IMPACT OF USER BEHAVIOUR AND INTELLIGENT CONTROL ON THE ENERGY PERFORMANCE OF RESIDENTIAL BUILDINGS

AN EU POLICY CASE FOR ENERGY SAVING TECHNOLOGIES AND INTELLIGENT CONTROLS IN DWELLINGS

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EXECUTIVE SUMMARY

Objective

The focus of the current study is to analyse the impact of user behaviour on the overall energy consumption of residential buildings. This includes user specific technology choices during construction phase as well as the effective user behaviour. The main question this study wants to answer is **whether specific cost efficient technologies show a consistent and positive impact on the primary energy demand of a building in use**. If that is indeed the case, specific stimuli might need to be developed in order to increase the market penetration and assure a widespread impact.

Motivation and approach

Residential energy consumption amounts for over 29% of total final energy use in the European Union. To achieve the European targets regarding energy savings and carbon emission reduction, changes in the consumption pattern of EU households are therefore necessary.

Current tendencies show, amongst other as a result of legislation and industrial initiatives, an improved energy efficiency in buildings, heating and ventilation systems, lighting as well as for household appliances. However, energy consumption tends to increase and varies strongly between households and across the EU. Socio-economic and cultural differences might explain part of this. Though, analyses reveal substantial differences in energy consumption and possession of appliances, even between similar households living in comparable conditions. It is clear that, besides the quality of the building and the installations in it, the behaviour of the occupants is decisive.

Therefore, in the current study a distinction is made between building related measures and behaviour related measures. A first quantitative analysing method is applied for the building related aspects. A second, more qualitative analysing method focusses on behaviour related measures, and more specifically on user feedback systems.

Building related measures

The measures evaluated in this section are inherently connected to the building: heating and ventilation and their control[1], building envelope quality and lighting. These measures are evaluated for a range of cases (considering climate type, type of dwelling and family type), covering the broad diversity of residential energy profiles in Europe.

The calculations are based on the EU standards ISO 13790 and EN 15603. Therefore, they do not incorporate the electricity use for appliances and entertainment. Numbers for the latter are given throughout the text and in more detail in ANNEX A where it is clearly shown that the use of the Best Available Technology for these energy consuming devices and a good practice in their usage results in considerable electricity savings.

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[1] Intelligent controls taken into account comprise the advanced HVAC controls that have a recognized calculation methodology. Actual Home Energy Management Systems (HEM's) are still in an early stage and no general savings can be estimated. The approach of the current study is to consider HEMS as a combination of smart controls on all HVAC devices. This can however be considered conservative.

The results of the so-defined 36,288 simulations are presented in graphs showing the global cost versus the primary energy use. Such presentations allow technical-financial evaluations to select cost optimal parameter combinations. Through highlighting specific input cases, the relative importance of specific measures on energy use and global cost is visualized.

- The use of **outside temperature compensated control** is one measure for which the extra energy savings make up for the additional investment cost. Its impact depends on the effective heating hours and therefore becomes substantial when applied in colder regions and in case of a higher occupancy rate (in case of an indoor temperature control system). Although its impact is linked to the number of heating hours, investing in outside temperature compensated control becomes only superfluous when considering a building envelope quality close to passive in a warm climate region.
- Installing a **central temperature sensor** clearly pays off compared to the use of thermostatic valves only. The extra energy savings generated by using a system controlling indoor temperature for each room individually will in some cases outweigh its (substantial) additional investment cost, more specifically in cold climate regions and in (large) dwellings with a standard (not significantly energy performant) building envelope and a high occupancy rate.
- **Demand controlled ventilation**, including the use of a presence detection system in the form of CO2 sensors, results in both a lower primary energy use and lower global cost. Since ventilation losses are not directly linked to the building envelope quality, the savings potential of intelligent control for ventilation remains high, even for building with high levels of building envelope quality (insulation and air tightness).
- With (new) regulation on energy performance in buildings that is continuously focussing on reducing energy consumption for heating and sanitary hot water production, the relative share of other domestic energy consumers increases. Although the investment cost of **LED's** is still considerably higher when compared to a business as usual type of investments, the longer (expected) lifetime and lower energy consumption results in a significantly lower global cost.
- **Home Energy Management Systems (HEMS)**, here considered as a combination of intelligent controls for heating, ventilation and lighting, consistently results in the lowest primary energy use for the lowest global cost.

Behaviour related measures

In the current study, the emphasis is on technological solutions for improving energy efficiency. Regarding behavioural measures, technological solutions focus primarily on confronting users with their energy consumption pattern. The technological solutions currently available for that are the so-called in home display's (IHD's). They provide feedback in different ways, mainly:

- Direct feedback: real-time feedback about consumption and costs available at any time
- Indirect feedback: processed information that provides no direct access to the actual consumption data

At this stage, the IHD's are mostly in experimental stages and applied in demonstration projects. Reported savings on household's energy consumption are in the range of 5 to 20% using direct feedback, 10% when indirect feedback is used.

Mostly, these numbers relate to experiments with limited time duration. When prolonging the experiments, different studies report lower savings rates. However, time does not undo all energy savings.

General Conclusion

The current study clearly shows that user behaviour can have a significant impact on the overall energy consumption of residential buildings. This includes specific technology choices of users during construction/purchasing phase of a dwelling as well as the effective user behaviour. Stimulating the development and implementation of energy saving technologies could result in significant primary energy savings and lower global costs for households, serving both public and private interests. These stimuli can take the form of new policy (either on European level or on the level of the member states), e.g. specific subsidy schemes for new technologies, demonstration projects, etc.

One way of assuring an impact is through the deliberate selection of technologies and their control. The different simulations revealed that application of intelligent automated control on heating and ventilation resulted in energy efficiency improvements. However, not all intelligent control systems can yet be simulated in the current official Energy Performance evaluation tools. Furthermore, it has been shown that simple technological solutions that interact with the user and confront him/her with the actual energy consumption can significantly impact user behaviour to assure a reduction in energy consumption.

Upcoming intelligent control systems such as various types of Home Energy Management Systems (HEMS) have convincing energy saving potentials. Their saving potential is larger than the sum of the savings of each of the intelligent controls on heating, ventilation and others.

The fact that innovative intelligent control systems can currently not be valorised within the official Energy Performance evaluation tools of the different EU member states clearly slows down the large scale deployment of these promising energy saving measures. Stimuli regarding cost reduction schemes, new modes of interaction and automated personalized feedback could further open the market.

TABLE OF CONTENTS

1 INTRODUCTION

The energy consumption of the European built environment takes a 29% share of the total primary energy consumption in Europe. While devices have become considerably more efficient due to amongst other eco-design directives and energy labelling, residential energy consumption has been increasing over the last years. Countering this increase requires actions on different domains: the technological solutions and the way they are used.

The focus of the current study is to analyse the impact of user behaviour on the overall energy consumption of residential buildings. This includes specific user specific technology choices during construction/purchasing of a dwelling as well as the effective user behaviour. The main question this study wants to answer is **whether specific cost efficient technologies show a consistent and positive impact on the primary energy demand of a building in use**. If that is indeed the case, specific stimuli might need to be developed in order to increase the market penetration and assure a widespread impact.

Energy performance requirements on building level are currently in force in most EU member states stimulating energy efficiency improvements of their building stock. The related energy calculation methodologies are not intended to reflect the actual energy consumption of buildings in use, but are set up in order to compare different buildings. For residential buildings the calculation includes the building envelope composition, compactness and orientation, heating, cooling and ventilation, as well as on-site renewables and internal heat gains.

The aim of this study is to provide a technology-neutral policy supporting document, analysing the impact on the energy performance of residential buildings of both user behaviour including buying behaviour and the impact of intelligent control on domestic devices

2 IN DEPTH ANALYSIS

2.1 METHODOLOGY FOR ANALYSIS

2.1.1 Introduction

The aim of this analysis is to show policy makers the potential **that specific technological solutions on different levels of control and user interaction can have on the primary energy demand of a building in use**.

The overall aim is to achieve more energy savings in the residential sector and boost those technologies that can contribute to it. In general, three ways can be proposed to reduce residential energy consumption: replace existing housing stock with or renovate existing stock to low-energy buildings, promote use of high efficiency domestic equipment and promote energy-conscious behaviour (Wood, 2003). The first two can be combined in building-related measures: improved insulation and air tightness, selected HVAC technologies and their control, etc. The last one focusses more on the building user and how he uses the technologies within the building. Measures targeted to influence this can be summarized under behavioural measures.

Most of today's established savings in energy consumption took place in the sector of building related measures, mainly focussed on reducing energy consumption for space heating. This can be explained by the improvements in space heating technologies as well as tighter building codes enforced by policies (EEA). Aydin and Brounen (Ayden, 2013) however, emphasize that these tighter building codes only have an effect on new buildings (1,1% of total building stock), which implies the impact on the energy use of the total building stock is rather limited. Different studies, such as the BPIE study on building refurbishment, emphasize the need to increase the renovation standard, including heating and cooling devices, and more ambitious renovation rates. The stimuli towards a higher renovation rate can be found in EU subsidies for new technologies and for demonstration projects, as well as in the EU's directive for energy performance of buildings. Different countries focus specifically on renovation with financial incentives, information campaigns and tax reductions for improving the energy efficiency of their building stock. The results of a broad range of studies (Balares C., et al., 2007), (Verbeeck G., Hens H., 2005) have indicated the type of building envelope measures to be taken when investing in energy saving measures. Therefore, this study does not focus on the impact of air tightness and insulation quality (indicated by U-values), but uses a variation of building envelope qualities to evaluate a range of technologies.

Another challenge Europe has been working on is the change towards more efficiency for (household) appliances in general as well as for lighting. The European Action Plan for Sustainable Consumption and Production (SCP) and Sustainable Industrial Policy (SIP) aim at ensuring a move towards greener and more efficient consumption. The list of actions contains amongst others Ecodesign standards, energy and environmental labelling, support to environmental industries and promotion of sustainable industry. A study of Waide (Waide, 2011) emphasizes the potential of labels as being able to pull the market towards energy efficiency, compared to standards that rather push the market. Labelling is in force for a wide range of domestic energy consuming products in Europe. Waide provides market data that confirm the effectiveness of the labelling and Ecodesign directive through the gradual phase out of energy inefficient variants of labelled products including lighting. The present study will not elaborate on ways to motivate users to replace their old appliances.

2.1.2 Approach

This study will focus on both building-related measures and behaviour related measures. For the former, the present study proposes an independent and neutral quasi-static calculation methodology that is in line with the European Standards ISO 13790 - EN 15603. Through minor adaptations, this tool allows to evaluate the impact of the use of the best available technology (BAT) and intelligent control for energy consuming devices.

Both for the overall intelligent control systems as for the behaviour related measures, the analysis is further completed by data from literature.

The first section of the analysis describes the variation of energy consumption across European households. The use and efficiency of household appliances and occupancy profiles influence the indoor heat gains, as described in EN 15603. The results of the literature study are compared to the relevant formulas that are embedded in the selected quasi-static evaluation tool.

The selected tool is the energy performance evaluation tool as implemented in the Flemish region in Belgium. It is nearly identical to the tool applied in the other Belgian regions and is in line with the ISO 13790 - EN 15603 guidelines. The method applies a monthly estimation of the energy balance of the building and takes into account heating, cooling, ventilation, hot water, auxiliary energy and renewable energy production. The latter is not considered in this study as not relevant for the analysis of how technological solutions can improve the efficiency of energy consuming devices in residential buildings.

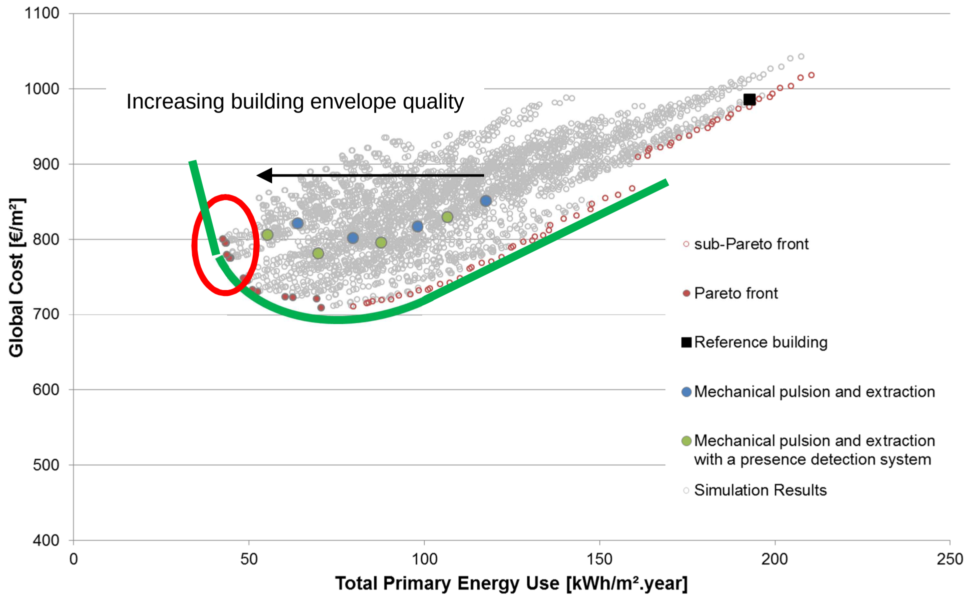
The effective electricity use for appliances and entertainment is not embedded in the global energy estimation of the calculated results. The analysis in ANNEX A provides details on variation of energy consumption per appliance.

The applied tool is consequently discussed with attention to the adaptations that have been implemented in order to take into account the impact of user behaviour and to evaluate controls and devices that are not or not yet implemented. The range of simulations is selected to represent 3 different European climate zones with relevant building envelope characteristics, 2 family types and 2 building typologies. The results of the simulations are presented in so-called Pareto graphs (see chapter 2.1.3 and 2.3). These graphs show primary energy consumption versus the global cost for a large number of simulation cases and allow analysing whether a specific technology implementation will lead to energy savings and/or cost savings independent of the building envelope quality or user profile. The method is applied for technologies for which prices and performances are readily available.

Home Energy Management Systems (HEMS) are not embedded in the calculation tool. Relevant prices and effectiveness of these devices are not yet generally available to provide a sound basis for calculation input. Therefore, these aspects are discussed based on literature. A distinction is made between In Home Displays focussing on providing feedback to influence user behaviour and effective Home Energy Management Systems that control overall home energy system and the interaction between devices, i.e. a more building related measure.

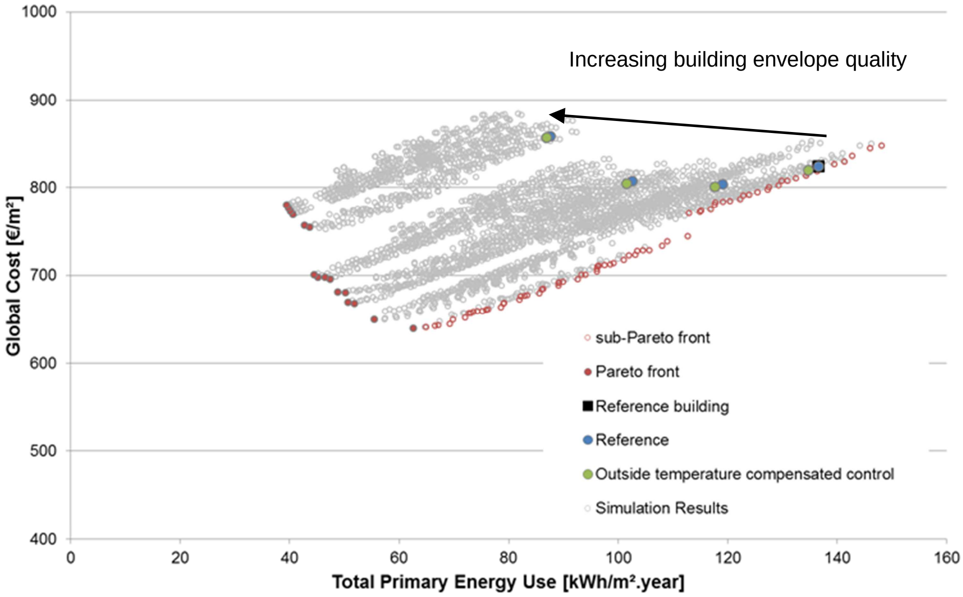
2.1.3 How to read a Pareto graph

The impact of building-related measures will be analysed by interpreting the calculation results through so-called Pareto graphs. These graphs (presented further in this report) give the total annual primary energy use in kWh/m²on the x-axis and the global cost in €/m² on the y-axis. The global cost corresponds to all capital expenditures (CAPEX) (including reinvestments) and operating expenditures (OPEX) during a certain evaluation period. A single dot in the graph thus indicates a certain combination of input parameters that comes with a specific primary energy use at a specific cost. By simulating a wide range of combinations, a so-called Pareto front can be formed. This Pareto front (in green in the graph below) represents the cases resulting in the lowest global cost for a specific primary energy use or, just as well, that give the lowest primary energy consumption for a specific global cost.



The shape of the Pareto front also reveals that there is a point where more primary energy savings can only be achieved at considerable higher cost. The red oval in the above graph illustrates this: moving more to the left on the x-axis immediately results in high increases in global cost: the highest energy savings can thus only be realized through disproportionate investments. The simulation results in the bend of the green curve show the optimal combination of parameters.

In this study, the aim of the simulations is to reveal the energy savings that can be achieved using more advanced or more intelligently controlled devices. These savings should be analysed for a range of residential buildings and a range of occupants to understand their potential independent of user behaviour. Therefore, the spectrum of parameter variations considers different building envelope compositions, different indoor temperature settings, etc. for a comparison of the reference case with the technology under study. The graph below shows this in more detail.



The graph shows the results for an external temperature compensated control. For each of the building and user cases, the reference case with this control shows to be better compared to the same case without this control. Better is than defined as achieving more savings (a lower primary energy use) over the lifetime considered compared to the investment and maintenance cost (global cost) of the technology.

The graph shows the simulation results for different building envelope qualities. Increasing quality shows to lead, as expected, to reduced energy consumption. Throughout the text the results in the graphs will be highlighted for specific cases. The above explanation explains that it is not because they are not in the bend of the Pareto front that they do not systematically indicate an effective and interesting technology. It is the comparison with building cases of the same type that reveals the effective potential independent of building quality and user behaviour.

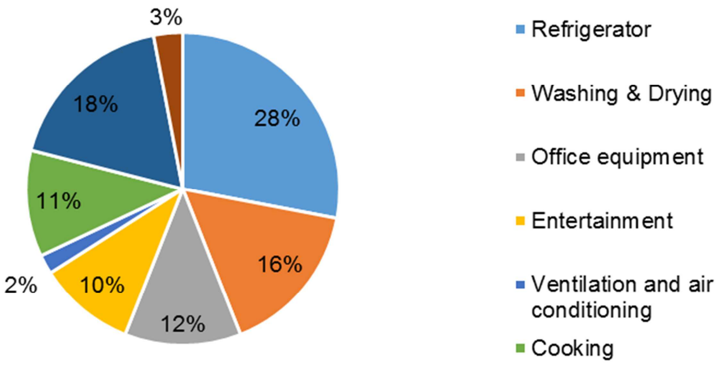
2.2 IMPACT OF USER BEHAVIOUR

2.2.1 Introduction

Despite more efficient buildings, there is an increase in the final energy consumption of households. Both the International Energy Agency (IEA) Energy Conservation in Buildings & Community Systems (ECBCS) annex 53 as well as the European Environmental Agency (EEA) recently confirmed this trend. The latter organisation has quantified the energy efficiency increase of the residential space heating technologies and electrical appliances in Europe on 24 % over the period 1990-2009. The EEA estimated the increased final energy consumption of households to be 8% over the period 1990-2009. Specifically electricity consumption, which takes an average 25% of the total EU household energy consumption according to the EEA, grew with an average annual rate of 1,7 %. Although the energy-use for space heating and water heating dropped with 6% and 1% respectively, electrical appliances and lighting showed an increase of 5%.

IEA ECBCS annex 53 discussions revealed the growing use of smart devices as smartphones, tablets and alike to be at least partly responsible for this increase in electricity consumption. This is confirmed by a study conducted by Coleman et. al. (Coleman et al., 2012) about the energy use of information, communication and entertainment (ICE) appliances in UK homes: Coleman et al. show that the average household electricity consumption from ICE appliances equals 23% of average whole house electricity consumption.

Ellegard (Ellegard, 2010) further indicates an increase in single households, bigger living areas, more appliances and the trend of purchasing several appliances of the same sort, as contributing aspects to increasing energy consumption in households (e.g. multiple TV`s per household). The EU Remodece-project (REMODECE, 2009) presents results based on a large scale monitoring campaign. The electricity breakdown they derived is given in the chart below.



The Remodece report confirms these findings and adds the shift in the population landscape towards not only more single family houses in larger dwellings, but also more elderly people living alone and mainly indoors, consequently using more energy. In spite of the efforts, the increased energy efficiency of home appliances is not sufficient to compensate for the increase in quantity of appliances a household owns and uses nowadays (Vassileva, 2012). The EEA (EEA, 2013) estimates that 50% of the energy improvements are offset by increasing energy consumption due to the above trends of larger homes, more appliances, ….

The below section will therefore start will an analysis of internal gains and how they are currently estimated in energy performance evaluations. Consequently; the different elements that will be considered in detail in the energy performance calculations are discussed. These include lighting, heating and ventilation devices as well as indoor temperature setting.

2.2.2 Internal gains

Energy consumption due to appliances shows a strong variation in Europe. A detailed analysis of relative spread and usage of household appliances is given in annex A. In this section, these data are compared to the standard calculation of internal heat gains in the energy performance evaluation tool used for this study.

Standard calculation of internal heat gains

The standard calculation of internal heat gains considers all heat gains produced by internal sources: appliances, people and lighting. In the energy performance evaluation software for residential buildings in Belgium (this formula is used in the 3 Belgian regions), the following formula is applied:

$$Q_{i,sec,m} = \left(0{,}67 + \frac{220}{V_{EPW}}\right) V_{seci} t_m$$

Where

$Q_{i,sec,m}$ is the monthly internal heat production (MJ)

V_{EPW} is the volume of the residential building (m^3)

V_{seci} is the volume of the energy sector (m^3)

t_m is the length of the month (Ms)

This formula results in the following values for the annual heat gains of the single family house and the apartment used in this study (see details in ANNEX A)

- Single family house: 5144 kWh
- Apartment: 3645 kWh

In the Passive House Planning (design) Package (PHPP) the internal heat gains are given a standard value of 2.1 W/m^2, unless a more detailed calculation method is selected by the evaluator. The more detailed method requires input on presence and type of specific appliances. Using the value of 2.1 W/m^2, the following yearly values can be calculated:

- Single family house: 3440 kWh
- Apartment: 1784 kWh

The resulting numbers show to differentiate considerably. For the present study it is important to understand to what extend this difference would impact the results of the Pareto multi-parameter optimization. Therefore, a calculation has been done using the standard method in the energy performance evaluation tool as well as the data from the passive house calculation methodology.

Analysis of the results (example shown in Figure 1) learns that the same combinations of measures take similar positions in each of the Pareto fronts.

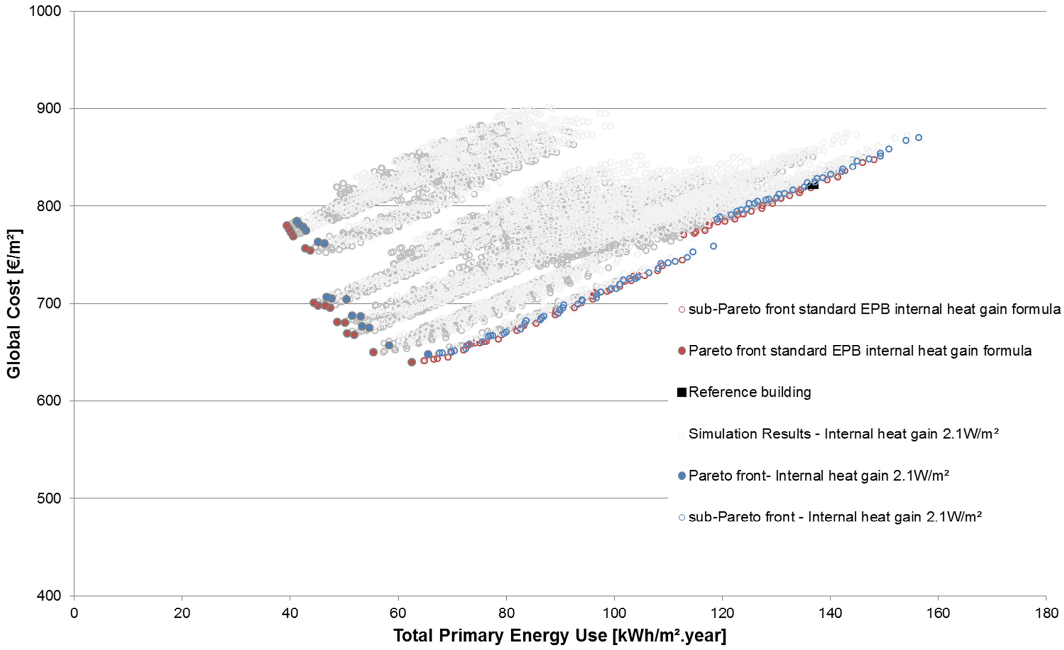


Figure 1: Comparison of Pareto front optima for 2 different internal gain calculation methods (EPB vs PHPP) (results shown for a moderate climate / 4-person family / single family house)

Internal heat gains estimation based on statistical data

The data in ANNEX A provide input on relative spread and yearly energy consumption of different appliances. Where available, the energy usage of the reference scenario and the Best Available Technology (BAT) is given. The resulting numbers are given in the table below. It is assumed that 90% of this energy consumption is directly or indirectly emitted as heat.

Internal heat gain appliances (kWh)	Reference	BAT
Washing machine	206	83
Dryer	650	-
Dishwashers	305	188
Cooking appliances	1000	500
Freezer	/	/
Fridge	75	141
Fridge-freezer combination	/	149

Electronic devices, including multi-media[2]	855	855
TV	173	35

People emit on average 100 W for a healthy adult and 75W for a child. Sleeping reduces the emitted heat, but studies report increasing heat emission due to evaporation with resulting heat emission reduction in the range of 5% only (Garby et al., 1987). For the two family types that will be considered hereafter, the following annual internal heat gains result from the occupants' presence:

- 2 person family, at home most of the time: 1752 kWh
- 4-person family working outdoors, kids at school (i.e. outdoors between 8 a.m. and 6 p.m. on weekdays and 2 hours per day in weekends): 2040 kWh

For lighting, the gradual phase out of inefficient light bulbs will strongly affect the actual energy consumption for lighting in residential buildings. Below a more detailed overview is given (chapter 2.3.4), but the data for the Netherlands are used for the Belgium case and the BAT considers a case where 90% savings are achieved. Energy consumption of lighting is considered as heat, directly or indirectly. This results in the following annual energy consumption:

Internal heat gain lighting (kWh)	Reference	BAT
Single family house	407	41
Apartment	785	79

The combined internal gains result in the following numbers:

Internal heat gain (kWh)	2 person		4 person	
	Reference	BAT	Reference	BAT
Single family house	5801	3781	6089	4069
Apartment	5423	3744	5711	4032

Compared to the above numbers, the values for the single family house show to be in line with the estimates of the standard calculation method for the reference case and with the PHPP method for the BAT. For this dwelling type, deviations are between 4% and 12%. Figure 1 above has shown that such differences do not influence the Pareto front composition.

However, the values for the apartment deviate considerably: 3% to even 115%. Especially the PHPP value hardly allows two people to be home constantly, while the standard method results in values

[2] Calculated as 22% (Coleman) of the annual average electricity consumption based on the data as provided by Enerdata (Enerdata).

really close to the BAT scenario. A considerable underestimation of internal heat gains will increase the heating demand and put more emphasis on the impact of intelligent HVAC devices and their control. This could lead to design decisions that do not deliver as such in real life conditions. But, as shown in the Figure 1, these will remain valuable measures with an attractive global cost.

However the analysis illustrates that the electricity consumption due to the use of appliances does not change the Pareto optima, it is clear that user behaviour, including buying behaviour, substantially influences the overall energy consumption.

2.2.3 Building heating and cooling demand

BPIE provides insight in the energy mix used for heating across Europe. Gas takes the largest share, whether in south, central or northern Europe. While for northern and southern European countries, electricity is the next most used energy source, in central and eastern European countries this second place is for renewable energy and electricity is third. According to the JRC study (Bertoldi, 2012), space heating equipment is the single largest electricity end consumer in the residential sector with an annual electricity consumption of 150 TWh in 2007. This includes direct electrical heating, heat pump heating and monitoring equipment for gas and oil fired burners.

BPIE further performed a detailed analysis of the heating load in European residential buildings (BPIE, 2011). The study revealed large difference per country based on the year of construction. E.g. for Slovenia, pre 1971 constructions show an average final annual heating consumption of 179 kWh/ m^2, while post 2009 residential buildings show values around 34 kWh/m^2. Sweden dropped from 187 kWh for 1968 housing to 53 kWh/m^2 for post 2010 buildings. The data are not available for all countries, nor is the variation given for buildings dating from the same year of construction.

Delghust et al. (Delghust, 2012 have analysed this for a specific case of 36 nearly identical Belgian social dwellings. They emphasize the huge influence of user behaviour on real heating demands. The measurements showed annual energy demands for heating varying between 26 kWh/ m^2 and 75 kWh/ m^2. Multi-zoning of the house model in energy estimates, as well as improved assumptions for intermittency and heating set point selection could decrease the difference between model and reality. Furthermore, their detailed heat flux and air tightness measurements showed large variations, although the buildings dated from the same period.

The variation of heating energy demand depends on a range of parameters, some are building envelope related, HVAC-related and/or depend on user preferences or user behaviour. Below, a description is given on the variation in insulation quality (indicated by U-values), airtightness and ventilation, heating system and indoor temperature settings.

Insulation quality (indicated by U-values)

U-values are indicators of statically calculated transmission losses. They depend on thickness and thermal resistance of the composing layers. The most decisive is the insulation. For older buildings, a recently launched online database summarizes the available information for a wide range of countries as function of age of the building, residential building typology and building component (BPIE, 2014). The database shows U-values for walls of above 1 W/ m^2K for most EU countries for the period before 1960. Exceptions in the database are the countries with colder winters: Denmark, Sweden and Finland.

A considerable amount of the EU residential building stock dates from before that period: on average 37% of residential buildings in the South, 42% in the North-West and 35% in Central and East Europe. For the period till 1990, the U-values of the building stock show a clear decrease. However, only Denmark, Finland, Sweden, Switzerland and the UK report U-values below 0.5W/m^{2}K for walls. Still, the timeframe 1961-1990 represents 49% of residential buildings in the South, 39% in North and West Europe and 48% in Central and East Europe.

Energy consciousness, increasing energy prices and building regulation have changed building practices. The table below lists the U-values for several building components and for a range of European countries as of January 2014 (Atanasiu, 2013). For some countries, such as Sweden, the U-values are replaced by other energy targeting properties. In Sweden, the specific energy consumption (heating, hot water and residential electricity) has to remain below a certain level, depending on the climatic zone of the country. For Stockholm, for a non-electrically heated dwelling, the target since 2011 is to remain below 90 kWh/m² annually. When heated with electricity, this has to drop further down to 55 kWh/m².

U-value (W/m²K)	Wall	Roof	Window	Floor above ground
Belgium (Flanders)	0.3	0.24	1.1	0.3
Belgium (Walloon region)	0.24	0.24	1.1	0.3
Luxembourg	0.32	0.25		0.40
Ireland	0.21	0.16	1.6	0.21
Austria	0.35	0.2	1.4	0.4
Bulgaria	0.35	0.28	1.7	0.4
Czech Republic	0.3	0.24	1.5	0.45
Portugal				
Greece (national average)	0.48	0.42	2.9	0.88
Finland	0.17	0.09	0.17	0.16
Germany	0.28	0.2	1.3	0.3
Italy	0.33	0.29	2	0.32
Romania	0.56		1.3	0.22
Spain	0.74	0.46		0.62

Given the further evolution towards Nearly Zero Energy Buildings by 2020 (EC, 2010b), the above listed values are expected to decrease further. The number of passive and zero energy buildings is increasing. The Intelligent Energy Europe project PassNet estimated the number of passive houses in 2010 to be 27 600 in the 10 European countries participating in the study. A positive estimate was to reach 65 000 passive buildings by 2012, but that number has not been verified (Pass-net, 2009). However, the numbers show the feasibility of building low energy or passive buildings. Already in 2006, Schnieder proposed, based on a technical feasibility analysis, U-values of 0.08 W/m^{2}K for walls and roofs and 0.6W/m^{2}K for windows (Schnieder, 2006). The above table is thus expected to change considerably in the near future.

Airtightness: infiltration and ventilation

Little is known about the actual infiltration and ventilation rates in residential buildings. The previously mentioned BPIE study (BPIE, 2011) reports some values of air tightness and thus infiltration rates. However, no data are found for all European countries. While most reported values show feasible n50 values of above 3 for buildings dating from before 2003, some data must still be refined. No data is given on ventilation rates.

The Tabula report of the Belgian building stock (Cyx et al., 2011) lists values for Belgium as v50-values for different building typologies and a selection of construction periods. The value n50 gives the air changes per hour as a result of a 50 Pa pressure difference and is expressed as 1/h. The v50-value is given in m³/hm² and gives the leakage of air averaged over the building envelope surface area, again with a pressure difference of 50 Pa. Reported values decrease from 18 m³/hm² for dwellings built before 1971 down to 6 m³/hm² for those built after 2005. Dimitroulopoulou et al. (Dimitroulopoulou, 2005) report measured infiltration and ventilation rates for UK dwellings. Infiltration rates, again with a 50 Pa pressure difference, varied between 4.8 ACH and 20.2 ACH in winter and 8.1 ACH and 19.4 ACH in summer, with average values of 12.9 ACH and 13.9 ACH for the tested seasons respectively. Ventilation rates varied between 0.19 ACH and 0.68 ACH in winter and 0.19 ACH and 1.06 ACH in summer. Brelih and Seppanen (Brelih, 2011) recently compared the ventilation rates in European standards and national regulations. However, it is known that people tend to adapt the settings to a lower value compared to the design loads. The publication of Dimitroulopoulou (Dimitroulopoulou, 2012) shows the measured and simulated air exchanges for a wide range of countries. The listed values have been derived using different techniques and assumptions. While care must be taken in using these summarized data, for this study on sketching the variation across Europe, the listed data show to be well in line with the above given values.

Table 1: Effective ventilation and infiltration in residential buildings across Europe (Dimitroulopoulou, 2012)

country	infiltration (ACH)	Ventilation + infiltration rates (ACH)	comment
Belgium	0.4	1.03±0.37	Natural ventilation, n50 of 12 ACH
	0.4	1.02±0.32	Exhaust ventilation, n50 of 12 ACH
	0.4	1.29±0.21	Mechanical ventilation, n50 of 12 ACH
	0.067	0.83±0.24	Mechanical ventilation, occupancy controlled, n50 of 12 ACH
	0.1	0.603±0.09	Mechanical ventilation, n50 of 3 ACH
Czech Republic	0.13-0.27	0.75±0.43	
Denmark		0.67	Mean
Finland		0.45±0.22	Single family house
		0.64±0.30	Apartment
		0.41±0.22	Natural ventilation
		0.46±0.19	Mechanical exhasut ventilation
		0.49±0.26	Balanced ventilation
	0.02	0.4	Newly built, detached houses with MVHR
Germany		0.36-1.2	
Greece	0.33	1.5	Natural ventilation
	0.13	0.5	Natural ventilation
Netherlands		0.3-0.9	Natural ventilation
		1.5-8.3	Balanced ventilation
Norway		0.6-0.75	
Portugal		0.51-0.81	
Sweden		0.37	Natural ventilation
		0.32	Mechanical exhaust ventilation
		0.44	Balanced ventilation
Switzerland		0.83±0.46	
United Kingdom		0.44±0.11	Dwellings built after 1995
		0.62±0.42	Peak level

Inhabitants tend to reduce the flow rate mainly because of either thermal discomfort or noise levels. The legal requirements are summarized in (Dimitroulopoulou., 2012; Brelih, 2011). Overall house values are given for the Czech Republic, Denmark, Norway and Finland. In all but the latter the minimum is 0.5 ACH, for Finland the minimum is 0.4 ACH. The other European countries provide requirements per room or based on the number of occupants. Brelih and Seppanen conclude that there is a large inconsistency in ventilation requirements across Europe. A simulation of 2 residential buildings where one was a 2-person 50m² housing unit and the second was a 4-person 90m² housing unit, showed ventilation rates between 0.23 and 1.21 ACH for the first dwelling and 0.26 to 0.98 ACH for the second house. The rates for the case of the Netherlands were obviously higher compared to any other EU country: 1.21 versus the second highest of 0.7 ACH for the small housing unit and 0.98 ACH versus 0.7 for the apartment. Besides the Netherlands, also Belgium is known to have high ventilation rates. These high rates are also reflected in the measured values listed in the above table.

Limited data is available on ventilation systems installed in residential buildings. In 2012, REHVA published a report on ventilation system types in some European countries (Litiu, 2012). This research summarized the variation of ventilation systems installed as function of age of the building. The study reveals that natural ventilation and fan assisted natural ventilation account for more than 50% of the European residential ventilation systems. According to that study, Finland was the first EU country to adopt mechanical ventilation systems. Already in 1959 mechanical supply and/or extract systems were gradually installed in new buildings, with from 2004 onwards all residential buildings being equipped with mechanical ventilation. In the UK, mechanical ventilation accounts for half of the ventilation systems installed in new houses since 2011. In Romania, since 2010 20% of newly built residential housing has mechanical ventilation. In Belgium, 40% of all new housing since 2008 has mechanical ventilation with or without heat recovery. The trends on increasing number of mechanical ventilation systems installed and improving air tightness is expected to continue as indoor air quality gains more attention. Market tendencies show an increasing variety of ventilation systems with heat recuperation and improved control, such as demand controlled ventilation.

2.2.4 Heating system

While extensive reports have been published on heating in European countries, including the 2012 JRC study on heat and cooling demand and market perspective (Pardo, 2012), limited data is available on the actual systems installed in residential buildings across Europe. Pardo provides data for the combined residential and service market. The study reports a 79% share for gas fired systems in 2004, of which less than 10% are condensing boilers. The 2007 preparatory study on Eco-design of boilers (Kemna, 2007) gives comparable numbers. They estimated the number of wet systems to be 72% of all EU residential heating systems, of which 65% are individual systems. The study further indicates 7% of individual wet central heating systems being gas condensing boilers and 65% non-condensing. For Belgium, a 2008-survey in 110 dwellings showed a similar distribution (Peeters, 2008): 4% of installed boilers were condensing boilers, 62% of all boilers were gas-fired. Boiler ages varied strongly with some installations dating from over 40 years back. Most surprising was the oversized boiler capacity, impacting the lifetime and efficiency of the devices. Lack of heat loss calculations was indicated as the main cause.

Since, efforts have been done to increase the share of renewables and decrease the use of fossil fuels for low exergy applications as house heating. Classifying heat pumps as a renewable energy application, favours them above conventional heating systems. To compensate for the higher investment cost multiple EU countries, e.g. UK and Italy, have special subsidies or reduced electricity prices for heat pumps.

Furthermore, the above referenced Kemna-report mentions 10% of dwellings in Europe to be connected to a district heating system. The same data show a considerable decrease, i.e. from 14% to 6%, in the use of solid fuel boilers in individual wet systems between 1990 and 2004. Also the use of oil-fired systems has decreased over the same period.

Limited data is available on the installed heat emission systems. The above references paper of Peeters et al. revealed that 95% of installed emitters were radiators and convectors. Floor heating took a share of 5%. In most cases radiators and convectors were controlled using a central thermostat located in the living room, combined with thermostatic radiator valves (TRV's) in the other rooms. Whether these numbers derived for Belgium can be extrapolated is questionable as distribution system operators have been stimulating the use of TRV's as an energy saving measure.

2.2.5 Indoor temperature settings

Indoor comfort in international standards is based on the theory of Fanger (Fanger, 1970). Fanger predicts the indoor temperature as well as the number of unsatisfied occupants based on an equation that takes into account a range of physical parameters: e.g. air velocity, mean radiant temperature, physical activity and clothing insulation. Interior temperatures in residential buildings tend to deviate from Fanger's theory and vary considerably (Fiala, 2001; Van der Linden, 2006, Guerra Santin, 2009; Heubner, 2013).

There are multiple factors explaining these variations:

- Adaptations (Brager, 1998), i.e. the changing evaluation of the thermal environment because of the changing perceptions.
    - Psychological adaptation: depends on experiences, habituations and expectations of the indoor environment
    - Physiological adaptation: can be broken down into two main subcategories: The first deals with effects on timescales beyond that of an individual's lifetime. The latter comprehends settings of the thermoregulations system over a period of a few days or weeks. In both cases, it is the response to sustained exposure to one or more thermal environmental stressors.
    - Behavioural thermoregulation or adjustment: includes all modifications a person might consciously or unconsciously make, which in turn modify heat and mass fluxes governing the body's thermal balance: personal adjustment, technological or environmental adjustment and cultural adjustment.
- Rebound effect: the rebound effect is discussed below in more detail. In brief, it is the effect of increased energy consumption when energy performance increases.
- Economic factors: fuel poverty or just the fact that people have to pay for residential heating themselves
- Building zones' characteristics: the desired temperatures in the different zones of a residential building vary (Peeters, 2009): bathrooms have higher temperature demands compared to bedrooms. The ratio of the surface area of the different zones will influence the overall average indoor temperature.

Conditions in residential buildings are not quite comparable to those during the experiments of Fanger. The first overall analysis for neutral temperatures in residential buildings (Peeters, 2009), used empirical data of multiple European countries. The study divides the residential building in 3 zones: bedrooms, bathrooms or wet zones and other zones. The indoor temperature in each of these zones is linked to a weighted average of the daily mean outdoor temperatures of the current and the past 3 days. Preferred indoor temperatures should be expressed as operative temperatures, being a weighted average of the air and mean radiant temperature. While this 3-zone weather dependent approach already brings a more realistic indoor temperature representation, the data used as a bases for this methodology showed wide variations. One of the few experiments on indoor temperatures in bathrooms (Toshihara,1998) showed variations in preferred air temperatures between 22°C and 30°C. Preferred temperatures even depended on whether a person was about to take a bath or had taken a bath. The study did not mention mean radiant temperatures. For typical other rooms, like living rooms, both Becker and Paciuk (Becker, Paciuk, 2008, thermal comfort in residential buildings – Failure to predict by standard model) and the extensive study of Nicol and McCartney (Nicol , 2000) reported measured values that strongly deviate. Especially the latter study showed measured preferred operative temperatures with differences of 10°C for the same conditions (pre-experiment activities and outdoor conditions).

Furthermore, besides variations in these neutral temperatures, indoor temperatures can show larger fluctuations as a result of temperature set back. Temperature set back is the adjustment of the thermostat to lower (in winter) or higher (in summer) values during inhabitant's absence in order to save energy. The effective temperature that can be reached during set back is not necessarily the programmed value: building thermal mass, U-value, indoor gains and outside conditions are some of the parameters affecting the actual temperature drop or rise. While the above mentioned publication (Peeters, 2008) reported only 54 % of installed thermostats to be programmable, the same publication also referred to sales data of 2005 where only 1.5% of sold thermostats were non-programmable. The means to apply set back are thus absent in a large amount of residential buildings, but no data is available on how effective they are being used.

2.2.6 Increasing energy consumption due to rebound effects

The term rebound has a broad range of interpretations. Its first application was in microeconomics. The narrow explanation was that there is a direct increase in demand for an energy service whose supply has increased as a result of technical improvements in the use of energy (Greening, 2000). The further, wider, application has replaced the 'technical improvements in the use of energy' by a more general 'decrease in energy price'. The review of Greening et al., revealed that all space heating, space cooling and hot water use are subject to rebound[3]. Rebound is the development of behavioural patterns that are more energy-intensive. It is a common phenomenon that leads to a discrepancy between expected and effective energy consumption after energy efficiency improvements. The presence of rebound has been shown through multiple studies (Hens, 2010). The JRC published a report on heating and cooling (Pardo, 2012) and referred to a study on indoor temperature changes in residential buildings across the UK. They indicated a 3°C increase in de period 1999-2009. The European Commission issued a study on ways to address the rebound effect (Maxwell, 2011).emphasize the importance of the rebound effect. The study request that policy makers should anticipate rebound when developing strategies to achieve certain energy saving targets.

The rebound-effect can be divided in two types, direct rebound and indirect rebound.

The direct rebound effect means that increased efficiency and associated cost reduction for a specific product or service can result in an increased consumption because it becomes cheaper. It is commonly related to heating energy consumption, i.e. the indoor temperature settings increase as it becomes less energy intensive to heat up the building and so the inhabitants opt for more comfort for the same price. The same applies for cooling. Table 2 results from research of the EEA and indicates the size of the rebound effect. As reported by the EU project Remodece (REMODECE, 2009), another example of the direct rebound effect is that more efficient appliances are replaced by bigger appliances or higher lighting levels, lowering the estimated potential energy savings. (Nassen, 2009) report the impact of direct rebound based on previous studies. Numbers of 8-12% higher energy consumption compared to estimates where achieved for heating in the US, 13% for cooling. Reported values for Austria were considerably higher, i.e. 20% to even 30% difference between estimated and actual savings. A recent

[3] Whether rebound is a separate effect or indirectly incorporated in the psychological adaptation is an open discussion. As stated by Rehdanz (Rehdanz, 2007) and Sardianou (Sardianou, 2008) there is an effect of price on the temperature settings in residential buildings.

working paper of Schleich (Schleich, 2014) indicated 6.5% energy increase compared to estimates for lighting.

Table 2: Estimated size of rebound effect by technology (EEA, 2013)

Sector	End use	Size of rebound effect
Residential	Space heating	10–30 %
Residential	Space cooling	0–50 %
Residential	Water heating	10–40 %
Residential	Lighting	5–12 %
Residential	Appliances	0 %

Indirect rebound adverts more to the given that the decrease in the households` spending for energy leads to an increase in spending for other activities on another scale that also demand energy, like travelling (Hens, 2010; EEA, 2013).

Rebound effect and fuel poverty are to be considered separately. As this is outside the scope of this study, but relates to a non-negligible amount of EU citizens, the current study refers to a 2011 report on fuel poor families in the UK (Jenkins, 2011), a recent publication of the climate report on fuel poor policies in the UK and France (Tyszler, 2013) and an in-depth discussion of 2009 (Pett, 2009) for further detail on the matter.

2.3 BUILDING RELATED MEASURES

The above overview has indicated a range of building related measures, inherently connected to the building: heating and ventilation and their control, building envelope characteristics and lighting. As described in chapter 2.1.2, a neutral, quasi-static calculation methodology in line with the European Standards ISO 13790 - EN 15603 will be used to evaluate the impact of these measures. The calculation methodology has been adapted to account for:

- Building and time averaged indoor temperatures
- Electricity consumption for lighting
- Outdoor temperatures and solar radiation

A range of simulation cases has been defined, that are evaluated using the quasi-static evaluation tool. These cases are selected to cover the broad diversity of residential energy profiles:

- non-building related conditions:
    - A cold, moderate and warm climate
    - A single family house and an apartment unit
    - A retired couple with reduced outdoor activities and a family with 2 kids at school and parents working outdoors.

  The different conditions are described in detail in ANNEX A.

- building-related conditions
    - The building envelope quality defined by the insulation and air tightness of the building shell;
    - The type of heating system defined by the heat production system, the emission system and intelligent control options;
    - The type of indoor temperature control installation;
    - The type of ventilation system and control;
    - The lighting installation

  These building related measures are described in detail in ANNEX C.

The results of the so-defined 36,288 simulations are presented in graphs showing the global cost versus the primary energy use. Such presentations allow applying a Pareto evaluation to select the cost optimal parameter combination.

Through highlighting specific input cases, the relative importance of specific measures on energy use and global cost can be visualized.

The below section presents the impact analyses for several building related measures. To give a clear view on the impact of an individual building related measure, the analysis in chapters 2.3.1 to 2.3.6 (and the resulting graphs) all start from a specific ‘reference’ setup, i.e.:

- A building envelope quality in line with the current minimal energy performance requirements in the specific regions;
- A gas condensation boiler with radiators (temperature regime 50/40°C) without outside temperature compensated control;
- Use of thermostatic radiator valves (no other indoor temperature control system);

- A ventilation system using mechanical extraction for the cold and moderate climate region. Natural ventilation is the only ventilation option considered for the warm climate region;
- A lighting installation using halogen spots.

In chapter 2.3.6, the combinations of measures will be displayed and the Pareto-front (with the cost optimal combination of measures) will be analysed in detail.

2.3.1 Outside temperature compensated control

The weather naturally has the largest influence on the heat demand of a building. Changing constantly, so does the heat load required to warm up a house. An intelligent electronic controller in the heating system can pro-actively adjust the supply of heat to keep it at exactly that point by detecting changes in the weather conditions outside. The control unit gets its signal from an outdoor temperature sensor (placed on the shadow side of the building). The sensor registers the actual temperature and the electronic controller adjusts, if necessary, the heat supply (flow temperature) to reflect the new conditions.

Outside temperature compensated control improves the efficiency of a (gas) condensation boiler when working in partial load conditions, which is particularly relevant in moderate to cold climate regions. We specifically consider this intelligent control technology because of its low additional investment cost (compared to (gas) condensing boilers without outside temperature compensated control).

Figure 2 gives the results for the use of outside temperature compensated control for a gas condensing boiler in comparison with the reference situation (results for a 4-person family, living in a single family house in a moderate climate).

Outside temperature compensated control results in a lower yearly primary energy use, as can be expected. In the case of the condensing boiler, the extra energy savings make up for the additional investment cost. This is not always the case for the non-condensing boiler, which is due to the higher additional investment cost to implement outside temperature compensated control[4].

The impact of outside temperature compensated control depends on the total heating demand and therefore increases when applied in colder regions and in case of a higher occupancy rate (resulting in more heating hours in case of an indoor temperature control system). Figure 2 illustrates that, although still a cost optimal measure, the impact of outside temperature compensated control diminishes when considering a more energy performant building envelope in a moderate climate. In a warmer climate, investing in outside temperature compensated control becomes superfluous once a building envelope quality close to passive is reached.

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[4] We consider an additional cost of 302 € to implement the use of outside temperature compensated control for a non-condensing boiler, compared to 60€ for a condensing boiler

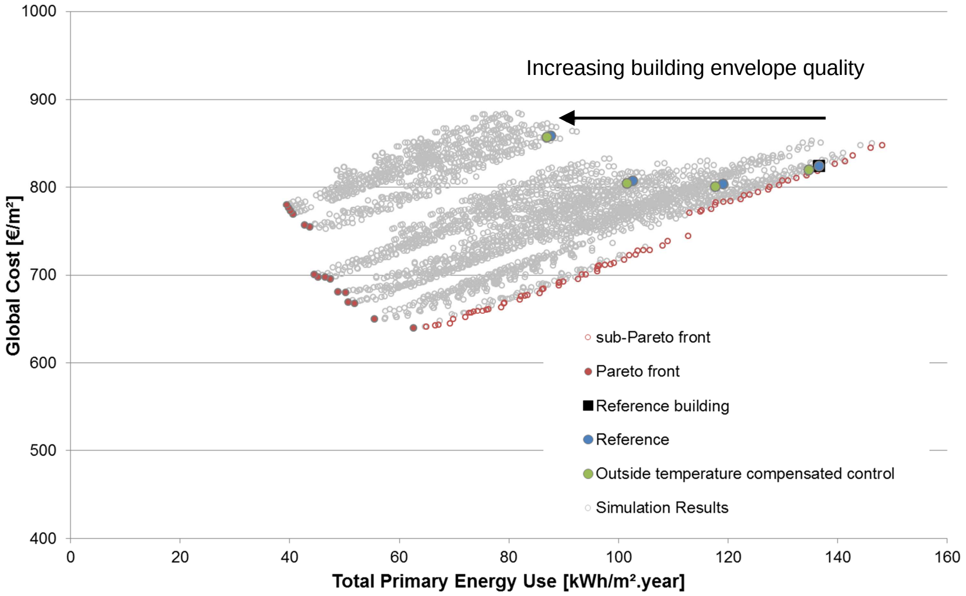


Figure 2: Impact of outside temperature compensated control for a gas condensation boiler – moderate climate / 4-person family / single family house for 4 levels of building envelope quality (BAU to the equivalent of a passive dwelling)

Outside temperature compensated control is considered an intrinsic part of heat pump technology for heating purposes and is therefore not considered as a separate intelligent control measure for this technology.,

2.3.2 Indoor temperature control

Figure 3 gives the results for the different indoor temperature control options in comparison with the reference situation (results for a 4-person family, living in a single family house for a cold, moderate and warm climate). The results are given for the 4 building envelope quality levels considered in this study.

Installing a central temperature sensor clearly pays off when compared with the reference situation, i.e. thermostatic valves for all radiators. Making use of system that controls indoor temperature for each room individually naturally results in an even higher energy saving. This additional energy saving can in some cases outweigh the (substantial) additional investment cost for this type of system (compared to a central thermostat), making it the most cost optimal option. This is however more likely in case of a high heating demand, i.e.: a cold climate, a standard (not particularly energy performant) building envelope, a large dwelling and/or a high occupancy rate (resulting in more heating hours). Vice versa, it will be less likely in case of low heating demand.

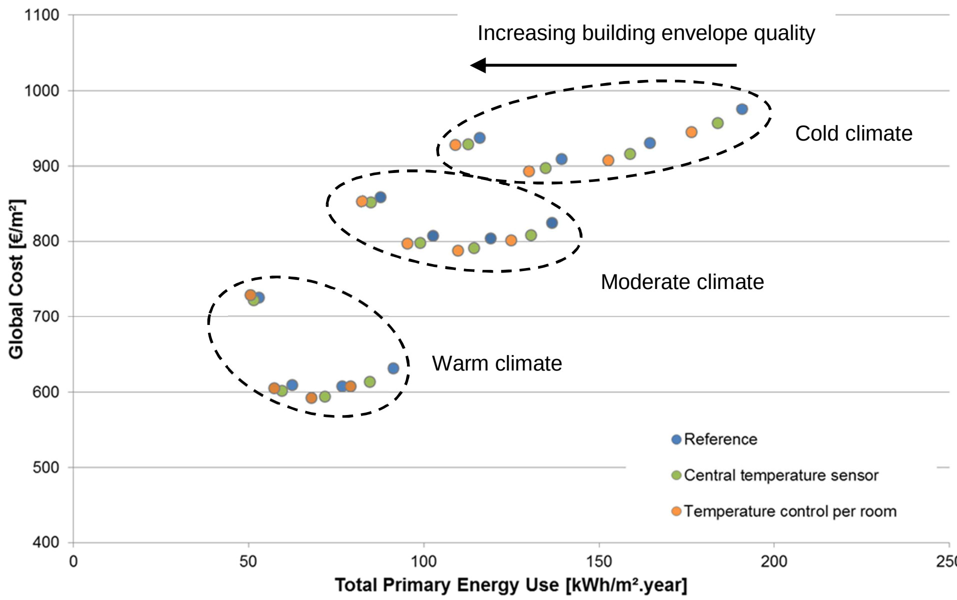


Figure 3: Impact of temperature control options – 4-person family / single family house for 4 levels of building envelope quality (BAU to the equivalent of a passive dwelling)

2.3.3 Ventilation

As illustrated in Figure 4, both demand controlled ventilation and a full presence detection system (making use of a CO2 sensor) are more cost optimal variations of a standard mechanical extraction ventilation system (the latter being the most interesting option). Both variations result in a lower primary energy use (due to lower heat losses through ventilation) and in a lower global cost in comparison with the reference system.

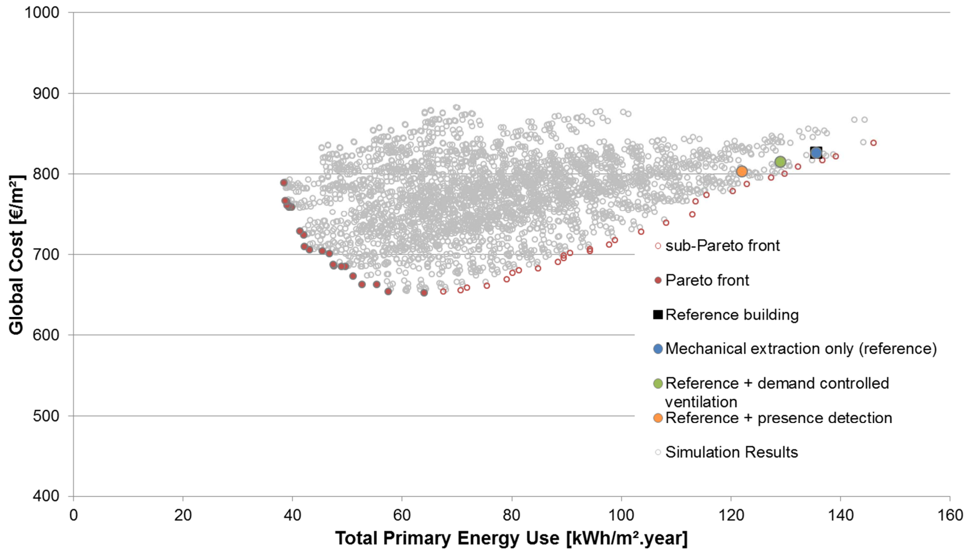


Figure 4: Results for mechanical extraction ventilation variations – moderate climate / 4-person family / apartment

The results as depicted in Figure 5 show that the energy saving potential of a presence detection system is even larger for a ventilation system with mechanical supply and exhaust. The additional investment is more than paid back by the resulting energy savings, making this the cost optimal option for this type of ventilation system.

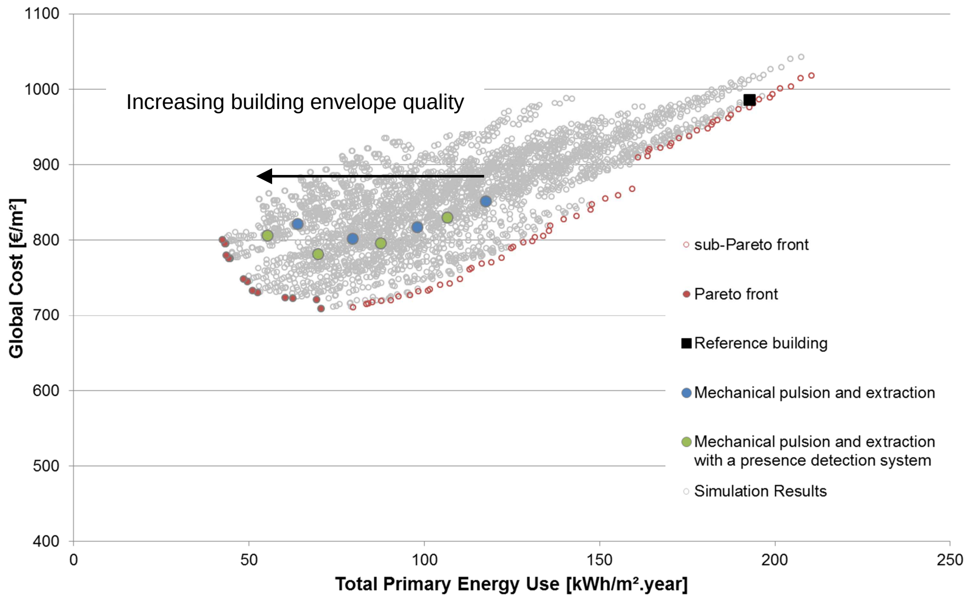


Figure 5: Idem Figure 4, but for a ventilation system with mechanical pulsion and extraction (blue point) and a similar system equipped with a presence detection system (green point) - cold climate / 2-person family / apartment

Analogues with some of the intelligent control for heating, the impact of intelligent control for ventilation is function of the total heating demand of the building and becomes more interesting in cold climate regions and for larger dwellings.

The impact of intelligent control for ventilation is not directly linked to the building envelope quality. Different from the intelligent control measures regarding the heating system, the savings potential of intelligent control for ventilation remains largely unaltered no matter the building envelope quality. We can conclude that the current evolution towards more stringent regulation regarding building envelope quality will result in a larger focus on intelligent control for ventilation.

2.3.4 Lighting

As can be deducted from the results (Figure 6), the impact of the type of lighting installation on the total primary energy consumption of a dwelling is not to be underestimated. Although the cost of LED's is still considerably higher when compared with halogen spots (or even compact fluorescent lighting), this is clearly offset by the much larger number of lighting hours and the energy savings realised due to the low power (and therefore energy consumption) of LED lighting.

The electricity consumption for lighting is not linked to the building envelope quality. The savings potential of lighting remains largely unaltered no matter the building envelope quality. An energy efficient lighting system can help to bring further down the energy costs in dwellings with a high building envelope quality (e.g. passive houses). Even more, LED's or other lighting systems for which energy losses through heat dissipation are minimal, will become essential in dwellings with a high building envelope quality if only to reduce the risk of overheating.

These results can be considered as conservative since an expected further decrease in cost price of LED's was not taken into account in the financial calculations.

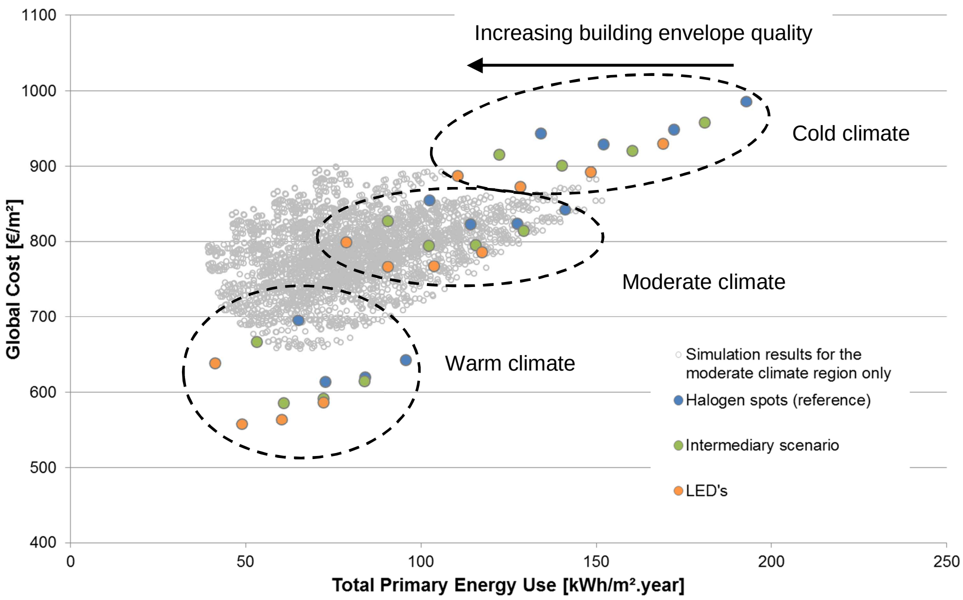


Figure 6: Impact of lighting installations – 2-person family / apartment for 4 levels of building envelope quality (BAU to the equivalent of a passive dwelling)

2.3.5 Home Energy Management Systems (HEMS)

Home Energy Management Systems (HEMS) can be divided in three groups. In-Home Display systems (IHD`s) display energy consumption data in real-time, but do not directly control the appliances. The Home Automation (HA) systems comprise the stand-alone systems that include sensors and an information display communicating with these sensors and potentially the utility meters. These HA enable control with one or more devices. The last group is composed of networked systems that have a communication between the HEMS and the energy utility, making demand response possible.

IHD's are currently not considered in building energy performance evaluation. It would also be a challenge to develop a calculation methodology to account for the aspects related to change in energy consuming behaviour only, without any feedback towards devices' control. Therefore, IHD's are considered separately in the present study and categorized as technology to support behaviour change, i.e. they are considered a behaviour related measure.

Also for the other categories of HEMS, energy savings are hard to estimate. The use of intelligent control of heating, cooling or ventilation devices, as a kind of HEMS, is embedded in the energy performance evaluation tools in a general way. Specific controls that claim to achieve more savings could demand for being recognized as such. An example is intelligent demand-controlled ventilation. In general such device controls, or a combination of them, are considered HA. However, this is still far away from the synergy that is expected to be achieved through overall energy management in residential buildings. Lack of standards, no consistent embedded saving methodologies and too limited data are just a few of the factors that currently delay the development of a general calculation methodology to be embedded in the energy performance calculation tools.

Systems reacting to the energy grid are not yet incorporated in building energy performance evaluation legislation in Europe. However, the draft of the EN 15603 proposes the use of a dynamically varying (quarter of an hour values) value for the energy conversion factor between primary energy and electricity. If this evolution is to be implemented in the near future, the market penetration of intelligent and so called smart grid ready technologies will further increase. The relevance of policy and regulation at grid level is also indicated by Navigant Research. They recently published a report on HEMS (Strother N., 2013, Home Energy Management: research report) and pointed the drivers to be related to home occupants (desire to reduce the bill and/or be greener), as well as related to external factors such as mandates of public utilities and service providers. Furthermore, they also emphasize that the move towards smart grids and the implementation of variable pricing schemes are expected to boost the demand for HEMS.

Currently, the effective number of HEMS as real building energy management systems is limited in residential buildings. At present, as Van Dam et al (Van Dam S, Bakker C., Buiter J. 2013, Do home energy management systems make sense? Assessing their overall lifecycle impact, Energy Policy, vol. 63, pp 398-407) state, the implementation of this type of HEMS is limited to field tests. Savings are therefore difficult to generalize. Van Dam studied the potential pay back for 3 different types of HEMS. The actual energy management system, as an advanced HA, showed to hardly reach a return on investment in the 5 year span they considered relevant. The main hurdle is the high investment cost. The extensive report of Waide (Waide et al., 2013) and the HEMS-study of Fraunhofer US (LaMarche et al., 2012) confirm this conclusion: the unclear return of investment is a major barrier preventing large scale deployment. The extensive market research done by the Fraunhofer researchers revealed limited actors providing HA with multiple functionalities end of 2012. Over a year after the Fraunhofer study, Waide reports that still limited additional energy saving data are available.

In the present study the best assumption for the energy saving potential of HEMS is therefore to consider the combination of intelligent controls for heating and ventilation and analyse whether this results in a cost optimal solution with maximum savings for each of the building and user scenarios. Detailed analyses of the results reveal this is the case considering cold and moderate climates. In a warm climate however, the combined investments in the considered intelligent control technologies can no longer be paid back by the resulting energy savings on heating due to the overall lower heating demand.

2.3.6 Cost optimal combination of building related measures

In the above paragraphs, attention was given to the impact of an individual building related measure by comparing its impact with a specific ‘reference’ setup (chapters 3.3.1 to 3.3.5).

By combining the right individual measures a cost optimal solution can be attained resulting in the highest primary energy saving while minimising the global cost.

Figure 7 visualises the Pareto fronts for several simulation cases. The cost optimal solutions (as indicated in the graph) are dominated by the following building related measures:

- A ground-water heating system in combination with floor heating;

- A ventilation system using presence detection (CO_2 sensors) to control the mechanically extracted ventilation flow
- A LED based lighting system
- The cost optimal building quality level depends on the climate region and type of dwelling considered. For cold climate regions, the cost optimal insulation value for floor, wall and roof revolves around 0.22 W/m²K.
  For moderate and warm climate regions, this cost optimal depends on the type of dwelling. Apartment units (with a higher volume/heat loss surface ratio) require a lower investment cost to reach a certain insulation level.

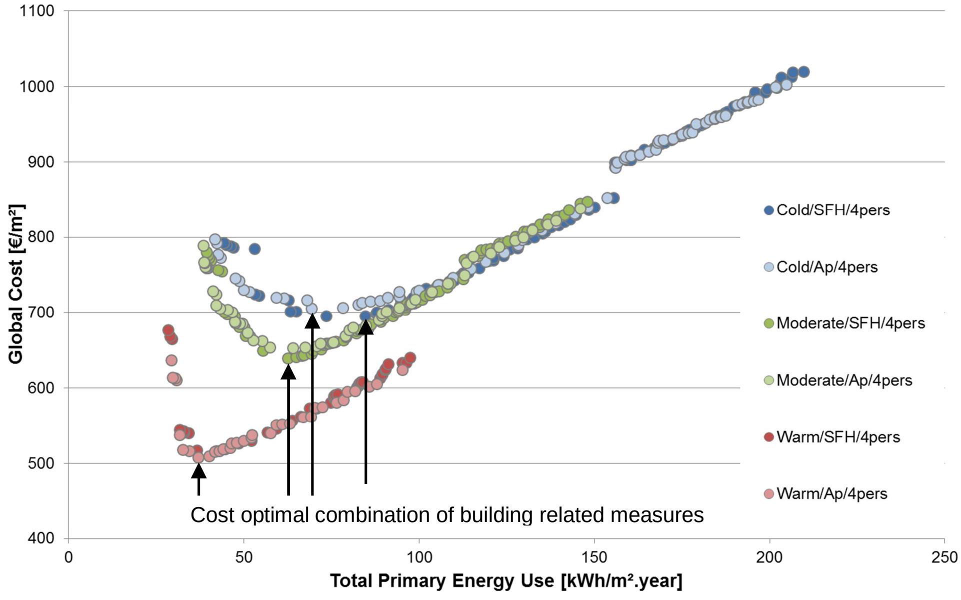


Figure 7: (Sub)Pareto fronts for both a singly family house (SFH) and an apartment unit (Ap) inhabited by a 4 person family working/going to school (4pers) or a 2 person family with limited outdoor activities (2pers) in a cold, moderate and warm climate region

2.4 BEHAVIOUR RELATED MEASURES

Studies have shown that changing residents' behaviour has the potential to reduce energy consumption up to 20 % (Darby, 2006). The **occupants` knowledge and attitudes towards energy consumption** is a factor to be considered. This correlates with their **motivation and willingness** to decrease the energy consumption. Vassileva (Vassileva, 2011) defines motivation as environmental or economical: low income households tend to have a financial incentive, i.e. lower their energy cost, while in high income households environmental issues would be more motivational since money is less an issue.

The particular motivation seems to depend on the individual situation of the households. Next to costs and environmental attitude, Ek and Soderholm (Ek, 2009) define a third type of motivation, namely social interactions between households. Hargreaves et. al. (Haggreaves, 2010) add a fourth and fifth to the row, namely the desire to gain more information about their energy-use and technological interest. It should be noted that in general people are not, or little, willing to change habits they find indispensable in their life style. For example, sauna-use in Finland: interviews state that, although they realise the high consumption of a sauna, the Finns are not prepared to give up this habit (Karjalainen, 2011).

Clearly, the influence of the occupant of a building, its characteristics, behaviour, knowledge and motivation is not to be underestimated. The feature of a household is not a factor that can be gravely influenced, but a fixed boundary condition. The potential to decrease energy usage can be found in users` behaviour and knowledge. The structure of a household could be used as a starting point to alter user behaviour and increase knowledge and motivation.

Measures to achieve a change in behaviour and raise awareness could include awareness campaigns, energy labelling, but also feedback through smart metering, more informative billing and in-home energy consumption displaying systems.

In the below section the emphasis is on technological solutions for behavioural change, independent of device control. The most common approach to do so is by means of In Home Display's (IHD's) that confront inhabitants with their energy consumption. Abrahamse (Abrahamse, 2007) emphasizes the importance to incorporate tailored feedback. Hargreaves (Hargreaves, 2010) puts it clear: smart energy monitors in whatever format are only as good as the household, social and political contexts in which they are used.

The below section will discuss the means to provide feedback, the encountered effects and the barriers that exist for effective implementation.

2.4.1 User behaviour through feedback

The current invisibility of domestic energy consumption is one of the most important causes of energy waste. In order to improve energy-conscious behaviour, energy-users need accurate information about their consumption. For people to change their behaviour, they need to understand the power requirements of appliances and the correct way of using them. Energy consumption should become a clear, dynamic and controllable process (Coleman, 2012; Darby, 2006; Faruqui, 2009; Hargreaves, 2010). An IHD makes the consumer aware of the energy consumption, enabling him to make manual adjustments to obtain energy savings (Waide, 2013). When implemented correctly, in-home displays or other direct information systems could induce prompt action and result to effective changes in behavioural patterns (Coleman, 2012; Hargreaves, 2010). The Intelligent Energy Europe project ESMA (Beama, 2010) proposes feedback as part of a learning process. When taking in information concerning their energy use, people gain understanding by interpreting the events. This leads them to change their behaviour in a particular way

Two main types of feedback can be distinguished:

> **Indirect feedback** is feedback that has been processed before reaching the consumer. This implies that the end-consumer has no direct access to actual consumption data and always responds to previous consumption behaviour, even though this could have changed already. Indirect feedback demands a certain level of interest and commitment to consult the data regularly, because the user needs to switch on the specific medium channel to receive or visualize the feedback. A form of indirect feedback could be feedback received frequently through informative billing containing historical and comparative information on energy consumption. Another example is regular feedback through websites, e-mail, sms… (Darby, 2006; EEA, 2013)
>
> **Direct feedback** is real-time feedback about consumption and costs available at any time. Direct feedback makes it possible for a consumer to continuously and immediately see what the consumption is at that time and respond accordingly, without having to switch on an optional feedback device. Direct feedback could exist of information received via the households` computer, or via smart meters in combination with an In-Home Display (IHD). Also pre-payment systems or time related pricing can be seen as a form of direct feedback given they are providing information on status (Darby, 2006; EEA, 2013)

Additionally, Darby proposes a few other types which will not be elaborated on in this overview, e.g. inadvertent feedback by association or infrequent feedback by professional energy audits (Darby, 2006). Ellegard and Palm (Ellegard, 2011) suggest time diaries as a way to understand energy-related activities in a household. Time diaries can be seen as a reflective tool to discuss a family`s daily routine in relation to their energy consumption. This further provides a basis to discuss how these activities can be changed, taking into account the values and routines a family finds indispensable to maintain a good life.

2.4.2 Reported effects

Research and pilot programs demonstrate that direct feedback has the potential for savings up to 5-20% on household energy consumption, while indirect feedback shows a potential reduction of 10% at maximum. Darby confirms direct feedback to be the most promising tool to reduce a households' energy consumption (Darby, 2006). Direct feedback can provide information that contributes to the planning of daily routines and the purchases of new equipment. Although it is rare that people plan entirely new routines or change certain particular rhythms of the household. (Hargreaves, 2010) In general people won`t change behaviours they look upon as essential in their daily lives. But the increased awareness, reported by many researchers, will indirectly influence future choices.

The EEA proposes a combination of direct and indirect feedback as being the most successful. In that case the consumers` awareness on energy consumption can be increased, while maintaining the motivation to keep them actively engaged in reducing energy consumption (EEA, 2013). Wood and Newborough (Wood, 2003) compared the impact on energy use for cooking using direct feedback versus having provided antecedent information. The achieved differences where substantial: 15% versus 3% respectively.

Table 3: Achieving energy efficiency through behaviour change: what does it take? (EEA, 2013)

Intervention	Range of energy savings
Feedback	5–15 %
Direct feedback (including smart meters)	5–15 %
Indirect feedback (e.g. enhanced billing)	2–10 %
Feedback and target setting	5–15 %
Energy audits	5–20 %
Community-based initiatives	5–20 %
Combination interventions (of more than one)	5–20 %

Studies show the need to develop ways to influence end-users before, during and after using appliances (Wood, 2003). Feedback should build durable knowledge that induces behavioural change. In order to form a new persisting durable behaviour, it needs to be formed over a period of three months or longer. Continuous, if not constant, feedback is needed to achieve long-lasting results, keep consumers interested and encourage other further changes (Darby, 2006; EEA, 2013). However a 15-month pilot study with IHD`s conducted by Van Dam et.al {Van Dam, 2011) shows that the initial electricity savings of 7,8 % after 4 months could not be sustained in the medium-to-long term.. The impact of the initial savings reduced significantly for all participants, those who retained the IHD and those who did not. Van Dam, as well as Nilsson (Nilsson, 2014) concluded that IHD campaigns should be targeted at a specific niche of motivated consumers in order to achieve savings that are still substantial after longer periods. However, the addition of new appliances might demand for an update in the IHD as energy monitors mainly curtail existing behaviour. Renewal of appliances should also be embedded in the IHD software in order to avoid rebound effects.

However, time does not remove all effects of energy saving. A living lab study of a home energy management system, conducted by Schwartz et.al. (Schwarz 2013), led to the conclusion that the participants over time developed an understanding of their overall household energy consumption on different moments, as well as a better knowledge of basic information like tariffs set by the energy provider. The participants tended to reflect on their previous energy consumption in order to link certain energy consumption to particular activities in the past. Because of the ability to see the real-time consumption, the consumers developed the ability to make better decisions concerning their energy-usage. Another action the participants developed was the comparison of different types of appliances and different appliances in the same category.

An important remark regarding the generalisation of the reported energy savings is that mostly the IHD's were allocated to families with an interest in participating. Only a minority of investigations targeted the average consumer with potentially limited interest in energy savings. However, general awareness raising regarding energy and increasing energy prices will increase the knowledge and motivate people to save energy and accept the tools provided to support and personalize that.

2.4.3 Barriers

Most of the tested systems are feedback systems, whilst limited effective home energy management systems are available today. Cost of such extensive management systems can be seen as one of the main barriers. But even for introducing feedback systems in buildings through direct or indirect feedback, a range of barriers is present:

- Radical changes are rejected (Vassileva, 2012). In general, people are not, or little, willing to change habits they find indispensable in their life style. Potential for changing is to be found particularly in low-cost behaviours (time, effort, convenience) (Abrahamse, 2007).
- There is a need for further information between psychological barriers and the provided information (and suggested actions). The findings of such research could lead to new and more effective designs of user feedback.
- The rebound effect minimises the expected impact of the measures. Correctly estimating this effect is a challenge.
- Most users lose interest after a few months. Software developments should anticipate a decreasing interest.

3 CONCLUSIONS AND CLOSING REMARKS

The present study clearly shows the importance of user behaviour and the potential of specific technologies in reducing the energy consumption of a residential dwelling. Due to policy and regulation, devices have become more efficient in the last decade. However, numbers on energy consumption across Europe show an increase in total energy consumption for residential end consumers. The growing number of appliances and increasing use of multi-media and electronic entertainment combined with the decreasing number of people per household are decisive parameters.

The analysis of the electricity consumption due to appliances, entertainment and alike emphasizes the large variation across Europe, both in number of devices as well as in their energy consumption. The global cost and effective energy savings potential resulting from selected technological solutions for heating and ventilation is shifted due to an increase or decrease in internal heat gains. However, the impact does not affect the optimal selection of technologies for heating and ventilation. These optima have been calculated using a standard calculation tool for energy performance evaluation of residential buildings. The selected tool is the Flemish one, which is in line with the description of the quasi static calculation methodology of ISO 13790 - EN 15603. In order to provide results that show the optima for a wide variation of users, 2 different family types, 2 dwelling types and 3 climatic zones have been defined. Simulations are performed for 4 different building envelope qualities, i.e. a combination of air tightness levels and insulation quality.

The tool has been adapted to account for user impact analysis through a variation in indoor temperature settings and electricity consumption for lighting. Furthermore, the outdoor climatic conditions have been varied to estimate the impact in 3 different climatic zones.

Different technological measures have consequently been tested to evaluate their potential given different user profiles. For each of the technologies, the simulation results have been presented in a graph comparing the primary energy consumption with the total global cost, each per square meter floor area. A Pareto front in these graphs shows the optimal combinations. For the simulated technologies, the following conclusions could be drawn:

- The use of **outside temperature compensated control** is one measure for which the extra energy savings make up for the additional investment cost. Its impact depends on the effective heating hours and therefore becomes substantial when applied in colder regions and in case of a higher occupancy rate (in case of an indoor temperature control system). Although its impact is linked to the number of heating hours, investing in outside temperature compensated control becomes only superfluous when considering a building envelope quality close to passive in a warm climate region.
- Installing a **central temperature sensor** clearly pays off compared to the use of thermostatic valves only. The extra energy savings generated by using a system controlling indoor temperature for each room individually will in some cases outweigh its (substantial) additional investment cost, more specifically in cold climate regions and in (large) dwellings with a standard (not significantly energy performant) building envelope and a high occupancy rate.
- **Demand controlled ventilation**, including the use of a presence detection system in the form of CO2 sensors, results in both a lower primary energy use and lower global cost. Since ventilation losses are not directly linked to the building envelope quality, the savings potential of intelligent

control for ventilation remains high, even for building with high levels of building envelope quality (insulation and air tightness).

- With (new) energy performance in buildings regulation continuously focussing on reducing energy consumption for heating and sanitary hot water production, the relative share of other domestic energy consumers becomes larger. Although the investment cost of **LED's** is still considerably higher when compared to a business as usual type of investments, the longer (expected) lifetime and lower energy consumption results in a significantly lower global cost.
- **Home Energy Management Systems (HEMS)**, here considered as a combination of intelligent controls for heating, ventilation and lighting, consistently results in the lowest primary energy use for the lowest global cost.

To impact the energy consumption of users, an additional technology is available: In Home Displays (IHD's). These IHD's provide the occupants with direct or indirect feedback on their energy consumption. A broad variety in level of detail is available, and different methods of motivating the end user are implemented. Reported savings are up to 20%, so the effective potential of energy saving through behavioural adaptation is not negligible. However, studies have reported a decreasing saving as function of time. Research should focus on the means and methods to provide tailored feedback and anticipate the fading interest as function of time.

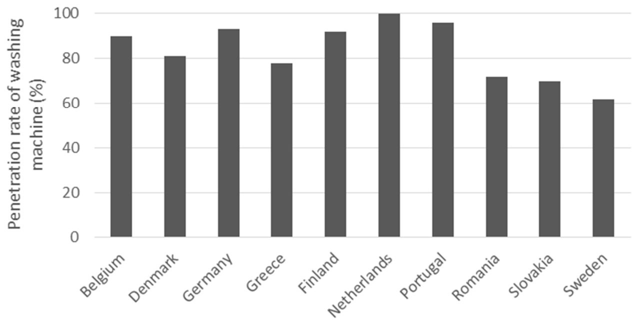
Based on the present study, it can be concluded that upcoming intelligent control systems such as various types of Home Energy Management Systems (HEMS) have convincing energy saving potentials. Their saving potential is larger than the sum of the savings of each of the intelligent controls on heating, ventilation and others.

The fact that innovative intelligent control systems can currently not be valorised within the official energy performance evaluation tools of the different EU member states clearly slows down both the further development and the large scale deployment of these promising energy saving measures. Stimuli regarding cost reduction schemes, new modes of interaction and automated personalized feedback could further open the market.

ANNEX A ENERGY CONSUMPTION THROUGH APPLIANCES IN THE EU

Washing machines

In 2011, 80% of the washing machines sold in the EU were label A devices, 8% had and A+ label and 7% A++ or better. 5% was B or less (Bertoldi, 2012). Market penetration rates for washing machines are shown in the chart below (Odyssee, 2013). The data in the chart reveal that the majority of EU households have a washing machine. Penetration levels are lower in some Eastern European countries. The data reveal the 2012 situation and divide the washing machine stock by the total number of occupied single and multifamily dwellings.



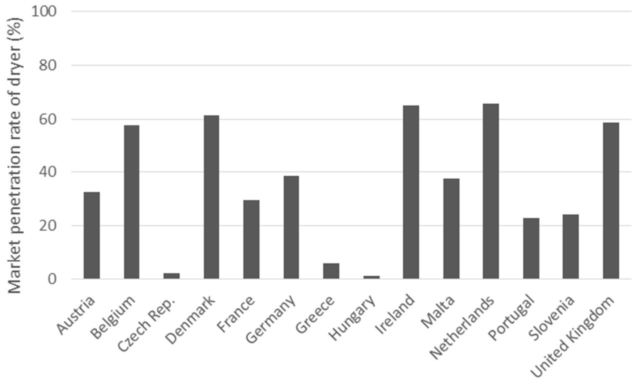
The energy consumption of a washing machine depends on the intensity of use, the selected cycle, the potential overloading and the appliance characteristics. The CECED study (CECED, 2001) calculated some projections on energy consumption with ranges between 0.92 kWh to 0.37 kWh per cycle of 2.7 kg. CECED estimates the average number cycles per household to be 224.

Dryers

Dryers are energy consuming devices. Most models are energy label B or even C, with consumptions above 1.2 kWh per cycle for 3 kg load. The worst available on the market in 2006 consumed 2.9 kWh per cycle for 3 kg of laundry (Bertoldi, 2012). Dryers energy label A+, mostly heat pump dryers, reduce the consumption to 0.7 kWh per cycle of 3 kg.

Data from (Bertoldi, 2012) shows that of those households with a dryer, the percentage with an A-labelled device was low: in Switzerland almost 16% had an A-labelled device, while large countries with considerable GDP (Gross Domestic Product) as Germany and the Netherlands, showed market penetration rates below 5%.

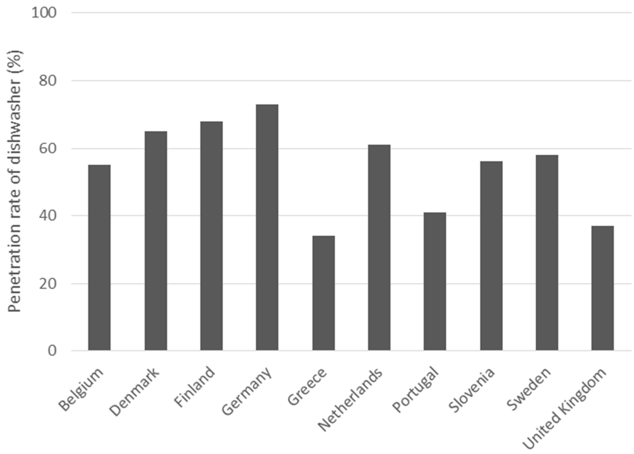
While washing machines are installed in most households, the percentage of households with a dryer is substantially lower (Odyssee, 2013). Dryers remain a luxury item or an item consciously not bought because of environmental reasons. Data in the below graph represent the 2008 situation.



Dishwashers

Dishwashers are increasingly popular in households across Europe, with a clearly higher number of dishwashers in higher income homes (Mills, Schleich, 2009). Their usage accounts for 3% of the energy consumption on average. The low number, however, might be misleading due to the low market penetration rate (Odyssee, 213). 2008 data revealed very low penetration rates for most eastern European countries. 2011 data are less complete, but show an increase in most EU countries. The energy consumption is strongly affected by the selected program.

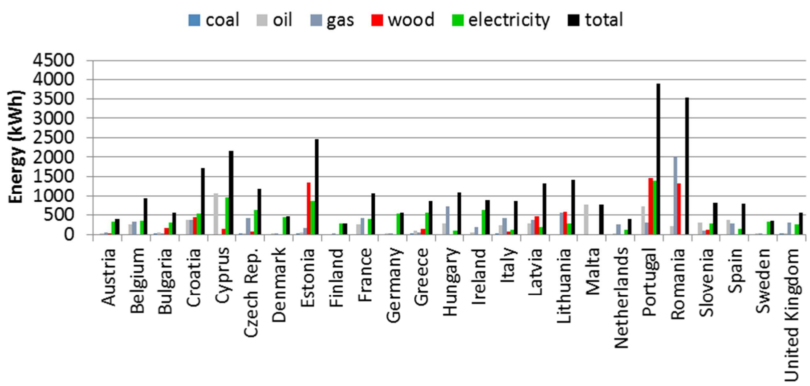
Energy labelling for dishwashers is in place since 1997 (EC, 1997), with a revision in 2010 (EC, 2010a). The directives have had a major impact: appliance shops offer almost no label B or lower ranked dishwashers. The most efficient devices, with A++-labelling, report yearly energy consumptions of 188 kWh for a typical 280 cycles. Average lifetime of dishwashers is 9 years, so some older devices might still be in operation. A typical 2005 dishwasher consumes 305 kWh on a yearly basis, using 15 litres of water.

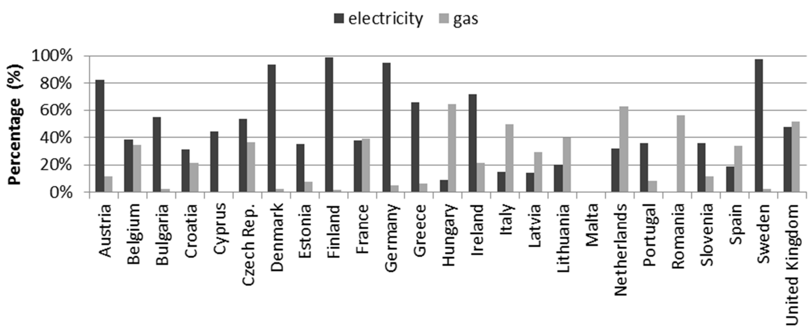


Dishwashers take a growing share in household electricity use. However, when fully loaded, they consume considerably less water, and thus energy to heat that water, compared to using the sink. A test with Europeans from different countries (Stamminger et al., 2003) revealed that in close to all tested cases, the energy consumption and water usage of using a dishwasher was clearly lower: a test with 113 persons showed that the average consumption to clean 12 place settings of dishes was measured to 103 litres of water, 2.5 kWh of energy and 79 minutes time compared to the consumption of 15 litre of water and 1,05kWh of energy for the high efficiency dishwasher. Cultural differences across Europe were shown, with especially Spain and Portugal having large consumptions of both water and energy.

Cooking appliances

Energy use for cooking is shown to be very diverse in energy source as well as amount of energy used. The graph below shows the household energy use for cooking, both split per energy source and as a final number (Odyssee, 2013). Especially Portugal and Romania show a substantially high energy use. Electricity and gas together take the highest share. The type of cooking appliance used strongly depends on cooking traditions and is thus culturally determined. As can be expected, comparing with the household sizes reported for 2008 in the Eurostat database, there is a correlation between household size and energy used for cooking.



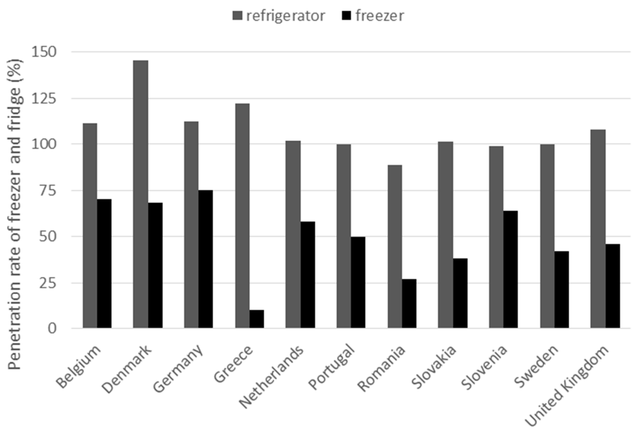


Cooking devices can have substantial differences in efficiency. Induction plates are known to be highly efficient, gas and traditional electrical plates lose energy in the form of heat emission to the indoor environment. An average consumer microwave has an efficiency of 64%, the remainder is lost through heat removal, DC/AC conversion, lights and turntable motor. Steam-cooking food is more efficient than many other technologies, but the required appliances are expensive.

No data was found on the frequency of cooking and eating at home across Europe. Nor on the actual energy consumption of preparing a specific meal. According to the previously mentioned report of Bertoldi (Bertoldi, 2012) 5% of the overall household energy consumption is used for cooking. Given the large variation in the above, it can be assumed that a representative share consumes about a 1000 kWh. They estimated the potential energy savings in Europe in the order of magnitude of 50%. The Best Available technology therefore consumes about 500 kWh.

Freezers and fridges

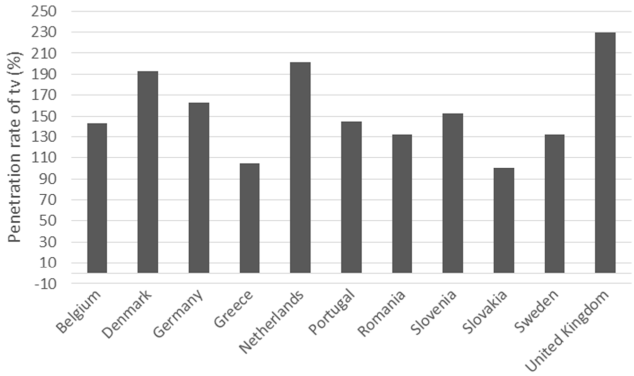
The graph below is extracted from the Odyssee database with data of 2011 (Odyssee, 2013), for some countries no market penetration rates of freezers was found. As for TV's, the market penetration rate of fridges is high. People tend to keep their old fridge in the garage or basement for extra storage. The quality of fridges installed and operating in European homes is therefore mixed. Increasing awareness and energy labelling have been proven successful: sales statistics in Europe for 2011 show less than 2% of refrigerators to be below energy efficiency class A. For freezers this is 5%.



There seems to be no tendency in increasing market penetration rates for freezers. Market research reports that mostly people opt for a combined fridge – freezer appliance rather than to buy a separate freezer (Bertoldi, 2012). Based on the numbers reported in that study, the average installed refrigerator (mixed with and without freezer) consumed 748 kWh annually. For freezers this was 728 kWh. Those data refer to the 2005-situation. Since then, cold appliances have become considerably more efficient. For comparison, a large fridge (346 litres) class A+++ consumes 75kWh in energy labelling test conditions; a fridge-freezer (215 litres, 89 litres respectively) energy label A+++ consumes 149 kWh for the same conditions. For a large freezer (237 litres) class A+++ this is 141 kWh.

Electronic devices, including multi-media

The market penetration of home entertainment electronics has been increasing in the past decade. New features, as well as a decrease in the age of first use, have increased the energy consumption related to small appliances (Bosseboeuf, 2012). The market penetration rate of TV's is given in the chart below, based on data provided through the Odyssee database (Odyssee, 2013). TV's have market penetration rates well over 100% in most European countries. A recent publication by Coleman et al. (Coleman et al., 2012) confirmed that TV is less a social happening compared to a decade ago. The time spent watching TV strongly varies over Europe. In the UK, the average person watches 28 hours a week, while in Finland this is 18 hours. The JRC analysis (Bertoldi, 2012) reports European daily average values of 231 minutes, i.e. close to 27 hours a week. The same study mentions average yearly consumptions of 173 kWh for a single TV. Eco-design criteria are expected to largely impact the consumptions, with JRC reporting savings of 80% (Hirl, 2011).



Tablets, laptops and smart phones are devices even more oriented towards individual use. According to CISCO (Cisco, 2012) the average number of consumer devices and connections per household will be increasing from 4.01 to 6.08 between 2012 and 2017 for Central and Eastern Europe and from 6.17 to 10 for Western Europe. A study by IPSOS for google (Ipsos, 2012) estimates the smartphone penetration at 62.9% in Sweden, 33.5% for Belgium and 32.1% for Portugal. The same study reveals that multimedia devices are used while performing another task or having another device on. No recent statistical data on household availability of multimedia devices is presented in the Eurostat database, the last survey results date from 2006.

The Joint Research Centre (JRC) electricity break down (Bertoldi, 2012) indicates a share of 7.2% of the residential electricity consumption for office equipment (computers, printers and alike), 1.7% for set-top boxes and 8.3% for entertainment and 4.1% for other (which might include other than electronic devices). The values are in line with the 22% of the total electricity consumption reported by (REMODECE, 2009). Hirl (Hirl, 2011) reports savings due to the Eco-Design directive in the range of 65% for set-top boxes, 60% for external power supply and 80% for home appliance stand-by in general.

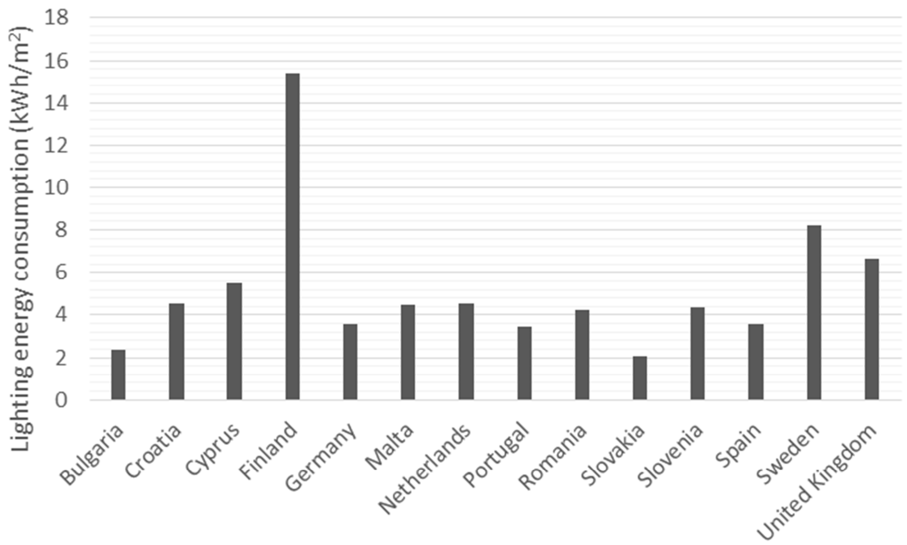
Energy usage of electronic devices is mainly when at home and awake. However charging periods are diversely spread over 24 hours. No detailed measurements of usage and energy demand are available for Europe. The most in-depth analysis is given by (Coleman et al., 2012), reporting results of a UK-only study.

Lighting

Lighting depends on the climate, building orientation and building design. A sunny day has an illuminance of 10 752 lux. Indoors this is much less: in homes, a minimum of 150 lux is required for typical daily activities. On average European households have 24 light points indoors (Van Tichelen, 2009) with strong variations across the different climate zones and depending on the building surface area. The highest number of 40 is found in the Netherlands and the lowest, i.e. 6 bulbs per household, in Lithuania.

The chart below gives the average electricity consumption for lighting in kWh per m^2. Data are extracted from the Odyssee database (Odyssee, 2013) and collected for 2008. They are consistently lower compared to the data from the International Energy Agency annex 45 (Halonen et al., 2010), but the data presented in the latter result from an analysis done in 2006 when market penetration of improved light bulbs was still low.

Finland and Sweden have the highest values. In (de Almeida and Fonseca, 2008) and the previously mentioned (Van Tichelen, 2010), the type of light bulbs was analysed for households in different European countries. These studies revealed that the number of efficient light bulbs was already increasing before 2009, i.e. when most European countries started to phase out energy inefficient incandescent light bulbs. Phase-out regulations effectively ban the manufacturing, import or sale of current incandescent light bulbs for general lighting. The regulations would allow selling of future versions of incandescent bulbs if they are sufficiently energy efficient. The IEA Information paper (Waide, 2010) on the phase out of incandescent light bulbs describes the potential alternative scenarios for a.o. Europe. It can be expected that compact fluorescent lights and LED will take the majority of the market and halogen lamps will gradually phase out by 2017. Compared to the lighting bulbs before the phase out, savings can be expected in the range of 50% to 90% depending on the actual market penetration of LED's and the effectively installed light bulbs before the phase out.



The phase out of inefficient lamps seems to be successful, in 2010 an increase of 45% was reached on the sales of compact fluorescent light bulbs compared to 2006 (Bertoldi, 2012). There is a lack of more recent data on energy consumption for lighting.

While LED is the most efficient lighting technology, almost no residential buildings are currently equipped with LED only. The McKinsey report (Baumgartner, 2012) on the worldwide lighting market reports an expected 69% market share for LED applied for general lighting by 2020. The LED market share in residential lighting worldwide was 7% only in 2011, but is expected to rise rapidly to over 70% of that market by 2020. The Belgian demonstration project ZEHR (ZEHR, 2013) will be one of the first LED only cases. Lighting requirements and energy estimates were done by lighting producer Modular revealing savings of 20% compared to the most efficient non-LED lighting, with light bulb lifetimes at least twice as high for the selected LED's compared to the best available non-LED alternatives.

A reference scenario for the mid-European moderately cold climate of Belgian is considered to be close to the case of the Netherlands, assuming an annual 4,2kWh/m^2. The BAT alternative is at 10% of that.

ANNEX B CASES CONSIDERED FOR BUILDING RELATED MEASURES

Cases are describing the ‘unchangeable’ aspects. The building related measures discussed below (ANNEX C) are evaluated for three case parameters and two or three variations per case parameter. An overview is given in the table below

Table 4: All cases considered for the building related measures

Case Parameter	Variations
Region	• Belgium (BE) • Sweden (SE- • Portugal (PT)
Family type	• 2 persons - present during work/school hours e.g. retired couple • 4 persons - not present during work/school hour
Dwelling type	• Single family house (SFH) • Apartment

Region

As a range of energy consumption are climate dependent, a variation of climates could bring new insights regarding actual impact of user behaviour on building’s energy performance as well as regarding the potential impact of building automation. The impacts are amongst others related to:

- Transmission losses
- Ventilation and infiltration losses
- Lighting energy consumption
- Energy gain from renewables
- Heat gain from solar radiation and impact of solar shading

The selected climates are therefore connected to some of the above described indoor energy consumptions. The selection is based on a combination of representative climates and availability of detailed information regarding inhabitants’ energy consumption. Sweden, Belgium and Portugal have a wide range of data in different databases and each of these countries is situated in a different climatic zone. The climate data for Brussels, Lisbon and Stockholm are widely available and will be used in this study.

The selected region is translated into variations for the following parameters:

- Average monthly outside temperature
- Insolation

Average monthly outside temperature

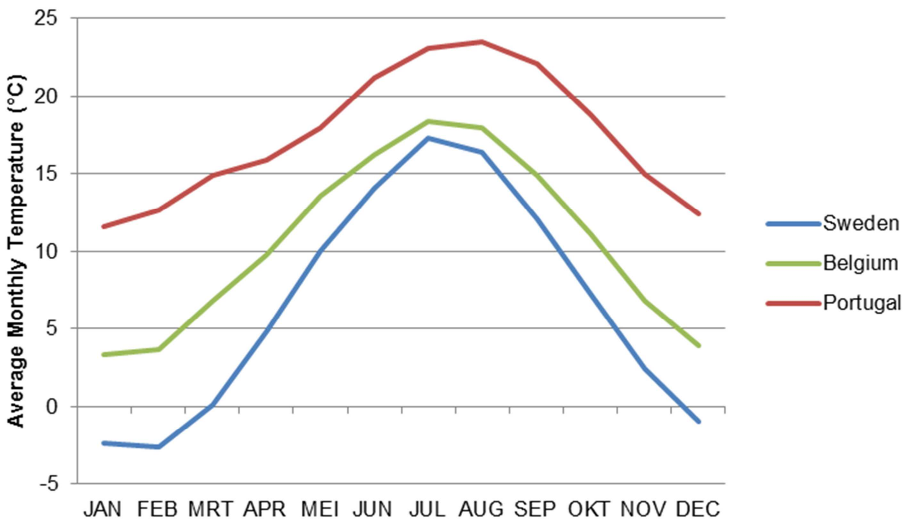


Figure 8: Average monthly outside temperature for Belgium (BE), Sweden (SE) and Portugal (PT)

Sources:

Belgium	Ukkel 1981-2010	http://www.kmi.be/meteo/view/nl/360955-Maandelijkse+normalen.html#ppt_5238195
Sweden	Stockholm 1981-2010	http://bolin.su.se/data/stockholm/homogenized_monthly_mean_temperatures.php
Portugal	Lisboa 1981-2010	http://www.ipma.pt/en/oclima/normais.clima/1981-2010/001/

Insolation

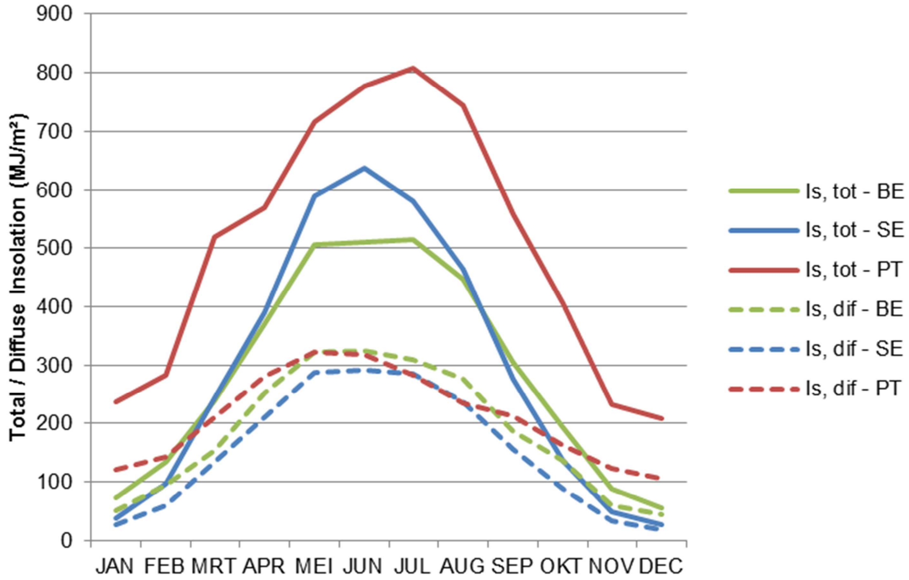


Figure 9: Average total insolation on a horizontal surface (Is, tot) and average diffuse insolation on a horizontal surface (Is, dif) for Belgium (BE), Sweden (SE) and Portugal (PT)

Source: Trnsys data

Family type

The number of hours people are at home is of relevance to both indoor heat gains as well as indoor temperature settings. Also, the family composition and age of inhabitants has an influence on energy consumption. To reflect that in the simulations, the following is considered:

- Number of occupants: 2 adults or 2 adults with 2 children
- Number of hours at home: constant (or most of the time) or only during 'out of office' hours.

We consider the following two cases which are detailed in the table below:

- 2 retired people with limited outdoor activities
- A family with 2 kids at school, parents working outdoors.

ID	2 pers - fulltime @ home	4 pers - @ work/school
Number of Occupants	2	4
Occupation (h/day)	20	14
Occupation (d/week)	6	6
Occupation ratio	71.4% (20h/day * 6d/week /	50.0% (20h/day * 6d/week /

	168h/week)	168h/week)
Heating ratio	42.9% occupation rate - 8h sleep a day	21.4% occupation rate - 8h sleep a day

Dwelling type

The selected building typologies are simplified cases. The single family dwelling has a tilted roof, 2 floors and a rectangular floor plan. The apartment is located on a single floor. It is neither the top nor the ground floor apartment of a multi-story building.

Table 5 gives an overview of the building characteristics for the single family house (SFH) and the apartment as considered for every region and every family type.

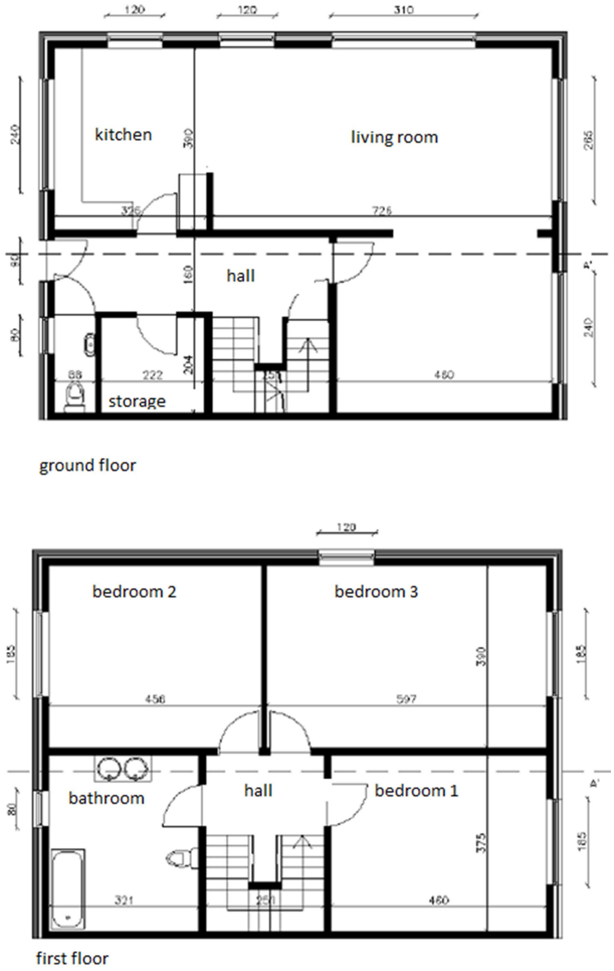


Figure 10: Ground plan for the single family house (SFH)

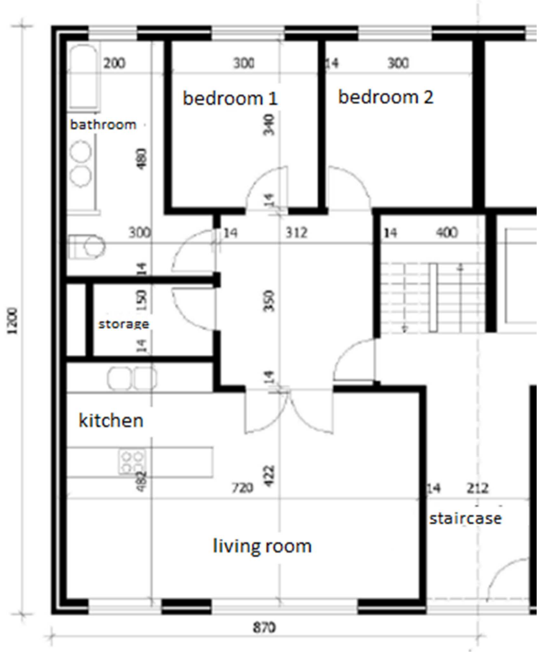


Figure 11: Ground plan for the apartment

Table 5: Building characteristics for the single family house (SFH) and the apartment as considered for every region and every family type (Kenniscentrum Energie, Thomas More Kempen, KU Leuven, 2013)

Parameter	SFH	Apartment
Description	SFH	Apartment
Volume (m³)	548.0	292.2
Total Floor Surface (m²)	187.4	97.4
Compactness	1.46	2.19
Ground Surface (m²)	93.7	30.5
Façade Surface (m²)	119.6	56.9
Roof Surface (m²)	131.4	32.5
Window Surface Orientation 1 (m²)	-	4.3
Window Surface Orientation 2 (m²)	8.0	7.2
Window Surface Orientation 3 (m²)	8.4	1.8
Window Surface Orientation 4 (m²)	13.2	-
Window Orientation 1 (°)	180	180

Window Orientation 2 (°)	-	-
Window Orientation 3 (°)	(90)	(90)
Window Orientation 4 (°)	90	90
Roof Window Surface Orientation 1 (m²)	-	-
Roof Window Surface Orientation 2 (m²)	-	-
Roof Window Orientation 1 (°)	180	180
Roof Window Orientation 2 (°)	-	-
Roof Window Inclination 1 (°)	45	-
Roof Window Inclination 2 (°)	45	-

ANNEX C BUILDING RELATED MEASURES

Building envelope quality and characteristics

The selected parameter values

For all variations, we consider the following hypotheses regarding building envelope characteristics.

Building envelope parameters applicable to all buildings	Value
Thermal Capacity	117,000 J/K
Building Nodes	EPB method BE: B+
g-value glass	0.55
LTA value glass	0.80

4 building envelope variations are defined:

- B1: Business as usual
  For Belgium and Sweden, we considered the building envelope characteristics according to the "energy performance in buildings" regulation for new buildings anno 2014 in Flanders (Belgium)[5]. Considering the warmer climate for Portugal, less stringent energy performance characteristics are considered for this reference.
- B2 - B4: We consider gradually improved building envelope characteristics for these options.

Table 6: Building envelope characteristics for the Belgium (BE) and Sweden (SE) case

Building envelope parameters for BE and SE	B1	B2	B3	B4
n50 (1/h)	3.00	2.00	1.00	0.60
Ufloor (W/m²K)	0.30	0.22	0.15	0.08
Ufloor' floor heating (W/m²K)	0.34	0.24	0.16	0.08
Uwall (W/m²K)	0.30	0.22	0.15	0.08
Uroof (W/m²K)	0.30	0.22	0.15	0.08
Uglas (W/m²K)	1.10	1.00	0.80	0.60
Uframe (W/m²K)	1.45	1.30	1.15	1.00
psi-value (W/mK)	0.10	0.08	0.05	0.00
Uwindow (W/m²K) 75% * Ug + 25% * Uf + 3 * psi	1.49	1.30	1.04	0.70

[5] http://energiesparen.be/epb/welkeeisen

Table 7: Building envelope characteristics for the Portugal (PT) case

Building envelope quality PT	B1	B2	B3	B4
n50 (1/h)	6.00	4.00	2.00	0.60
Ufloor (W/m²K)	0.70	0.50	0.30	0.08
Ufloor' floor heating (W/m²K)	0.97	0.63	0.34	0.08
Uwall (W/m²K)	0.70	0.50	0.30	0.08
Uroof (W/m²K)	0.60	0.40	0.20	0.08
Uglas (W/m²K)	2.90	2.00	1.00	0.60
Uframe (W/m²K)	1.45	1.45	1.45	1.45
psi-value (W/mK)	0.10	0.10	0.10	0.10
Uwindow (W/m²K) 75% * Ug + 25% * Uf + 3 * psi	2.84	2.16	1.41	1.11

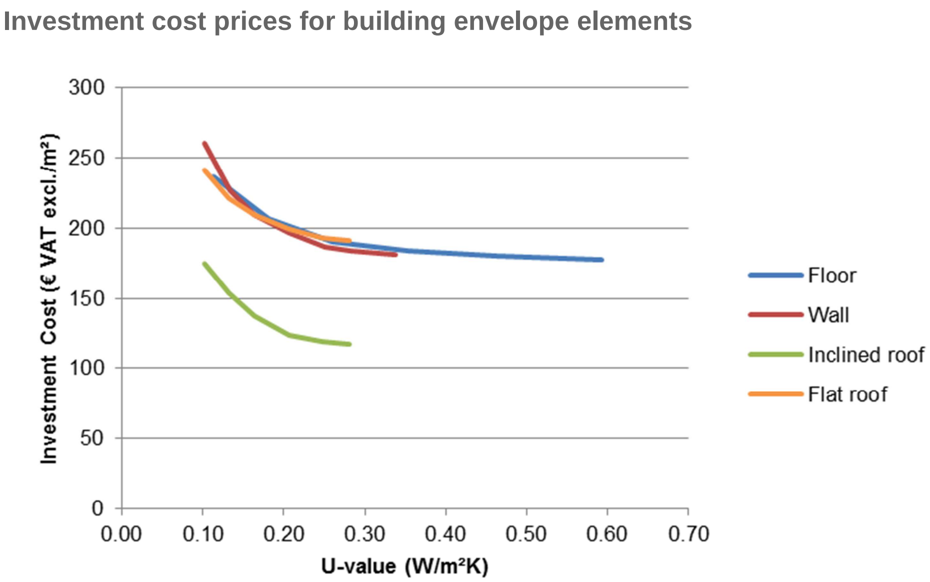


Figure 12: Investment cost curves for the different building envelope parts in function of the U-value (Kenniscentrum Energie, Thomas More Kempen, KU Leuven, 2013)

For windows, we work with an average surface for the windows of 1.5 m².

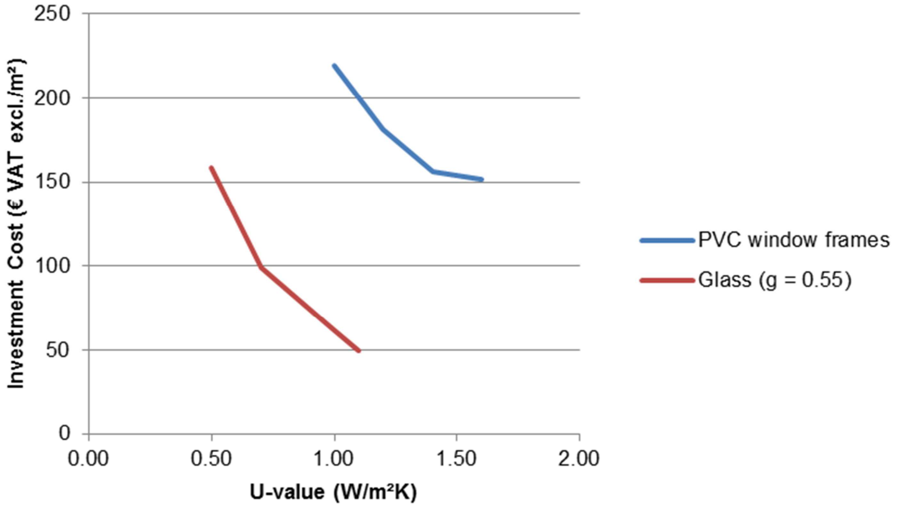


Figure 13: Investment cost curves for window parts (considering PVC window frames) and in function of the U-value (Kenniscentrum Energie, Thomas More Kempen, KU Leuven, 2013)

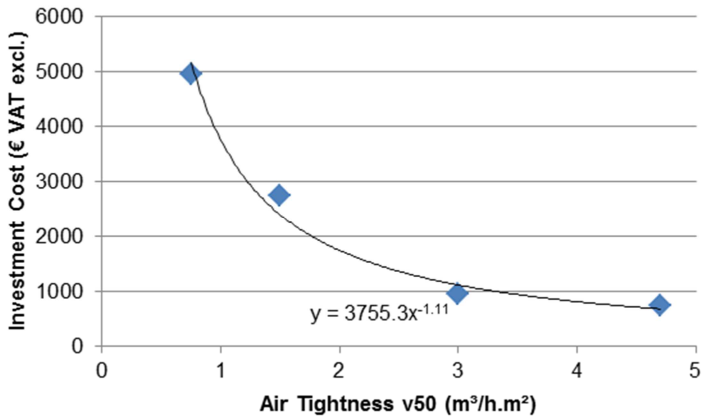


Figure 14: Investment cost curve in function of the air tightness objective

Heating system

The heating system applied, can be rather diverse. But it is especially the combination of heating, distribution, emission and control that is decisive for the overall energy consumption (Peeters L. et al., 2008).

The heat production systems simulated for this study are (condensing) gas boilers and air-to-water and geothermal heat pumps. Each can be combined with either low temperature radiators or floor heating.

The control unit consists of a monitoring device for outside temperature which communicates with the heat production system adapting the temperature of the water departing to the heat emission system.

Selected heating systems

Heat production system	Condensing boiler	Condensing boiler	Condensing boiler	Condensing boiler
Heat carrier	Gas	Gas	Gas	Gas
Primary energy factor	1.00	1.00	1.00	1.00
Heat emission system	Low-T radiators	Low-T radiators	Floor heating	Floor heating
Design temperature of the water departing to the heat emission system (°C)	50	50	40	40
Design temperature of the water returning from the heat emission system (°C)	40	40	30	30
Ration lower to higher heating value for gas (LHV/HHV)	0.90	0.90	0.90	0.90
Production efficiency at a partial load of 30%	108%	108%	108%	108%
Boiler inlet temperature at partial load of 30%	30	30	30	30
f ctrl, heat	0.50	0.50	0.50	0.50
Outside temperature compensated control	No	Yes	No	Yes
Lifetime heat production & emission system (year)	20	20	20	20
Investment cost of the control unit (€ TVA excl.)		60		60
Total maintenance cost (€ TVA excl./year)	50	50	50	50

Heating system parameters	H5	H6	H7	H8
Heat production system	Non-condensing boiler	Non-condensing boiler	Non-condensing boiler	Non-condensing boiler
Heat carrier	Gas	Gas	Gas	Gas
Primary energy factor	1.00	1.00	1.00	1.00
Heat emission system	Low-T radiators	Low-T radiators	Floor heating	Floor heating
Design temperature of the water departing to the heat emission system (°C)	50	50	40	40
Design temperature of the water returning from the heat emission system (°C)	40	40	30	30
Ration lower to higher heating value for gas (LHV/HHV)	0.90	0.90	0.90	0.90
Production efficiency at a partial load of 30%	95%	95%	95%	95%
Boiler inlet temperature at partial load of 30%	30	30	30	30
f ctrl, heat	0.50	0.50	0.50	0.50
Outside temperature compensated control	No	Yes	No	Yes
Lifetime heat production & emission system (year)	20	20	20	20
Investment cost of the control unit (€ TVA excl.)		60		60
Total maintenance cost (€ TVA excl./year)	50	50	50	50

Heating system parameters	H9	H10	H11	H12
Heat production system	Ground-water heat pump	Ground-water heat pump	Air-water heat pump	Air-water heat pump
Heat carrier	Electricity	Electricity	Electricity	Electricity
Primary energy factor	2.5	2.5	2.5	2.5
Heat emission system	Low-T radiators	Floor heating	Low-T radiators	Floor heating
Design temperature of the water departing to the heat emission system (°C)	45	40	45	40
Design temperature of the water returning from the heat emission system (°C)	35	30	35	30
Seasonal Performance Factor (SPF)	4	5	3	3.5
f ctrl, heat	0.50	0.50	0.50	0.50
Outside temperature compensated control	Yes	Yes	Yes	Yes
Lifetime heat production & emission system (year)	22.5	22.5	22.5	22.5
Total maintenance cost (€ TVA excl./year)	75	75	100	100

Investment cost prices for heating systems

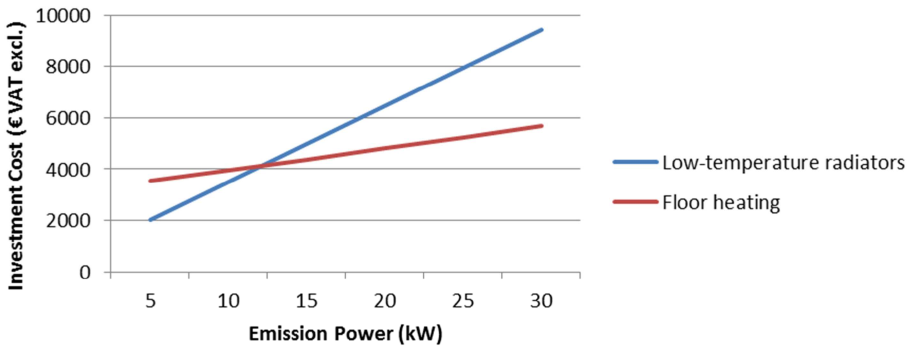
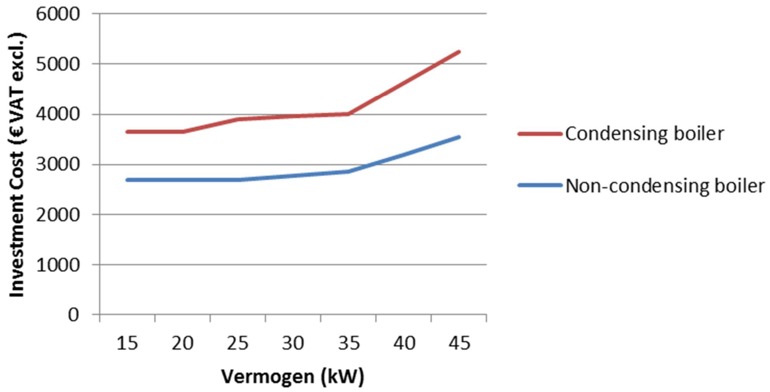


Figure 15: Investment cost curves for the heat emission systems considered in this study (Kenniscentrum Energie, Thomas More Kempen, KU Leuven, 2013)



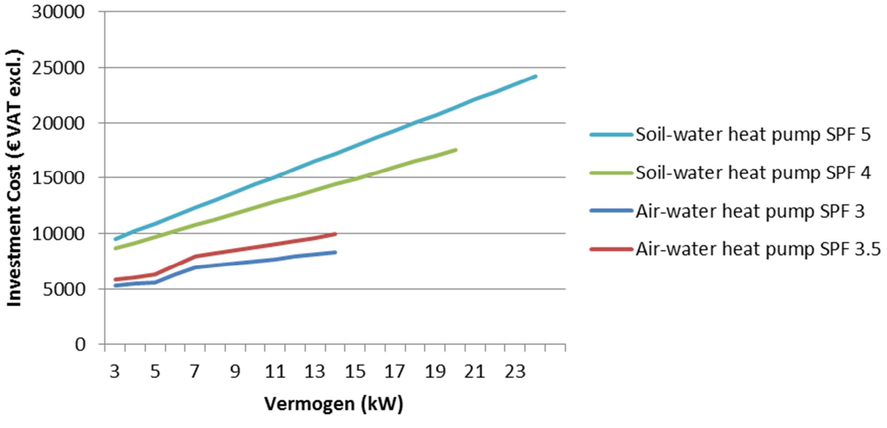


Figure 16 a-b: Investment cost curves for the condensing and non-condensing boiler (a) and the different heat pump variations (b) considered in this study, based on (Kenniscentrum Energie, Thomas More Kempen, KU Leuven, 2013)

Indoor temperature control

We consider three options for indoor temperature control:

- Thermostatic valves on all radiators in all rooms.
- A central thermostat in the living room/kitchen. Radiators in this room are equipped with normal radiator valves. Radiators in all other rooms are equipped with thermostatic valves.
- All rooms are equipped with a programmable temperature control unit. The radiators are equipped with normal radiator valves.

Indoor temperature parameters	T1	T2	T3
Description	Thermostatic valves radiators	Central thermostat & thermostatic valves radiators	Temperature control per room
Average indoor temperature (°C)	19.6°C	19.1°C	18.4°C
Investment cost (€ TVA excl.) • thermostatic valve • standard radiator valve • programmable room thermostat	 • 50 €/valve	 • 50 €/valve • 19.5 €/valve	 • 19.5 €/valve • 150 €/room
Investment cost (€ TVA excl.) • central thermostat • differential pressure regulator • central control unit	NA	 • 144 € • 48 €	 • 400 €

The average monthly indoor temperature is calculated as follows:

For T1 - Thermostatic valves only

With this variation, we consider the use of thermostatic valves only as a means of controlling the indoor temperature.

The average indoor temperature is calculated as follows:

$$T_{indoor,average} = S_{living/(kitchen)} \times 20°C + S_{bathroom} \times 24°C + S_{other} \times 18°C$$

With:

- $S_{living/(kitchen)}$: the Surface of the living room area (including kitchen in case of the single family house) as a percentage of the total area

- $S_{bathroom}$: the Surface of the bathroom as a percentage of the total area
- S_{other}: the Surface of all other rooms as a percentage of the total area

For this variation, we take into account the cost of the thermostatic valves and the cost of the radiator knob (one per radiator for the both of them)

For T2 - Central thermostat

With this variation, we consider the use of a central thermostat (with week program) for the living room area (including the kitchen in case of the single family house). This central thermostat allows for a precise control of the temperature in the living room area. In all other rooms, we assume radiators with thermostatic valves (analogue with T1). This variation results in less heating hours, a lower average monthly indoor temperature and therefore expected lower energy costs.

For this variation, the average indoor temperature is calculated as follows:

$$T_{indoor,average} = S_{living/(kitchen)} \times (HR \times 20°C + (1 - HR) \times 18°C) + S_{bathroom} \times 24°C + S_{other} \times 18°C$$

With:

$$HR\ (Heating\ Ratio\ in\ \%) = \frac{(x-8) \times y}{168}$$

Occupation	Single family house	Apartment
x	20 hours/day	14 hours/day
y	6 days/week	6 days/week
HR	42.9 %	21.4%

For T3 - Advanced indoor temperature regulation per room

With this variation, we consider the use of an advanced indoor temperature regulation per room. This advanced regulation allows for a precise control of the temperature in every individual room. This variation is expected to result in even less heating hours compared with the use of a central thermostat[6], a lower average monthly indoor temperature and therefore expected lower energy costs.

For this variation, the average indoor temperature is calculated as follows:

$$T_{indoor,average} = S_{living/(kitchen)} \times (HR \times 20°C + (1 - HR) \times 18°C) + S_{bathroom} \times \frac{(x \times 24°C + y \times 18°C)}{24hours} + S_{other} \times 18°C$$

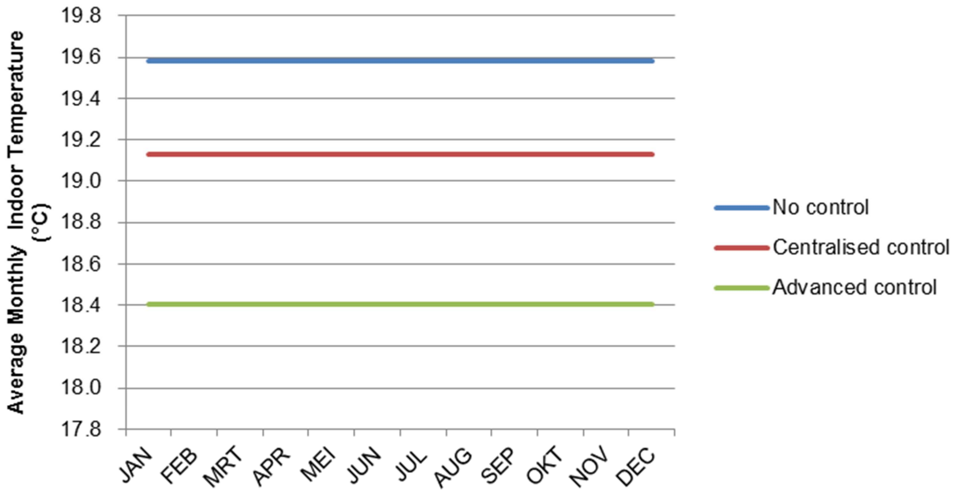
With:

$$x = 2\ hours\ (assumed\ daily\ use\ (heating)\ of\ bathroom\ area)$$

$$y = 24\ hours - x$$

[6] Again, considering a consistent comfort level

With these calculations rules, we arrive at the following average indoor temperature (set point)



We assume the lifetime of the indoor temperature control units equal to the lifetime of the heating system.

The total number of radiators is defined as follows:

- For the single family house: a total of 9 radiators
  Living room: 3, kitchen: 1, bathroom: 1, hallway: 1, bedroom: 1 (3 in total)
- For the apartment: a total of 5 radiators
  Living room/kitchen: 2, bathroom: 1, bedroom: 1 (2 in total)

Ventilation

The ventilation variations considered in this study depend on the country for which the technical-financial analysis is made. For Portugal, we only consider natural ventilation. For Belgium and Sweden, several variations of mechanical ventilation systems are considered.

General

The impact of regulation on the energy use for heating follows from lower ventilation losses due to a lowered ventilation rate. This impact of regulation is taken into account through the mheat,seci factor in the following formula

$$V_{vent} = \left(0.2 + 0.5 \times e^{\left(\frac{-V}{500}\right)}\right) \times f_{reduc} \times m_{heat} \times V$$

With:

- V_{vent}: the ventilation flow rate of the building in m³/h
- V: the volume of the building in m³

- F_{reduc}: a reduction factor in the case of a control unit which continuously measures and adapts the flow rate settings (CO2-controlled) or using presence detection (known as C+)
- m_{heat}: a reduction factor function of the type of ventilation system and quality of installation

Presence detection

Presence detection in ventilation systems allows for a reduction in ventilation flow and therefore lower heat losses. We considered but the extra investment cost for CO2-detectors in the different rooms.

Electricity use for ventilation

We assume DC ventilators for all ventilation options.

The electricity consumption of the ventilator fan(s) is based on the average electrical fan power which is calculated as follows:

- For a system C:

$$\frac{0.085 \times V}{3.6}\,(kWh)$$

- For a system D:

$$\frac{0.15 \times V}{3.6}\,(kWh)$$

With:

$$V = the\ Volume\ of\ the\ building\ unit$$

Note: the electricity consumption of the ventilation fans is based on 24/7 full capacity workload

Selected scenarios

Ventilation type	natural ventilation (PT only)	mechanical extraction	mechanical extraction &	mechanical extraction & presence detection
Lifetime (years)	90	30	30	30
Continuous measurement and adapting flow rate setting (CO2-controlled)	No	Yes	No	Yes
F_{reduc}	/	1.00	0.88	0.75
m_{heat}	/	1.33	1.33	1.33
Fixed investment cost (€)	-	2,000	2,500	2,500
Variable investment cost (€/m³)	-	2.0	2.5	2.5
Investment cost presence detection (€)				657

Maintenance cost (€/year)	-	50	50	50

Ventilation type	mechanical supply & extraction	mechanical supply & extraction & presence detection
Lifetime (years)	30	30
Continuous measurement and adapting flow rate setting (CO2-controlled)	No	Yes
F_{reduc}	1.00	0.75
m_{heat}	1.50	1.21
Fixed investment cost (€)	4,150	4,150
Variable investment cost (€/m³)	3.0	3.0
Investment cost presence detection (€)	-	1050
Maintenance cost (€/year)	150	150

Source: Kenniscentrum Energie / Thomas More Kempen / KU Leuven, Studie naar kostenoptimale niveaus van de minimumeisen inzake energieprestaties van nieuwe residentiële gebouwen, 22/04/2013

Lighting

The energy consumption for lighting depends both on the type (size) of dwelling and the user type (defining the number of operating hours). This study considers 3 lighting variations i.e.:

- A business as usual case where lighting is dominated by the use of 12V-50W spots
- A progressive variation considering the use of LED only (220V-6W)
- An intermediary case considering the average of these two cases for the electricity consumption, the investment and maintenance cost.

Table 8: Lighting variations as considered in this study

Lighting system	12V-50W (BAU)	220V-6W (LED)
Initial investment cost (€ excl VAT)	50	50
Average lighting hours (lifetime) per lighting point	3,000	30,000

(hours)		
Reinvestment cost (€ excl VAT/lighting point)	2.5	15

Selected lighting systems

Number of light points	Single family house	Apartment
living	10	6
hall	4	3
kitchen	5	3
storage	1	1
bathroom	5	4
bedrooms	3 x 2	2 x 2
total	31	21

Number of lighting hours	2 pers - fulltime @ home	4 pers - @ work/school
living	6.0	4.0
hall	1.0	1.0
kitchen	2.0	2.0
storage	0.5	0.5
bathroom	1.0	2.0
bedrooms	1.0	1.0
total	12	11

ANNEX D METHODOLOGY FOR BUILDING RELATED MEASURES

Global Cost Calculation

For the global cost calculation methodology, the general calculation approach of the EN15459 regarding the global cost method is used. This approach is described below. For some specific parameters, we

The calculation of global cost considers the initial investment, the annual costs for every year and the final value, all referring to the starting year. Global cost is directly linked to the duration of the calculation period.

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i) \right) - V_{f,\tau}(j) \right]$$

With:

- C_g (τ) global cost (referring to the starting year τ_0)
- C_I initial investment costs
- $C_{a,i}$ (j) cost during year i for energy-related component j (energy costs, operational costs, periodic or replacement costs, maintenance costs and added costs)
- R_d (i) discount rate for year i
- $V_{f,\tau}$ (j) final (= residual) value of component j at the end of the calculation period (referring to the starting year τ_0)

The **discount rate** R_d depends on the real interest rate R_R (market interest rate adjusted for inflation) and on the timing of the costs (number of years after the starting year). In this study, we consider a real interest rate R_R of 3% (consisting of a 1% risk free rent and an additional 2% covering the investment risks for individuals). This real interest rate is adjusted considering an inflation rate of 2%, arriving at a (nominal) discount rate R_d of 5%. The EN 15459 does not fix a specific calculation period for the global calculation method. In this study, we consider an evaluation period of 30 years, as this timeframe covers the lifetime of most of the measures assessed, is a time span for which fixed interest rates are offered (e.g. by banks), and beyond which reasonable forecasts for energy prices are quite difficult. 30 years is also the calculation period for residential buildings according to the guidelines accompanying Commission Delegated Regulation No 244/2012 on a comparative methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements (EC, 2012).

The final or residual value $V_{f,\tau}$ (j) of a component is determined by straight-line depreciation of the initial investment until the end of the calculation period and refers to the beginning of the calculation period. Costs or benefits from disposal, if applicable, can be subtracted or added to the final value.

The lifetime of an investment will rarely be exactly equal to the evaluation period (i.e. the lifetime of the building).

- If the lifetime of the investment is shorter than the evaluation period, a reinvestment is taken into account.
- If the lifetime of the (re)investment is longer than the evaluation period, a residual value is calculated).

Figure 17 illustrates the approach for an investment which has a longer lifetime than the evaluation period. With an assumed lifespan of 40 years and a straight-line depreciation, the residual value after 30 years (end of the evaluation period) is 25 % of the initial investment cost. This value has to be discounted to the beginning of the calculation period. (EC, 2012)

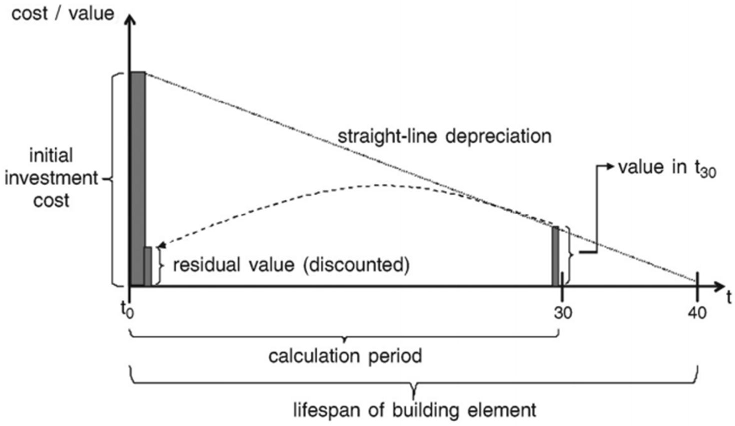


Figure 17: Calculation of the residual value of a building element (investment) with a longer lifetime than the evaluation period (lifespan of the building itself)

Figure 18 shows how the residual value is calculated for a building element which has a shorter lifespan than the evaluation period. With an assumed lifespan of 20 years the investment has to be replaced after that period of time. Once the element has been renewed a new depreciation period starts. In this case, after 30 years (end of the evaluation period) the residual value of the element is 50 % of the replacement cost. Once again this value is discounted to the beginning of the calculation period. (EC, 2012)

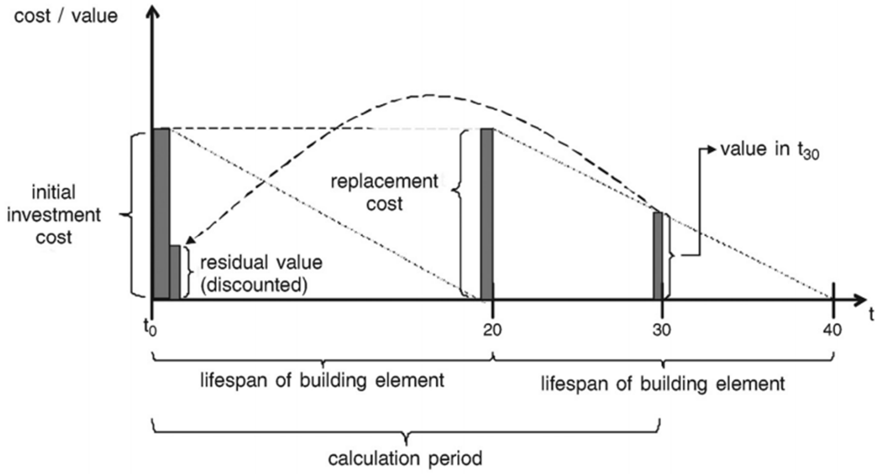


Figure 18: Calculation of the residual value of a building element (investment) which has a shorter lifetime than the evaluation period (lifespan of the building itself)

Gas & electricity

As illustrated by Figure 19, domestic electricity and gas prices vary significantly between EU-countries, (Geo-) politics, national (green) energy policies, etc. all play their role in this. The spread between one nation's electricity and/or gas price and the EU-28 average can be quite significant. This is e.g. the case for Sweden's gas price.

For this study, we selected Belgium, Portugal and Sweden as countries representing respectively Europe's moderate, warm and cold climate region. As can be deducted from the graph, there is no correlation between the electricity/gas price within a country and its climate. Using national energy prices would therefore result in conclusions which are not necessarily consistent between all countries within one climate region.

This study makes abstraction of the difference in national energy prices and uses the EU-28 average energy prices, i.e.: 17.2 c€/kWh for electricity and 6.08 c€/kWh for gas.

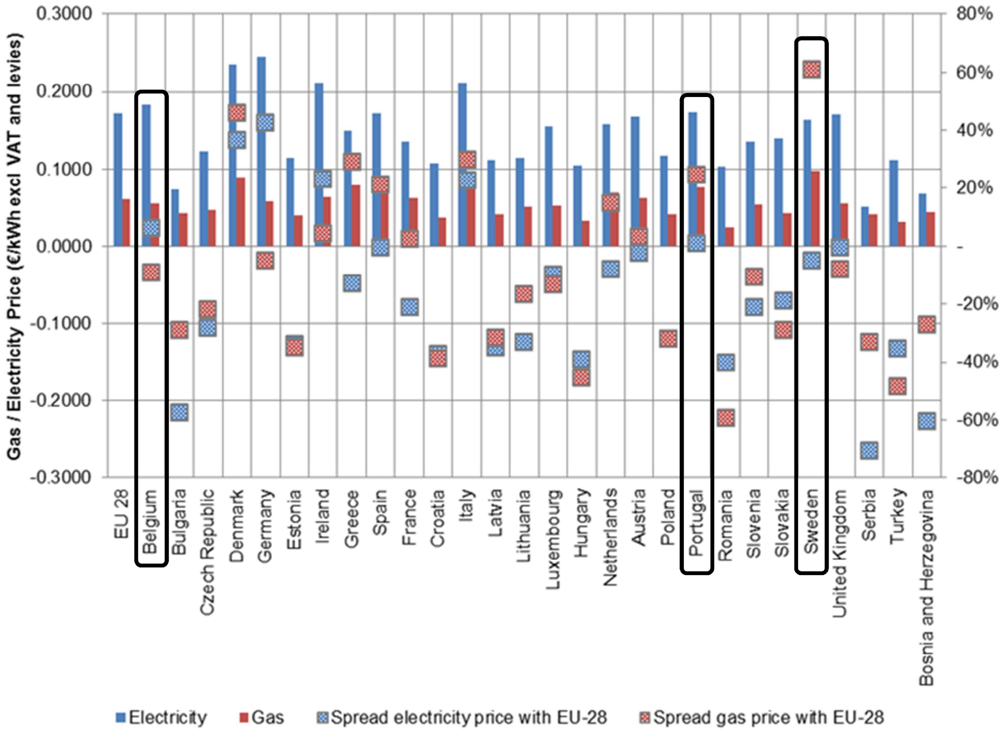


Figure 19: Domestic electricity and gas prices for several EU countries with an indication of the price spread with the average over all 28 EU-countries (Eurostat, 2nd half of 2013)

The primary energy factors used in this study are 1 for natural gas and 2.5 for electricity

Energy price evolution

According to annex II of Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 (EC, 2012), member states can take into account the estimated fuels and electricity price development trends as provided for by the European Commission on a biannually updated basis. These updates are available at the following website:
http://ec.europa.eu/energy/observatory/trends_2030/index_en.htm

In this study, we consider these same trends as described in the graphs below. Where needed, these trends were extrapolated beyond 2030.

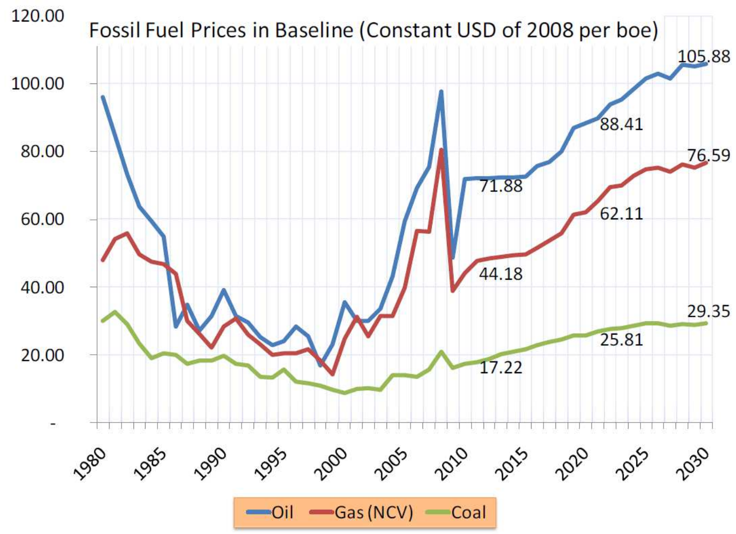
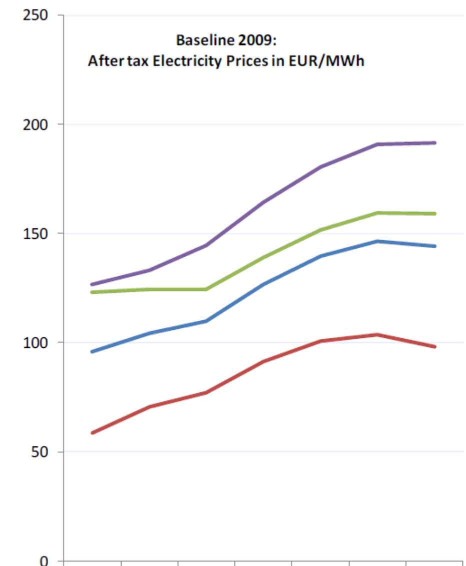


Figure 20: Source data price evolution fossil fuels according to the Baseline 2009 scenario (expressed in $2008/boe) (EC, 2010c)



	2000	2005	2010	2015	2020	2025	2030
Average	96	104	110	127	140	146	144
Industry	59	71	77	92	101	104	98
Services	123	124	124	139	152	159	159
Households	127	133	144	164	180	191	192

Figure 21: Source data price evolution electricity according to the Baseline 2009 scenario (expressed in €2005/MWh) (EC, 2010c)

Value Added Tax rate

This study considers building related measures, specifically in new residential buildings. For these types of investments, EU member states typically apply the standard Value Added Tax (VAT) rate. Table 9 gives an overview of these VAT rates for the 28 EU member states. The spread between member states is rather limited; the average VAT rate is therefore selected for this study, i.e. 21.54%

Table 9: Value Added Tax rates applied in the different EU member states (EC, 2014).

Member States	Code	Super Reduced Rate	Reduced Rate	Standard Rate	Parking Rate
Belgium	BE	-	6 / 12	21	12
Bulgaria	BG	-	9	20	-
Czech Republic	CZ	-	15	21	-
Denmark	DK	-	-	25	-
Germany	DE	-	7	19	-
Estonia	EE	-	9	20	-
Greece	EL	-	6,5 / 13	23	-
Spain	ES	4	10	21	-
France	FR	2,1	5,5 / 10	20	-
Croatia	HR	-	5 / 13	25	-
Ireland	IE	4,8	9 / 13,5	23	13,5
Italy	IT	4	10	22	-
Cyprus	CY	-	5 / 9	19	-
Latvia	LV	-	12	21	-
Lithuania	LT	-	5 / 9	21	-
Luxembourg	LU	3	6 / 12	15	12
Hungary	HU	-	5 / 18	27	-
Malta	MT	-	5 / 7	18	-
Netherlands	NL	-	6	21	-
Austria	AT	-	10	20	12
Poland	PL		5 / 8	23	-
Portugal	PT	-	6 / 13	23	13
Romania	RO		5 / 9	24	-
Slovenia	SI	-	9,5	22	-
Slovakia	SK	-	10	20	-
Finland	FI	-	10 / 14	24	-
Sweden	SE	-	6 / 12	25	-
United Kingdom	UK	-	5	20	-

ANNEX E REFERENCES

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