.086	0.052	0.004	0.103	0.050
	(-0.345)	(-0.146)	(0.185)	(0.765)	(0.444)	(0.040)	(0.889)	(0.517)
Electricity	-0.010	-0.078	-0.118	-0.093	-0.123	-0.134	-0.069	-0.098
	(-0.323)	(-1.309)	(-1.764)*	(-1.391)	(-1.748)*	(-2.049)**	(-0.987)	(-1.702)*
Heat pump	0.063	-0.120	-0.326	-0.196	-0.262	-0.207	-0.208	-0.106
	(1.381)	(-1.357)	(-3.319)***	(-1.992)**	(-2.534)**	(-2.149)**	(-2.051)**	(-1.242)
Low temparature boiler	-0.077	-0.123	-0.190	-0.006	-0.034	-0.105	-0.014	-0.040
	(-1.079)	(-0.879)	(-1.195)	(-0.037)	(-0.204)	(-0.679)	(-0.087)	(-0.292)
Normal boiler	-0.007	-0.055	-0.080	-0.004	-0.052	-0.029	-0.002	-0.062
	(-0.217)	(-0.836)	(-1.081)	(-0.050)	(-0.660)	(-0.405)	(-0.026)	(-0.972)
Other	-0.046	-0.152	-0.481	-0.288	-0.444	-0.425	-0.486	-0.305
	(-0.394)	(-0.652)	(-1.839)*	(-1.099)	(-1.609)	(-1.660)*	(-1.807)*	(-1.355)
Cooling production type								
Central cooling towers	-0.157	-0.094	-0.162	-0.078	-0.127	-0.401	-0.235	-0.124
	(-0.991)	(-0.296)	(-0.454)	(-0.218)	(-0.337)	(-1.143)	(-0.641)	(-0.404)
Central remote condensers	-0.092	-0.070	-0.353	-0.241	-0.304	-0.479	-0.317	-0.492
	(-0.573)	(-0.218)	(-0.985)	(-0.673)	(-0.801)	(-1.362)	(-0.859)	(-1.595)
District cooling network	0.034	0.135	-0.016	0.188	0.160	0.171	0.172	0.140
	(0.963)	(2.053)**	(-0.201)	(2.544)**	(2.044)**	(2.363)**	(2.256)**	(2.206)**
Groundwater source heatpump	-0.226	0.047	0.041	0.044	-0.070	-0.015	0.049	-0.047
	(-1.249)	(0.132)	(0.101)	(0.108)	(-0.161)	(-0.039)	(0.117)	(-0.133)
Individual production	0.048	-0.100	-0.097	-0.116	-0.121	-0.013	-0.091	-0.044
	(1.563)	(-1.666)*	(-1.432)	(-1.726)*	(-1.693)	(-0.198)	(-1.300)	(-0.750)
Refurbishment details								
Full / major / general refurbishment	0.003	0.196	0.144	0.125	0.161	0.126	0.182	0.095
	(0.079)	(3.039)***	(1.968)*	(1.700)*	(2.080)**	(1.753)*	(2.435)**	(1.504)
Facade / windows / roof / insolation	0.014	0.077	0.084	0.046	0.027	0.059	0.085	-0.035
	(0.423)	(1.166)	(1.134)	(0.624)	(0.346)	(0.812)	(1.112)	(-0.545)
Heating / cooling system	-0.032	0.029	0.057	0.023	0.015	0.030	0.022	0.001
	(-1.037)	(0.470)	(0.810)	(0.331)	(0.201)	(0.435)	(0.309)	(0.021)
Partly refurbishment	0.010	0.071	0.081	0.056	0.045	0.048	0.067	-0.016
	(0.288)	(1.048)	(1.063)	(0.733)	(0.555)	(0.639)	(0.852)	(-0.242)
Country effects (n)	12	12	12	12	12	12	12	12
Year effects, Green Rating audit year (n)	4	4	4	4	4	4	4	4
Adjusted R^2	0.875	0.496	0.361	0.363	0.287	0.386	0.325	0.528
AIC-Criterion	-219.98	156.20	221.06	220.19	251.23	210.40	236.38	138.62

Significance: *** 1%, ** 5%, * 10%

Not surprisingly, significant influence is revealed for each of the seven sub-categories entered into the regression model (column 1), besides the HDD and CDD to control the outdoor climate conditions. However beyond the effects of the sub-categories, the coefficients for ceiling height and the binary variable for single tenant exhibit a significant level. The positive coefficient implies an increase of actual energy consumption when the ceiling height is ascending in the office observations – at first sight representing an expected relationship for this physical building characteristic with reference to building heating and cooling load. The binary for single tenant explains – to some extent surprisingly – that single tenant occupied office buildings are associated with higher actual consumption than multi-tenant occupied. This first impression with regard to behavioural attributes will be analysed more detailed in the regression results for the single sub-categories.

In case of energy conservation from the sub-categories in columns 2-8, the elasticities are to be seen as the potential conservation effect of total energy consumption within the buildings. Meeting our expectations, heating consumption reveals the strongest impact on the total building consumption with regard to its relative share of more than 32% of the total actual consumption. Heating, cooling and ventilation are to be seen as the major driver when consuming more or saving energy towards the overall total consumption. Astonishing is the result for sub-category lighting, where a potential increment of 100% is followed by a 25% higher total energy consumption in the buildings – of course yielding some heating energy consumption savings. From this point of view lighting and to some extent IT equipment suggest the multivariate influence of the attributes. All coefficients of the sub-categories hold a significance level at 1%.

The coefficients of HDD and CDD have a significant negative effect on actual energy consumption. The effect of HDD is of less negative impact in comparison to CDD. One more HDD has the potential to reduce actual consumption between -1.3% and -1.8% in the regression output, whereas one additional CDD is followed by a decrement between -2.9% and -4.6%, depending on the sub-category introduced to the model. Our interpretation of the result is that the thermal building qualities – even with an increase in the number of HDD and/or CDD – feature a slight decrease in the actual energy consumption. In other words, with increasing number of HDD and/or CDD the thermal building characteristics always seem to provide a slight conservation in the actual consumption. Considering this impact, we argue that the thermal building characteristics are of better quality in response to the outdoor climate conditions to be expected at the location of the buildings. Thermal qualities seem to over-compensate the additional "expenses" from HDD or CDD surplus.

In any case, a behavioural response of occupants cannot be eliminated at all when discussing the phenomenon. On the one hand, it appears obvious that due to very low outside temperatures office buildings will be less and shorter ventilated if non-automated ventilation via window opening is available. On the other hand, the same appears if building and occupants are exposed to very high temperatures and the office space is equipped with air-conditioning.

Turning to further explanatory variables measuring influence from physical building characteristics we found the building age without explanatory power and lacking a higher significance. While the economic building age was derived under consideration of the construction year and the applicable refurbishment year as well as the intense of the refurbishment, we re-inspected our regression model without any refurbishment attributes. For addressing a potential selection bias issue, even when omitting all dummy variables containing differences in the refurbishment with reference to the impact on the thermal qualities of the buildings, no coefficient of higher significance for building age results from the model. This turns out to be a remarkable finding due to the overall expectation of an impact from the increased energy efficiency regulation within EU-member states over the past decade. This result draws the conclusion that increased building codes and construction standards are likely to increase the thermal quality of new or refurbished buildings. However, these attempts seem to emerge not with a significant impact towards the conservation of actual energy consumption, based on the 273 observations from the GRA portfolio.

The building area was estimated with a highly significant coefficient in the model with heating energy consumption as explanatory (column 2). 1% increase in the building area is followed by a slightly higher actual consumption of 0.07%, ceteris paribus. The expectation of less consumption due to economies of scale in heating and cooling is not withstanding for the tested portfolio. The building area allocated by office occupant is apparently not a factor of high significant impact on the energy consumption. Except in the model with sub-category for heating energy consumption as explanatory (column 2), where the coefficient denotes a marginal decrement in consumption if allocated area per occupant is rising (only significant at 10% level). However, this behavioural attribute may account for higher vacancy someway, as argued before. The ceiling height influence on actual consumption is estimated of poor significance as well, but suggesting higher energy consumption between approx. 11% and 14% when ceiling height rises by 1% and therefore meeting with our expectations (see columns 5, 6 and 8).

Having a look at another behavioural response attribute, the single tenant binary provides high significant results. The coefficients demonstrate evidently that single tenant attributed office buildings are of significantly higher energy consumption than multi-tenant occupied. With reference to omitted multi-tenant attribute the dummy variable[v] explains a higher actual consumption between approx. 14% to 19% depending on the calculated different models. Our expectation was that multi-tenant used buildings are of higher energy consumption because of somehow contradictory decisions when running the building. As the result does not foster this reasoning, we calculated the allocated building area per occupant in both sub-portfolios (single and multi-tenant) each with a mean of around 25 square meters and not discovering any bias. A conclusion might be that a single tenant (as a large tenant) intends more to heat, cool, ventilate and light a building centrally as a whole, not reacting to a needed (or available) differentiation between single building parts or floors, e.g. cooling of upper floors only. Within a multi-tenant building each tenant behaves in response to the issues more decentralised for the smaller part of the building occupied, thereby placing a distinct increment in energy consumption compared to single tenant observations. The more, a large single tenant might potentially consider energy prices with minor importance when referred to business turnover and allocated headcount cost.

With reference to the omitted variable district heating for the heating production type, the coefficients for electricity production show some and for heat pump higher significance. Both coefficients underline a decrement in consumption when heating is based on electricity or a heating pump in reference to a district heating network exposed to higher losses of load. Results for decentralised heat pump identify a reduction of energy between -18% (column 4) up to -28% (column 3) compared to district supply, holding a significance level of 5%. District cooling supply demonstrates a significantly higher contribution to energy consumption than the omitted reference dummy for centralised production, between 15% (columns 2 and 8) and almost 21% (column 4).

Turning to the refurbishment details introduced in our econometric approach we receive significant coefficients for the aggregated dummy, containing full/major/general refurbishment with reference to omitted observations without any refurbishment. The results reveal a significant impact on higher actual energy consumption for observations with a total or major refurbishment. Compared to buildings without refurbishment in the past, a total or major refurbishment induces a 17.5% (column 5) up to 21.7% (column 2) higher energy consumption. In the regression with sub-category heating energy consumption as explanatory (column 2) the result is significant at 1% level. Moreover, measuring the effects of a different intense for refurbishment details we did not find a significant impact on refurbishment associated with thermal qualities, contained in façade/windows/roof/insolation, nor on the replacement of heating/cooling systems towards any savings in actual energy consumption.

Results for intrinsic energy consumption

The idea behind our approach to regress the actual energy consumption sub-categories and remaining building and behavioural attributes on the intrinsic consumption is the question what of the actual attributes affects the intrinsic energy assessment in which intensity. At first sight the regression results including all seven sub-categories of actual consumption indicate significant positive coefficients for actual heating, lighting and elevator consumption, but still likely to adhere to some multicollinearity. Except for IT consumption the sub-categories in columns 2-8 explain that an increase in actual energy consumption in the respective sub-category is also followed by a higher intrinsic energy assessment on a significant level.

Table VIII: Regression results of log-linear hedonic model on intrinsic energy consumption as response variable in equation (2)

Response Variable: log(intrinsic energy consumption in kWh/sqm/a)

Explanatory Variables	1	2	3	4	5	6	7	8
Parametric Coefficients (t-values)	**Response Variable: log(intrinsic energy consumption in kWh/sqm/a)**							
Intercept	2.700	3.377	4.198	3.735	4.626	4.513	3.969	4.404
	(5.121)***	(6.714)***	(7.686)***	(6.969)***	(7.978)***	(8.670)***	(7.844)***	(8.330)***
No. of heating degree days in audit year (GRA)	0.012	0.009	0.009	0.009	0.007	0.008	0.010	0.008
	(2.054)**	(1.348)	(1.238)	(1.368)	(0.995)	(1.152)	(1.530)	(1.176)
No. of cooling degree days in audit year (GRA)	0.004	0.002	-0.009	-0.006	-0.010	-0.013	-0.007	-0.009
	(0.460)	(0.236)	(-0.883)	(-0.572)	(-0.953)	(-1.245)	(-0.699)	(-0.813)
Sub-categories energy actual consumption in kWh/sqm/a								
log(actual energy consumption heating in kWh/sqm/a)	0.195	0.226						
	(6.598)***	(7.235)***						
log(actual energy consumption cooling in kWh/sqm/a)	0.013		0.050					
	(0.606)		(2.067)**					
log(actual energy consumption lighting in kWh/sqm/a)	0.127			0.158				
	(3.941)***			(4.504)***				
log(actual energy consumption IT in kWh/sqm/a)	-0.045				-0.017			
	(-1.360)				(-0.439)			
log(actual energy consumption ventilation in kWh/sqm/a)	0.021					0.058		
	(1.081)					(2.641)***		
log(actual energy consumption elevator in kWh/sqm/a)	0.092						0.139	
	(3.950)***						(5.569)***	
log(actual energy consumption other in kWh/sqm/a)	0.012							0.038
	(0.653)							(1.792)*
Building / occupant response variables								
Building age (economic)	0.000	0.000	0.002	0.002	0.002	0.002	0.002	0.002
	(-0.121)	(-0.252)	(0.957)	(1.081)	(0.936)	(1.110)	(0.902)	(1.177)
log(building area in sqm)	-0.006	-0.003	-0.022	-0.021	-0.023	-0.035	-0.013	-0.031
	(-0.287)	(-0.112)	(-0.872)	(-0.864)	(-0.896)	(-1.368)	(-0.561)	(-1.221)
log(building area in sqm per occupant)	-0.010	-0.018	0.030	0.037	-0.006	-0.005	0.025	0.003
	(-0.208)	(-0.425)	(0.622)	(0.820)	(-0.102)	(-0.109)	(0.571)	(0.070)
Ceiling height in meters	0.113	0.099	0.155	0.154	0.147	0.156	0.162	0.149
	(1.904)*	(1.553)	(2.223)**	(2.283)**	(2.078)*	(2.249)**	(2.456)**	(2.137)**
Single tenant (single tenant = 1)	0.030	0.012	0.028	0.040	0.023	0.016	0.022	0.001
	(0.793)	(0.321)	(0.668)	(0.971)	(0.547)	(0.394)	(0.564)	(0.017)
Heating production type								
Condensation boiler	-0.037	-0.088	-0.057	-0.024	-0.049	-0.063	0.005	-0.048
	(-0.440)	(-0.973)	(-0.572)	(-0.256)	(-0.488)	(-0.643)	(0.056)	(-0.483)
Electricity	-0.084	-0.142	-0.173	-0.151	-0.179	-0.177	-0.114	-0.172
	(-1.656)*	(-2.631)***	(-2.926)***	(-2.641)***	(-3.006)***	(-3.029)***	(-1.992)**	(-2.902)***
Heat pump	-0.155	-0.233	-0.346	-0.281	-0.333	-0.308	-0.266	-0.304
	(-2.032)**	(-2.917)***	(-3.997)***	(-3.334)***	(-3.815)***	(-3.563)***	(-3.214)***	(-3.457)***
Low temparature boiler	-0.067	-0.130	-0.138	-0.056	-0.113	-0.113	-0.037	-0.099
	(-0.556)	(-1.026)	(-0.987)	(-0.414)	(-0.802)	(-0.818)	(-0.276)	(-0.710)
Normal boiler	0.005	-0.060	-0.069	-0.027	-0.064	-0.053	-0.006	-0.063
	(0.093)	(-1.004)	(-1.057)	(-0.429)	(-0.972)	(-0.806)	(-0.097)	(-0.967)
Other	0.181	0.157	-0.035	0.072	-0.020	-0.018	-0.072	0.000
	(0.919)	(0.739)	(-0.154)	(0.319)	(-0.086)	(-0.079)	(-0.329)	(-0.002)
Cooling production type								
Central cooling towers	-0.359	-0.313	-0.358	-0.303	-0.365	-0.440	-0.426	-0.353
	(-1.347)	(-1.093)	(-1.139)	(-0.995)	(-1.150)	(-1.403)	(-1.430)	(-1.119)
Central remote condensers	0.088	0.034	-0.158	-0.073	-0.181	-0.199	-0.095	-0.185
	(0.327)	(0.118)	(-0.498)	(-0.239)	(-0.565)	(-0.633)	(-0.317)	(-0.585)
District cooling network	-0.048	-0.055	-0.091	-0.021	-0.036	-0.034	-0.029	-0.040
	(-0.796)	(-0.919)	(-1.295)	(-0.334)	(-0.545)	(-0.522)	(-0.468)	(-0.615)
Groundwater source heatpump	0.175	0.181	0.191	0.179	0.224	0.169	0.170	0.183
	(0.573)	(0.554)	(0.532)	(0.515)	(0.613)	(0.475)	(0.500)	(0.508)
Individual production	-0.037	-0.078	-0.084	-0.088	-0.092	-0.054	-0.061	-0.079
	(-0.715)	(-1.429)	(-1.406)	(-1.525)	(-1.528)	(-0.888)	(-1.071)	(-1.314)
Refurbishment details								
Full / major / general refurbishment	-0.041	0.007	-0.011	-0.039	0.008	-0.019	-0.006	-0.012
	(-0.728)	(0.111)	(-0.168)	(-0.618)	(0.119)	(-0.295)	(-0.094)	(-0.183)
Facade / windows / roof / insolation	0.098	0.076	0.071	0.057	0.065	0.064	0.092	0.047
	(1.756)*	(1.280)	(1.085)	(0.901)	(0.984)	(0.979)	(1.487)	(0.720)
Heating / cooling system	0.124	0.140	0.153	0.136	0.154	0.145	0.128	0.143
	(2.346)**	(2.491)**	(2.487)**	(2.279)**	(2.445)**	(2.358)**	(2.185)**	(2.306)**
Partly refurbishment	0.146	0.142	0.141	0.132	0.136	0.130	0.142	0.122
	(2.548)**	(2.306)**	(2.088)**	(2.026)**	(1.997)**	(1.944)**	(2.221)**	(1.798)*
Country effects (n)	12	12	12	12	12	12	12	12
Year effects, Green Rating audit year (n)	4	4	4	4	4	4	4	4
Adjusted R^2	0.429	0.330	0.194	0.245	0.298	0.203	0.276	0.191
AIC-Criterion	64.17	102.89	153.26	135.43	157.99	150.16	124.10	154.48

Significance: *** 1%, ** 5%, * 10%

The two variables attributed to indicate behavioural response, building area per occupant and single vs. multi-tenant, are not of any significance. This corresponds to the GRA assessment for intrinsic energy by applying a standard formula for behavioural influence of occupants to each rated building. For the physical building attributes building age and area are insignificant as well. This might be an indication that building age is not an impacting criterion in the assessment due to refurbishment consideration for the buildings. Economies of scale seem not to be attributed when calculating intrinsic consumption. The results for ceiling highly correspond to those obtained from the regression of actual consumption. If ceiling height rises by 1% intrinsic energy increases approx. by 15% to 16%, holding a 5% significance level. Moreover, heating production with heat pump is associated with a much lower intrinsic consumption of up to almost -30% (see columns 3 and 5) with reference to district heating network (omitted).

Compared to the results for the attributes contained in refurbishment details on actual energy consumption before, the significant coefficients in the regression on intrinsic consumption reveal a controversial relationship. Here the renewal of heating/cooling systems and attributes aggregated to party refurbishment estimate a substantial increasing impact referring to the omitted dummy for no refurbishment. Renewal of heating/cooling systems accounts for a surplus of about 14% to almost 17% in intrinsic consumption. Partly refurbishment, containing specifications such as inside design, lighting, internal walls or electrical installation – expected to have only minor influence on the actual energy performance compared to the other refurbishment details available – was ascertained to have an increasing effect on intrinsic consumption of around 14% to 15% for partly refurbishment if compared to non-refurbished buildings as reference (holding a 5% significance level). We conclude that renewal of heating/cooling systems and partly refurbishment are associated with a significant impact for a higher intrinsic energy assessment, whereas a total or major refurbishment or thermal improvements (façade/windows/roof/insolation) are not attributed to increase intrinsic consumption.

Results for the spread between actual and intrinsic energy consumption

Regression of the spread between actual and intrinsic energy consumption in our final approach underlies the intention to explore the deviation between metered actual and assessed intrinsic energy consumption more in detail. As we identify the drivers for increase or decrement of actual energy consumption and of intrinsic assessment the question remains which attributes in a theoretical framework provide the most potential to reduce actual consumption towards intrinsic assessment.

Table IX: Regression results of linear hedonic model on spread between actual and intrinsic energy consumption as response variable in equation (2)

Response Variable: Δ (actual-intrinsic energy consumption in kWh/sqm/a)

Explanatory Variables	1	2	3	4	5	6	7	8
Parametric Coefficients (t-values)	**Response Variable: Δ (actual-intrinsic energy consumption in kWh/sqm/a)**							
Intercept	-425.566	-13.344	51.719	67.383	43.634	262.419	202.208	103.254
	(-3.738)***	(-0.091)	(0.350)	(0.442)	(0.273)	(1.901)*	(1.343)	(0.843)
No. of heating degree days in audit year (GRA)	-2.838	-5.179	-4.562	-4.996	-4.991	-5.043	-5.162	-4.127
	(-2.225)**	(-2.820)***	(-2.421)**	(-2.607)***	(-2.577)**	(-2.754)***	(-2.629)***	(-2.553)**
No. of cooling degree days in audit year (GRA)	-2.383	-2.793	-5.417	-4.763	-5.124	-7.854	-5.442	-4.039
	(-1.201)	(-0.983)	(-1.895)*	(-1.628)	(-1.738)*	(-2.797)***	(-1.822)*	(-1.641)
Sub-categories energy actual consumption in kWh/sqm/a								
log(actual energy consumption heating in kWh/sqm/a)	47.749	55.441						
	(7.485)***	(6.109)***						
log(actual energy consumption cooling in kWh/sqm/a)	20.030		33.536					
	(4.295)***		(5.106)***					
log(actual energy consumption lighting in kWh/sqm/a)	13.201			40.016				
	(1.891)*			(4.016)***				
log(actual energy consumption IT in kWh/sqm/a)	22.452				35.522			
	(3.109)***				(3.383)***			
log(actual energy consumption ventilation in kWh/sqm/a)	25.673					36.440		
	(6.112)***					(6.252)***		
log(actual energy consumption elevator in kWh/sqm/a)	-5.970						16.332	
	(-1.189)						(2.198)**	
log(actual energy consumption other in kWh/sqm/a)	43.958							52.862
	(11.229)***							(10.860)***
Building / occupant response variables								
Building age (economic)	0.409	-0.345	0.209	0.277	0.406	0.395	0.216	0.809
	(1.103)	(-0.647)	(0.390)	(0.508)	(0.734)	(0.755)	(0.387)	(1.747)*
log(building area in sqm)	3.837	20.033	15.512	15.542	15.909	7.445	16.248	2.644
	(0.802)	(3.001)***	(2.291)**	(2.251)**	(2.281)**	(1.108)	(2.294)**	(0.446)
log(building area in sqm per occupant)	0.953	-18.190	3.280	-4.370	13.575	-19.456	-9.980	-16.784
	(0.095)	(-1.477)	(0.254)	(-0.338)	(0.906)	(-1.583)	(-0.760)	(-1.557)
Ceiling height in meters	21.054	11.310	27.136	24.758	30.175	27.518	25.164	22.918
	(1.640)	(0.610)	(1.439)	(1.288)**	(1.548)	(1.496)	(1.279)	(1.416)
Single tenant (single tenant = 1)	14.962	39.175	46.038	46.040	36.377	38.445	41.475	12.815
	(1.854)*	(3.527)***	(4.046)***	(3.960)***	(3.092)***	(3.471)***	(3.504)***	(1.270)
Heating production type								
Condensation boiler	3.384	11.511	15.605	27.237	22.372	11.675	27.510	21.529
	(0.186)	(0.440)	(0.584)	(0.999)	(0.814)	(0.447)	(0.982)	(0.939)
Electricity	13.584	4.539	-0.839	2.459	-1.147	-4.133	3.331	4.085
	(1.235)	(0.290)	(-0.053)	(0.151)	(-0.070)	(-0.266)	(0.196)	(0.298)
Heat pump	28.561	-7.637	-41.972	-18.955	-28.062	-16.942	-23.966	6.572
	(1.734)*	(-0.330)	(-1.792)*	(-0.790)	(-1.167)	(-0.740)	(-0.974)	(0.323)
Low temparature boiler	-18.444	-22.634	-37.962	-3.953	-2.411	-21.043	-8.585	-6.411
	(-0.711)	(-0.614)	(-1.002)	(-0.103)	(-0.062)	(-0.572)	(-0.217)	(-0.198)
Normal boiler	-4.793	-8.611	-13.487	-0.302	-7.042	-2.738	-2.694	-9.817
	(-0.393)	(-0.497)	(-0.761)	(-0.017)	(-0.386)	(-0.158)	(-0.144)	(-0.645)
Other	-56.743	-79.132	-132.165	-99.133	-125.497	-120.783	-128.697	-93.367
	(-1.331)	(-1.287)	(-2.118)**	(-1.552)	(-1.954)*	(-1.984)**	(-1.975)**	(-1.740)*
Cooling production type								
Central cooling towers	-16.330	-2.388	-12.646	0.672	-2.448	-64.510	-21.553	-3.954
	(-0.283)	(-0.029)	(-0.149)	(0.008)	(-0.028)	(-0.775)	(-0.243)	(-0.054)
Central remote condensers	-37.118	-23.496	-65.399	-49.000	-48.676	-92.173	-64.663	-95.870
	(-0.637)	(-0.279)	(-0.765)	(-0.560)	(-0.551)	(-1.104)	(-0.724)	(-1.304)
District cooling network	20.279	44.582	12.489	52.962	47.904	50.690	49.953	43.723
	(1.558)	(2.577)**	(0.655)	(2.937)***	(2.635)***	(2.942)***	(2.710)***	(2.881)***
Groundwater source heatpump	-99.575	-28.024	-31.025	-28.834	-65.377	-43.928	-26.466	-51.878
	(-1.512)	(-0.295)	(-0.320)	(-0.292)	(-0.650)	(-0.464)	(-0.261)	(-0.622)
Individual production	20.338	-12.842	-11.132	-15.337	-15.899	7.329	-12.643	1.454
	(1.812)*	(-0.814)	(-0.690)	(-0.934)	(-0.959)	(0.453)	(-0.748)	(0.104)
Refurbishment details								
Full / major / general refurbishment	4.477	47.254	36.847	35.776	38.031	32.308	45.464	24.629
	(0.372)	(2.784)***	(2.112)**	(2.000)**	(2.110)**	(1.892)*	(2.511)**	(1.638)
Facade / windows / roof / insolation	-13.613	5.453	8.077	0.687	-5.502	3.048	5.503	-18.114
	(-1.124)	(0.316)	(0.457)	(0.038)	(-0.301)	(0.177)	(0.298)	(-1.188)
Heating / cooling system	-18.693	-4.723	0.103	-5.799	-10.614	-5.542	-4.916	-12.128
	(-1.642)	(-0.290)	(0.006)	(-0.341)	(-0.613)	(-0.341)	(-0.282)	(-0.846)
Partly refurbishment	-15.969	0.383	3.039	-1.976	-5.442	-3.890	-0.568	-18.425
	(-1.293)	(0.021)	(0.167)	(-0.106)	(-0.290)	(-0.219)	(-0.030)	(-1.173)
Country effects (n)	12	12	12	12	12	12	12	12
Year effects, Green Rating audit year (n)	4	4	4	4	4	4	4	4
Adjusted R^2	0.686	0.335	0.306	0.279	0.265	0.340	0.245	0.488
AIC-Criterion	2999.08	3198.88	3210.48	3221.16	3226.34	3197.09	3233.84	3127.62

Significance: *** 1%, ** 5%, * 10%

The results illustrated in table IX display highly significant coefficients for HDD, explaining that a growth in HDD is decreasing the spread between the two types of energy consumption. Thus one more HDD explains an easing of approx. -5 kWh/sqm/a from the spread. Results for CDD remain of less significance, except the coefficient when sub-category of actual consumption for ventilation is solely included in the model (column 6). The results are in line to our observation for explaining actual consumption. When actual consumption decreases with growing HDD and CDD as explained, also the spread as regressand tends towards a decrement lowering the delta.

Corresponding results are obtained when analysing the coefficients for the single sub-categories of energy consumption. If actual consumption for heating is increased by 1%, it introduces a surplus of ca. 0.6 kWh/sqm/a to the spread (column 2). Again, a strong influence for actual consumption of other (column 8) and of lighting (column 4) is appearing.

To some extent surprising are the significant results for building area. A surplus of 1% of building area is followed by up to 0.2 kWh/sqm/a increase in the spread, all else equal. This provides coincidence to the finding of higher actual consumption in larger buildings, what might be the case in high-rise office towers when compared to more compact structures. Therefore, a reduction in building area also lowers the spread between actual and intrinsic at the same proportion noted above for the surplus. Our supposition was to obtain significant coefficients for the allocated building area per occupant, displaying the deviance of the behavioural response from occupants in relation to the fixed standard formula integrated to the intrinsic assessment. However, this is not the case. An argumentation might be that the behavioural response expected in the allocated building area per occupant is correlated to the total building area, as the building area per occupant also accounts for the vacancy in the office buildings.

The single tenant binary matches with our results obtain for actual consumption. It indicates a highly significant contribution to an increment in the spread when compared to multi-tenant assets. Explanation for this might be the different behavioural response between the two as well as physical building attributes discussed when explaining actual consumption.

For the cooling production type we received highly significant influence – in spite of the results when regressing intrinsic consumption. Cooling district network is attributed to provide between ca. 45 kWh/sqm/a and 50 kWh/sqm/a more to the calculated spread if compared to a centralised cooling production.

The results of the coefficients for refurbishment details further foster our interpretation of an existing rebound effect within the tested portfolio. The attributes captured in total or major refurbishment explain a potential of a contribution to a higher spread between 36 kWh/sqm/a (column 4) and up to 47 kWh/sqm/a (column 2) depending on the specific regression model with significance at 5%.

VI. CONCLUSION

The objective of this research study was to determine the influence of physical building characteristics and the behavioural response by occupants on the actual energy consumption of office buildings in Europe. Furthermore, the data sample of our research study was applied with intrinsic energy assessment by Green Rating Alliance (GRA) as well as the spread between actual consumption and intrinsic measures to provide evidence regarding the potential drivers for increasing actual consumption and the spread.

The regression approach with intrinsic consumption was intended to discover how actual consumption relates to the intrinsic assessment measurement. While intrinsic consumption assessment inheres a standard formula for the behavioural response of occupants, our results exhibit no significant influence of the behavioural response attributes. Renewal of heating/cooling systems and attributes associated with a "light" refurbishment turn out to be of great effect for an increase in the intrinsic energy consumption calculation. Introducing the spread between actual and intrinsic consumption as response variable to our regression model the behavioural response of occupants was observed to have a significant impact explaining the difference between the two. However, the influence on the explanatory building area allocated per office occupant – assumed to contribute to the spread – is lacking of significance.

Confronted with our hypothesis the regression results explaining actual energy consumption reveal interesting results. For the physical building characteristics decentralised production types for heating and cooling have been investigated with much lower actual consumption, compared to heating or cooling network systems suffering from losses of load. The application of a heating pump reveals the highest savings compared to the other heat production types.

We hypothesise a behavioural response of occupants on office buildings being negatively related to energy savings. This was approved to be true for the distinction between single and multi-tenant occupied buildings. Single tenant buildings are of higher actual energy consumption between approx. 14% up to 19% compared to multi-tenant observations, thus per se demonstrating enormous potential for actual energy conservation which was indicated in the regression of the spread between actual consumption and intrinsic measurement.

The applied economic building age under consideration of major refurbishment in the past was investigated for all three explanatory variables to be not of a significant impact on energy consumption of the tested European portfolio. This turns out to be a remarkable finding due to the overall expectation of an impact from the increased energy efficiency regulation within EU-member states over the past decade. The results draw a conclusion that increased building codes and construction standards are likely to increase the thermal quality of new or refurbished buildings. However, these attempts do not emerge with a significant impact towards the conservation of actual energy consumption, based on the 273 observations in the GRA portfolio.

The more, refurbishment attributes introduced in our econometric approach reveal a significant impact on higher actual energy consumption for observations with a total or major refurbishment compared to those without any refurbishment in the past. We investigate a higher consumption associated with total or major refurbishment in a margin between 17.5% up to 21.7%, whereas the refurbishment dummies containing thermal qualities (façade/windows/roof/insolation) or replacement of heating/cooling systems remain insignificant. In the course of a total or major refurbishment affecting thermal building quality plus potential energy consumption savings from the renewal of HVAC systems the increased energy efficiency – evidenced by the influence of HDD and CDD – succeeds to a situation where heating and cooling are "cheaper", thus effecting a capacious increase in energy demand due to assumed "lower cost".

Recalling the results for building age the effect of refurbishment leaves no doubt for a contribution towards higher energy consumption for buildings undergone a total or major refurbishment in the past. After all, we provide clear evidence for the theoretical compound outlined in this paper that a rebound effect is inherent in the European office market if total or major refurbishment is executed for the existing office building stock. For this reason our results are contradicting the expectation of a tremendous energy consumption saving potential to be realised through refurbishment. All above, total or major refurbishment is identified as a factor increasing energy consumption. Despite expected carbon emission redemption for the durable building stock we found it contributing to a negative impact on climate change for the tested portfolio.

Beyond the recommendation to consolidate our research results on a more extensive database, we are of the opinion that fostering the awareness of actual energy consumption and towards potential savings by occupants is furthermore an issue. Apart from the technological progress and a more and stricter energy efficiency regulation, the design of an effective incentive mechanism for office occupants to shift their behaviour towards energy conservation might be an approach to achieve higher energy savings in practice. How this mechanism could be designed is subject to further research, especially in the field of behavioural real estate.

NOTES

[i] The term "refurbishment" is used within this paper referring to other terms used in the real estate industry, such as retrofit, redevelopment or revitalisation, to define major construction works affecting the thermal, technical and further energy consuming characteristics within the existing building structure.

[ii] The project "Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe (ENTRANZE)" was launched to support policy making by providing the required data, analysis and guidelines to achieve a fast and strong penetration of nearly-zero energy buildings and renewable energy sources for heating and cooling within the existing national building stocks of nine EU-countries, covering more than 60% of the EU-27 building stock.

[iii] In the course of the European Energy Performance of Buildings Directive (EPBD) the EPC ratings were introduced in 2002 and became mandatory by the year 2008.

[iv] The heating and cooling degree days received from the Weather Underground Website were calculated on a basis of 65 heating and cooling degree days (wunderground.com).

[v] For the interpretation of the coefficients for binary variables in a semi-logarithmic regression the percentage effect is calculated as anti-logarithm of the estimated coefficients with ($\exp(\beta x) - 1 * 100$) with regard to the omitted reference variable (see Halvorsen an Palmquist 1980, see Hardy 1993).

REFRENCES

Cajias, M., Piazolo, D. 2013. Green Performs Better: Energy Efficiency and Financial Return on Buildings. *Journal of Corporate Real Estate, 15 (1)*: 53-72.

ENTRANZE Project. 2014. Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe, ENTRANZE, www.entranze.eu.

Fahrmeir, l., Kneib., Lang, S. 2007. *Regression. Modelle, Methoden und Anwendungen*. Springer, Berlin.

Gillingham, K.M., Kotchen, M.J., Rapson, D.S., Wagner, G. 2013. The Rebound Effect is over-played. *Nature 493*: 475-476.

Greening, L., Greene, D.L., Difiglio, C. 2000. Energy Efficiency and Consumption – the Rebound Effect – a Survey. *Energy Policy, 6*: 389-401.

Guerra Santin, O., Itard, L., Visscher, H. 2009. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings, 41*: 1223-1232

Haas, R.; Auer, H.; Biermayr, P. 1998. The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings*, *27*: 195-205.

Halvorsen, R., Palmquist, R. 1980. The Interpretation of Dummy Varibles in semilogarithmic equations. *The American Economic Review, 70 (3)*: 474-475.

Hardy, M. A. 1993. Regression with Dummy Variables. *Sage Publications*: 56-59.

Kahn, M. E.; Kok, N.; Quigley, J. M. 2014. Carbon Emissions from the Commercial Building Sector: The Role of Climate, Quality, and Incentives. *Journal of Public Economics*, *113*: 1-12.

Knittel. C.R. 2012. Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector. *American Economic Review, 101 (7)*: 3368-3399.

Konrad, K. and Thun, M. 2012. The role of Economic Policy in Climate Change Adaption. *Max Planck Institute for Tax Law and Public Finance.*

Lam, J.C., Wan, K.K.W., Liu, D., Tsang, C.L. 2010. Multiple regression models for energy use in air-conditioned office buildings in different climates. *Energy Conservation and Management, 51*: 2692-2697.

Leopoldsberger, G., Bienert, S., Brunauer, W., Bobsin, K., Schuetzenhofer, C. 2011. Energising Property Valuation: Putting a Value on Energy-Efficient Buildings. *International Appraising 2011*: 115-125.

Leth-Peterson, S.; Togeby, M. 2001. Demand for space heating in apartment blocks: measuring effect of policy measures aiming at reducing energy consumption. *Energy Economics*, *23*: 387-403.

Malpezzi, S. 2003. Hedonic pricing models: A selective and applied review. *Housing Economics and Public Policy: Essays in Honor of Duncan Maclennan*: 67-89.

Rosen, S. 1974. Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *The Journal of Political Economy, 82 (1)*: 35-55.

Solomon, D. M., Winter, R. L., Boulanger, A. G.; Anderson, R. N. and Wu, L. L. 2011. Forecasting Energy Demand in Large Commercial Buildings Using Support Vektor Machine Regression. *Columbia University Computer Science Technical Reports. Columbia University Computer Science Technical Reports*: 1-9.

Wood, S., 2006. *An Introduction to Generalized Additive Models with R*. Taylor & Francis Ltd.

Wooldridge, J. 2002. *Econometric Analysis of Cross-Section and Panel Data*. The MIT Press, Cambridge, MA.

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